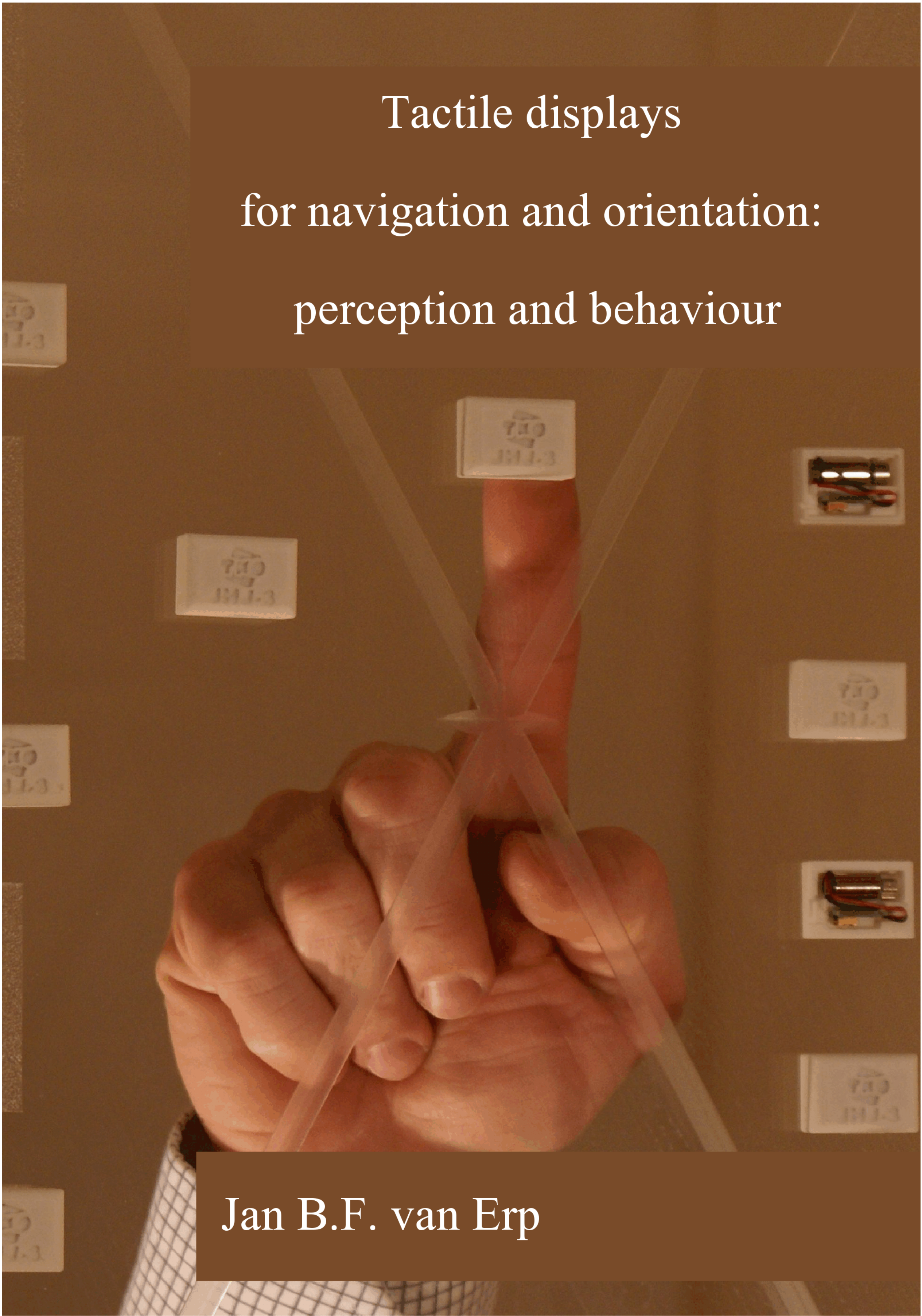
Tactile displays for navigation and orientation: perception and behaviour



Jan B.F. van Erp

Tactile displays for navigation and orientation: perception and behaviour

Tactiele displays voor navigatie en oriëntatie:
perceptie en gedrag
(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht
op gezag van de rector magnificus, prof.dr. W.H. Gispen,
ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen op maandag 4 juni 2007 des middags te 4.15 uur

door

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geboren op 9 juni 1969
te Lisse

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ISBN /EAN 978-90-393-4531-3.

The work described in this thesis was sponsored by
The Netherlands Organisation for Applied Scientific Research TNO.

This book is printed on FSC paper by Mostert & Van Onderen, Leiden, The Netherlands.

Contents

Chapter 1. Introduction[1]

Abstract

Navigation and platform control skills, i.e., route planning and moving about, are indispensable to survive the real and enjoy the virtual world. Access to navigation information rapidly becomes standard in many situations (such as GPS receivers and collision avoidance systems in cars). However, perceiving and processing the information may result in overloading the user's visual sense and cognitive resources. Developing information presentation schemes that reduce these overload threats therefore becomes increasingly important. Employing the sense of touch can reduce the visual load. Among the many functions of the skin, that of sensory system is underutilised in man-machine interfaces. By developing an intuitive information presentation concept, we may also lessen the cognitive load. In this concept, the display would evoke the user's response automatically. In the tactile sense, an intuitive presentation concept may be based on the proverbial tap-on-the-shoulder that can draw and direct an individual's attention. By extending the location of the taps from the shoulders to the whole torso, we may have an intuitive three-dimensional display at our disposal.

This thesis tries to tackle three issues: can a tactile torso display be used to present platform navigation and control information? Can a tactile torso display reduce the sensory overload? And finally, can a tactile torso display counteract the threat of cognitive overload by implementing an intuitive information presentation concept?

[1] Parts of this chapter have been published as:

Van Erp, J.B.F. (2006b). *The multi-dimensional nature of encoding Tactile and Haptic Interactions: from psychophysics to design guidelines*. Proceedings of the 50th annual meeting of the Human Factors and Ergonomics Society meeting, San Francisco. Santa Monica: Human Factors and Ergonomics Society.

Van Erp, J.B.F. & Werkhoven, P.J. (2006). *Validation of Principles for Tactile Navigation Displays*. Proceedings of the 50th annual meeting of the Human Factors and Ergonomics Society meeting, San Francisco. Santa Monica: Human Factors and Ergonomics Society.

1.1 Human behaviour in platform navigation and control

Darken and Sibert (1993, p157) define navigation as: "the process by which people control their movement using environmental cues and artificial aids such as maps so that they can achieve their goals without getting lost". In this thesis, navigation is seen from a steering and control tasks perspective, that is: human skilled behaviour in tasks like driving, flying and sailing. Prevett and Wickens (1994) distinguish two navigation sub tasks: a) to perform the actions necessary to get to a location, and b) to understand the spatial structure of the area being traversed. Wickens (1992) called these sub tasks local guidance and global awareness, respectively. Local guidance has an emphasis on the immediate surrounding environment, is focussed on manoeuvring along a route and interacting with objects along the route. Local guidance is related to physical challenges. Global awareness focusses on acquiring and maintaining spatial structural information and is related to cognitive challenges, including aspects such as understanding, planning and problem solving. Preferably, the information for global awareness must be presented in a world referenced (north-up) display (Wickens, 1992; see also Roscoe, 1968). However, local guidance tasks predominantly need correspondence between display and control in terms of left, right, etc. which requires an ego-referenced or heading-up display.

Navigation, although a critical skill in human survival, is no sinecure in platform control situations. Most people have experienced the feeling of being lost. Building a mental representation may be a tremendous effort, especially in complex areas like medieval towns with mazes of small streets and alleys, or in areas with little unique landmarks like modern cities with similar buildings for many blocks. Problems become even more apparent when we are using means of transportation that have a much higher speed than walking such as cars, boats and aeroplanes. Besides difficulties caused by the complexity of and the speed in our natural environment, navigation tasks outside our natural world become more and more challenging. Technological advances cause real worlds and simulated worlds to merge into what is called augmented reality. Augmented reality ranges from real museums augmented with a virtual guide to fully simulated worlds in which only your own hand is real. In augmented worlds natural navigation and manipulation are a real challenge, in particular when these environments allow for discontinuous displacement (e.g., hyperlinks) and other supernatural behaviour (Bakker, 2001). In virtual, augmented or remote environments including the internet, virtual communities, gaming, learning and simulation, tele-operation etc., navigation may not be critical for survival of the organism but it determines to a large extent the efficiency and pleasure in using them. Supporting people's performance to keep in pace with these developments in travelling speed, environmental complexity, and supernatural displacements constitutes an important human factors challenge.

Navigation support

Supporting platform navigation performance is as old as the hills, dating back to ancient civilisations that used celestial knowledge about the stars and simple dead reckoning techniques. Later, navigation tools such as the cross-staff, sextant and accurate compasses and clocks, enabled explorers to scout all continents, and return to their place of origin. Nowadays, we rely on navigation information from electronic systems such as radar, radio, the global positioning system (GPS), lane departure sensors, and park assists. Systems like GPS inform the user about his current location and orientation and the direction to go in more accurately and more frequently than ever before.
The abundant availability of high quality navigation information is by no means a guarantee that problems of platform navigation and control cease to exists. At the global awareness subtask, the changes are relatively small. Determining one's position with a map and compass requires well-developed skills while this information is directly available when using a GPS device. However, planning one's route or building

a mental representation with an electronic map on a computer screen and waypoints marked with a mouse click is not substantially different from using a paper map and a pen to mark the waypoints. The biggest change that electronic devices have brought the user, however, is probably at the local guidance level. Especially the continuous availability of local guidance information may introduce new problems. In ancient times checking the location of the pole star or the direction on a compass every other minute was more than sufficient to keep a course. However, nowadays we are almost continuously bothered with local guidance information. For example, when driving[2] we may encounter noisy rumble strips or lane departure warning systems that push us back into our lane, voices that inform us in how many metres from now we must turn left, warning signals that tell us that we are too close to a lead vehicle, and loads of traffic signs telling us how to interact with the road and the road users. Although these devices allow us to extend our operations or make them safer, we also become dependent on them. Failing to pick up local guidance information correctly and timely may have serious consequences, especially when travelling at non-natural speeds as we do on the highway. Potential bottlenecks to do so are sensory and cognitive overload. In this thesis, we will introduce a local guidance information presentation principle that tries to counteract both bottlenecks. The principle is based on: a) using the skin as an information channel to lower the risk of sensory overload, and b) using an intuitive[3] interface approach to lower the risk of cognitive overload (see Figure 1.1).

In the remainder of this Chapter, We will introduce a model for human navigation behaviour in platform navigation and control, specify the local guidance parameters and tasks in more detail (1.2), zoom-in on the two critical issues of sensory and cognitive overload (1.3) and explain why using the skin as an information channel can potentially counteract both risks (1.4). In Section 1.5, We will introduce the skin and in 1.6 the pros and cons of using the skin as an information channel. Section 1.7 is devoted to the important issue of introducing an alternative information channel, namely crossmodal perception. Finally, in Section 1.8, We will introduce the critical research issues and the outline of the thesis.

1.2 Modelling human behaviour in platform navigation and control

Although Wickens' subdivision in global awareness and local guidance is an important one, it is not a complete model of human behaviour in platform navigation and control. With respect to platform navigation and control, two different classes of models can be recognised[4]. The first class uses a closed-loop approach with several steps or (hierarchical) functions to describe behaviour, the second class categorises behaviour at different levels (like Wickens' sub tasks). Relevant models of the first class are Sheridan's model for supervisory (vehicle) control (1992), Wickens' more general information processing model (1984, 1992) and Veltman and Jansen's workload framework for adaptive operators (2004). Two models of the second class are that of Rasmussen which describes behaviour as skill-based, rule-based and knowledge-based (1982, 1983), and that of Vicente and Rasmussen which has two levels: analytical and

[2] Many examples in this chapter are related to driving since most people are familiar with this situation and can imagine the problems. However, the problems and this thesis is not only about driving, but includes flying, sailing, walking, and orienting in space.

[3] We use the following working definition of an intuitive display: an intuitive displays is a display that automatically triggers the required reaction and that minimises the use of cognitive resources.

[4] Please note that this thesis is not about human navigation, but about human behaviour in **platform** navigation and control.

perception-action (1988, 1990). We will describe these models in brief, establish the links between them and then combine them into one model called prenav.

Figure 1.1. A helicopter pilot showing a TNO Tactile Torso Display (TTTD) to support local guidance. The TTTD consists of a matrix of vibrating elements inside a multi-ply garment covering the pilot's torso. By using the skin as an information channel, this navigation display can potentially reduce the overload of the pilot's ears and eyes. Furthermore, the localized vibrations can act as a 'tap-on-the-shoulder' and may be intuitively processed by the pilot, thus reducing the risk of cognitive overload.

Sheridan's model for (supervisory) vehicle control

Figure 1.2 depicts Sheridan's loop for vehicle control. The three functions navigation, guidance, and control are serially executed and have their own feedback loop based on perception of the vehicle's behaviour. The navigation function refers to aspects such as planning, decision making and selection of waypoints. The link between the navigation and the guidance function is a plan. Guidance refers to the short term progress of the vehicle: is the vehicle still on the route, is there other traffic, etc.? Guidance is closely linked to pursuit tracking. The link between guidance and the next function is the route. The control function is involved with tasks such as pitch, heading, and lateral and longitudinal vehicle control and is closely linked to compensatory tracking. The link between the control level and the vehicle is established via control actions.

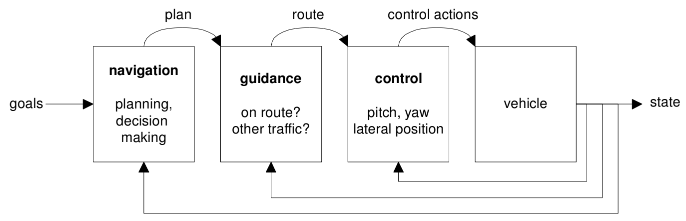

Figure 1.2. Sheridan's model of (supervisory) vehicle control.

Wickens' model of information processing

The second model that has a loop character is the information processing model of Wickens as schematically depicted in Figure 1.3, and similar variants such as the Framework for the Investigation of Navigation and Disorientation FIND by Bakker (2001, p. 4-9). Wickens also uses a serial process in which a stimulus results in a sensation that (based on attention and information stored in memory) leads to a percept[5]. This percept is the input for the decision making process that is also affected by memory and attention. The decision process ultimately leads to action selection, and when executed to a response that is also sensed thus closing the loop. For navigation behaviour, Wickens and Prevett (1995) introduced a model describing the knowledge and the displays required for the two sub tasks. Local guidance requires ego-centred knowledge and a display that has a duplicate frame of reference: a rotating frame with 3D perspective and zoomed-in; while global awareness requires world-centred knowledge and a duplicate display: a fixed frame (usually North-up) with a 2D perspective and a wide view (see also Van Erp & Kappé, 1997). When linked to the model of Sheridan, sensation and perception predominantly correspond to the feedback loop, decision to the navigation and guidance functions, and action to the control function.

Bakker used Wickens' model as basis for his FIND framework (Figure 1.3, lower panel) for use in Virtual Environment applications. In the FIND model, required movements are determined on the basis of information stored in the user's cognitive map of the VE and knowledge about his/her current location in the VE. The latter is based on a combination of path integration, visual recognition of the environment, and cognitive anticipation.

[5] sensation refers to the process by which information about external events is detected by the sensory receptors and transmitted to the brain, while perception refers to the interpretation of sensory input by the brain.

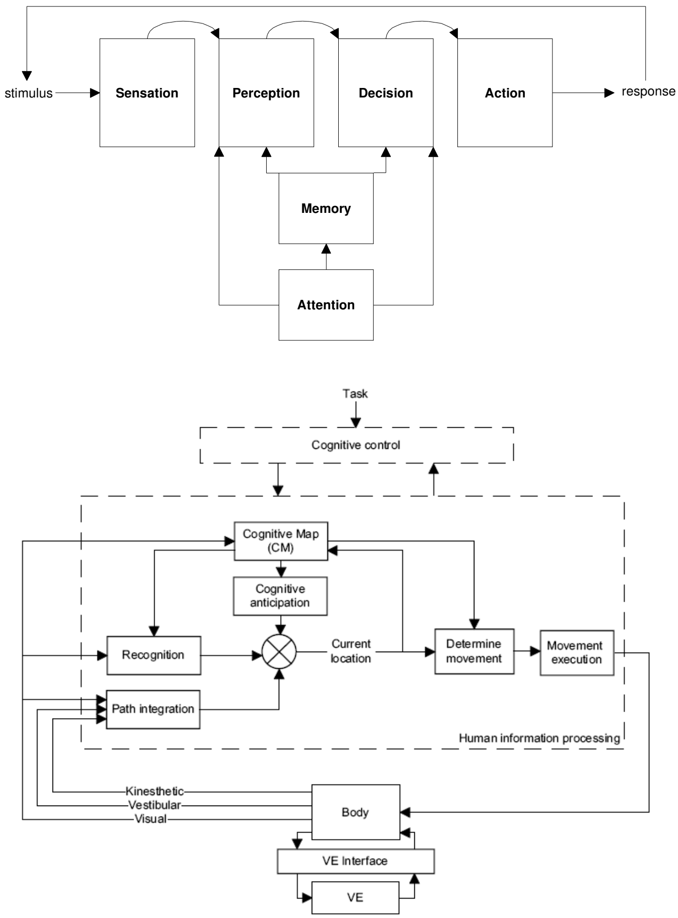

Figure 1.3. Wickens' model of information processing (upper panel) and Bakker's FIND framework (lower panel; from Bakker, 2001).

Veltman and Jansen's workload framework

A recent and for this work quite relevant model is Veltman and Jansen's workload framework (2004). This framework is based on perceptual control theory, which assumes that the difference between a required situation (goal) and an actual situation (sensor information) is crucial for the adaptive behaviour of biological systems (see Figure 1.4; left panel for the complete model and right panel for a simplified version). The core of the workload framework consists of two loops: an information processing loop and a state regulation loop which are crucial for the former (the state regulation loop is not depicted in the simplified version). Veltman and Jansen explain that state is often neglected in information processing models, while everybody knows that it is difficult to perform a cognitive demanding task while being in a sub-optimal state, for example due to sleep loss or fatigue. An important process to ensure a required state is investing mental effort. Herewith, Veltman and Jansen link mental workload with information processing. Another critical component in their model is that of (environmental) stressors. A stressor is an external state or state change that results in a response from an organism required to maintain homeostasis or in Veltman and Jansen's framework the task goals. External stressors such as noise, vibration, altered G environments, adverse lighting, confined spaces, air pollution, and extreme temperatures are assumed to affect the state of the operator. In their model, the intensity of the information processing loop is adjusted depending on the difference between the required and perceived actual performance.

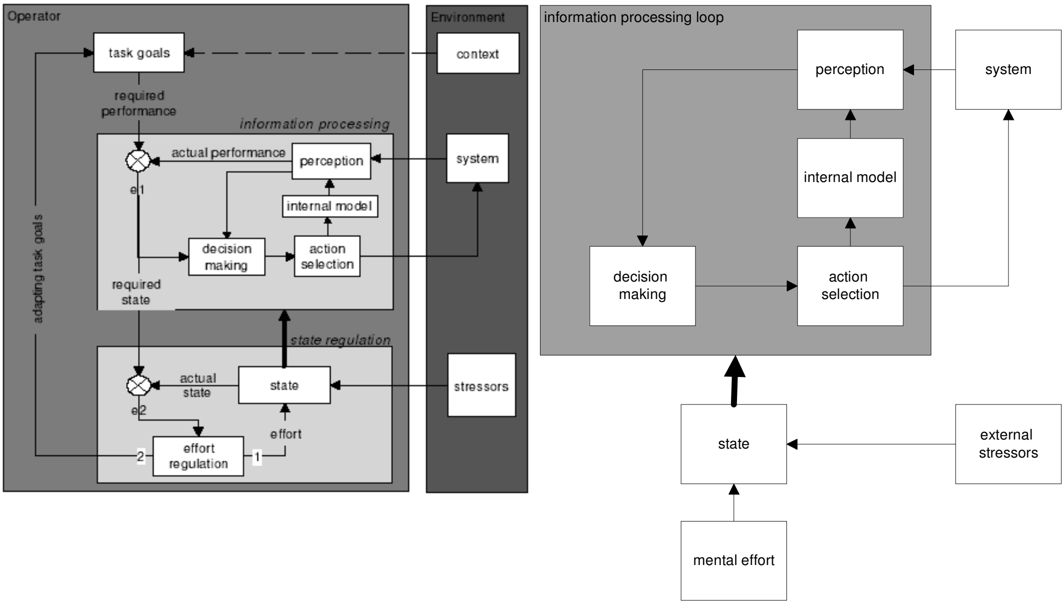

Figure 1.4. Complete (left) and simplified version (right) of the workload framework of Veltman and Jansen.

Rasmussen's and Vicente & Rasmussen's levels of human behaviour

Rasmussen distinguished three levels of behaviour: skill-based, rule-based and knowledge-based. Skill-based refers to well-learned sensory motor performance in continuous manual control tasks in stationary conditions. Rasmussen's rule-based and knowledge-based levels rely on cognitive resources (at the rule-based level on if... then... rules stored in memory, while knowledge-base refers to conscious analytical processes). Vicente and Rasmussen's two level model (analytical and perception-action) can be considered as a simplified version of Rasmussen's three level model. The analytical level is serial, requires deliberate attention and is slow and labourious, while the perception-action level is parallel, requires little attention and is fast and effortless. The three levels can be linked to Sheridan's model: knowledge-based behaviour predominantly corresponds to navigation / planning, rule-based to guidance and skill-based to control.

Prenav, an integrated model of human navigation

The previous paragraphs showed two things. Despite the unique aspects the individual models have, they can all be mutually linked (some more easily than others). Furthermore, there is not a model that is specifically focussed on human behaviour in platform navigation and control. This calls for an approach to come to an integrated model based on integrating and shaping the relevant aspects of the models described above. This approach resulted in the prenav model, described below and depicted in Figure 1.5. The prenav model is used as a framework in this thesis to explain and illustrate the relevance of choices and experiments and to interpret the experimental results and observations. Prenav is a simplification of the involved processes, does not result in quantitative predictions, and is therefore not formally tested in this thesis.

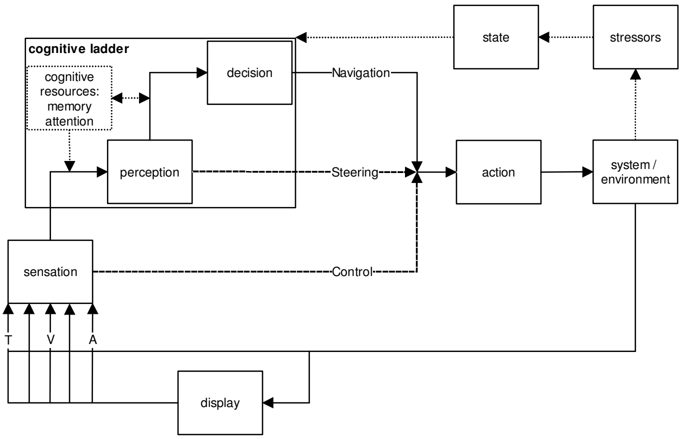

Figure 1.5. The prenav model for human behaviour in platform navigation and control. See text for explanation.

The information processing loop in prenav

An important loop in prenav is the information-processing loop: sensation→perception→decision→action, and back via environment or a display. The perception and decision steps are called the cognitive ladder in prenav. The five parallel arrows as input to sensation denote that different modalities (e.g., touch, vision, audition) can be involved and that the processing in these modalities is parallel at least up to the sensation level. After the sensation level, information may be further processed via the cognitive ladder. Under the influence of cognitive resources (e.g., memory and attention), the sensation is interpreted into a percept. Finally, again under influence of cognitive resources, a percept may lead to a decision (e.g., which route to take), which may also be stored in memory.

Contrary to many other models, the information-processing loop in prenav is not a serial process in which all the steps need to be completed. Specific for prenav is the existence of two shortcuts, indicated with dashed arrows in Figure 1.5. The first is the sensation→action shortcut. When a sensation directly evokes an action, it bypasses the cognitive ladder completely. Examples include maintaining our balance, braking when a child suddenly crosses the road or other reflexive or highly trained tasks. This shortcut resembles the skill based level of Rasmussen's model, defined as "well-learned sensory motor performance in continuous manual control tasks in stationary conditions".

The second shortcut is the perception→action shortcut. A percept may also directly result in an action, thus bypassing the decision process. This is the case for automated "if...then" rules, for example when you see a stop sign, you decelerate. This process does not involve a conscious decision, but requires the interpretation of the visual information as a stop sign (which is not needed when diving down when a baseball is coming right at you).

These shortcuts link to the concepts of automaticity and intuitive displays. The automaticity concept was further distinguished through Schneider & Schiffrin's discussion of decreased effort resulting from automaticity, gained from practice, and studies documenting concepts of automaticity and the role of expertise, practice, and training (Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977; Schneider & Fisk, 1982). For example, routine driving tasks can be highly demanding for a novice, and at least partially automated in expert drivers. Closing the sensation→action loop seems trivial for situations like keeping our balance and lane keeping while compensating for side wind[6]. However, when the sensation is mediated by a display, the design of the display is the critical factor whether directly closing the sensation→action loop will be possible or not. Based on prenav, we refine the earlier given working definition of an intuitive display to: "An intuitive display is a display that **enables closing the sensation→action loop**"[7]. According to this strict definition, an intuitive display allows to process the presented information without involving the cognitive ladder. We can therefore predict that an intuitive display results in low mental effort ratings and that performance is not affected by increased mental load of the operator. A less strict definition would be that an intuitive display enables closing the sensation→action loop <u>or</u> the perception→action loop. Both definitions make no distinction between innate reflexes and highly trained skilled behaviour.

The information processing loop and its shortcuts reflect three different levels of behaviour in steering and control tasks terms: control, steering and navigation behaviour. If we take car driving as example, control behaviour is concerned with lateral and longitudinal vehicle control; tasks based on cues such as vehicle sway picked up by the vestibular system, the optic flow from road markings and forces on the steering wheel. The steering level is concerned with functions such as short-term progress, dealing with other traffic, traffic signs, etc. In the example of car driving, this reflects the actions to be taken when approaching a crossing, such as slowing down and shifting gears. The navigation level is concerned with behaviour like planning, decision making and waypoint selection.

The workload loop in prenav

The second loop in the prenav model (indicated by the dotted lines) is based on the workload framework of Veltman and Jansen (2004) that stresses the role of the state of the operator on the information processing loop. In the workload framework model, external stressors, including G load, vibration, and wearing night vision goggles may affect the state of the operator. In the prenav model, the operator state specifically affects the cognitive ladder, but not the sensation→action loop. We can therefore predict that with an intuitive display performance is not affected by external stressors (as long as they don't affect the quality of the presented information, or the operator's sensory or motor system), because an intuitive display does not rely on cognitive resources.

Local guidance tasks and parameters

As stated in Section 1.1, supporting local guidance is an important human factors challenge. There are many tasks and task environments related to local guidance, each having its own specific set of parameters. For instance, to walk toward a waypoint, only lateral and longitudinal distance or heading and distance

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[6] This does not imply that behaviour at this level always comes without learning, just try to remember how difficult it was to ride a bicycle for the first time.

[7] There seem to be more definitions of an intuitive interface in the field of Human Computer Interaction then there are researchers. A general one is that of Charm (1996): "With an intuitive interface, the user needs no specific instructions to perceive its function or use it". Often, definitions also refer to short learning periods.

are required, while to maintain straight and level flight, at least five aircraft parameters (attitude, airspeed, altitude, rate of climb or descend, and heading) must be monitored and integrated. To structure this task space, We will use the three axes depicted in Figure 1.6. The first axis is the *controlled parameters* and distinguishes translation (lateral and longitudinal distance, altitude, speed etc.) from rotation (heading, pitch, roll, angle of attack, etc.). The second axis concerns the dimensionality of the *environment*: 2D versus 3D[8]. The third axis is the local guidance *task level*: steering versus control (or pursuit vs. compensatory). Figure 1.6 also gives several examples of tasks within this task space. For example, at the control level (the lower four points), tasks include staying within a virtual corridor or lane keeping (2D, translation), hovering within a defined box (3D, translation), or maintaining a specific orientation as in maintaining stable flight (2D or 3D, rotation), which are all compensatory tracking tasks. At the steering level are tasks like waypoint navigation (translation in 2D or 3D). Rotation parameters at the steering level include targeting (i.e., knowledge about the heading and pitch of a target or threat) and spatial orientation (i.e., knowledge about one's heading, pitch, and roll with respect to a certain reference frame). These tasks are related to pursuit tracking.

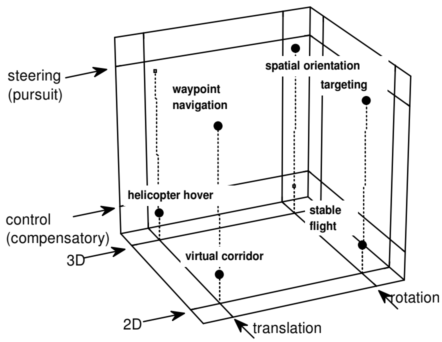

Figure 1.6. The local guidance task space can be divided along three dimensions: the controlled parameters: translation vs. rotation, the dimensionality of the environment: 2D vs. 3D, and the task level: control (or compensatory tracking) vs. steering (pursuit tracking). Tasks at the marked locations are investigated in this thesis.

1.3 The two critical problems with navigation and orientation tasks

We can use the prenav model to look more closely at the potential bottlenecks in local guidance tasks. Prenav actually predicts two such bottlenecks (marked in Figure 1.7): sensory overload and cognitive overload. Sensory overload refers to the possibility that the visual and auditory channels are not available or are overloaded. Through the use of support systems for platform navigation and control, the visual and auditory channels can become overloaded because these systems present additional messages, next to the information already arising from the work environment itself. Examples are not limited to operators in complex environments who work at the limits of their visual and auditory processing capacity such as pilots (Rupert et al., 1993; Sklar & Sarter, 1999), but also include users whose visual or auditory attention

[8] Please note that we refer to 2D and 3D environments, and not to controlling 2 and 3 rotation or translation parameters. For example: diving into a swimming pool and orienting yourself with your head to the surface is orienting in a 3D environment while the rotation around the body midaxis is a free parameter.

is preferably focussed on a specific area of interest, such as car drivers who need to concentrate on the road (Fenton, 1966; Gilson & Fenton, 1974), and soldiers who want to monitor the surroundings (Van Erp & Duistermaat, 2005).
Related to sensory overload is a condition called reduced information availability. For instance, a visual display may be useless for firefighters working in dense smoke, divers in dark waters, the visually disabled, speed boat drivers whose whole body vibrations make reading a display impossible unless the boat slows down, and operators who work in deprived sensory environments, such as remote operators (Browse & McDonald, 1992; Massimino & Sheridan, 1992).

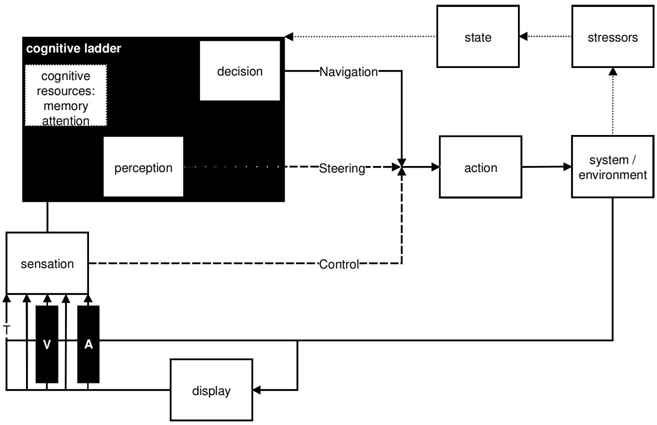

Figure 1.7. The prenav model with the predicted potential bottlenecks marked.

Cognitive overload refers to an over demand of the (momentarily available) cognitive capacities of the user. Again taking car driving as an example, evaluation of visual-based information systems has shown that they may negatively influence the drivers' scanning behaviour and attention allocation (in other words: they distract the driver; e.g., Wierwille et al., 1988). Recently, a meta-analytic investigation of listening and speaking during driving (e.g. using cell phones) found this to be detrimental to driving performance, regardless of whether the cell phones were hands-free (Horrey & Wickens, 2006, see also Spence & Read, 2003; Brown, Tickner, & Simmonds, 1969). The still increasing availability and complexity of in-vehicle technologies will put increased demands on cognitive resources such as our limited capacity spatial attention, and will increase the risk of cognitive overload.
Finally, visual navigation displays have a specific disadvantage when they present three-dimensional (3D) navigation information, for example to pilots. In general, the characteristics of an ego-referenced 3D (perspective) display are more ecological than those of a 2D display (Warren & Wertheim, 1990). A 3D, egocentric presentation has advantages for local guidance, as shown by many investigations (e.g., Haskell & Wickens, 1993; Prevett & Wickens, 1994; Ellis, Kim, Tyler, McGreevy & Stark, 1985; Kim, Ellis, Hannaford, Tyler & Stark, 1987; Van Erp & Kappé, 1997). However, because visual displays like CRT and LCD screens are flat or 2D, one (or more) dimensions must be compressed (depending on the elevation angle). This results in loss of information and usually requires cognitive effort to reconstruct the 3D picture from the 2D display.

The threat of cognitive overload is especially important in multiple task situations. Multiple task performance relates to a higher-level aspect of cognition that may be referred to in general as attention management. While it necessitates the ability to divide attention, the attention is not only divided between perceptual channels, but also between competing tasks with independent goals (Wickens, 1992; 2002). An important Human Factors model dealing with these aspects is Wickens' Multiple Resource Theory (MRT). The MRT predicts, to some extent, concurrent processing of tasks. Important aspect is whether the multiple channels/tasks share a goal or not. An example of a shared goal is a situation where a driver is navigating, processing visual information and a "copilot" is providing audio direction, such as "turn left after taking exit 50". Both channels of information have a shared goal of navigation, and so it is a situation not nearly as challenging as accomplishing multiple goals. The situation clearly becomes more complex with multiple goals. For example, the driver may be navigating territory while listening to speech instructing him what to do after he gets to his destination, asking for a status report, or he may be trying to predict the next action of an erratic driver in his or her field of view. This ability, and associated limitations, have been noted in numerous studies and situations, where operators were not able to effectively divide attention between required tasks, or dynamically prioritise and allocate attentional resources to competing threads of activity (Beilock, et al., 2002; Nikolic & Sarter, 2001; Yeh & Wickens, 2001; Yeh, Wickens & Seagull, 1999; Williams, 1995).

1.4 Supporting navigation and orientation tasks

The resource decomposition concept of MRT states that task interference (i.e. performance decline) will only manifest itself to the extent that the two tasks share resources, under conditions of a high overall workload. Single-resource theory did not explain discrepancies in some dual-task interference tasks. Several researchers, such as Allport, Antonis, & Reynolds (1972), and Wickens (1980; 1984) found that decrements in performance in multi-task-situations were not additive, as a single-resource theory predicts; instead, studies suggested that the decrement depended on the degree to which the competing tasks also competed for the same information channel. Timesharing between two tasks was more efficient if the two used different information processing structures than when they used the same. This suggests separate information channels have, to some extent, independent resources, that are still limited, but could function in parallel. This means that task interference will be reduced when the tasks' demands are maximally separated across resources. This separation can be along different resource dimensions such as sensory modality (including touch; e.g., Sklar & Sarter, 1999) and verbal versus spatial processing codes. MRT (Wickens, 1984, 1992, 2002; Wickens & Liu, 1988) predicts no performance degradation, under normal workload conditions, when independent resources or information channels are used to present information. Since critical information in many applications is predominantly visual (e.g. for the role of visual information in driving, see Van Erp & Padmos, 2003; Sivak, 1996), the MRT model would predict less interference of a second task when information is presented to another sensory modality. Traditionally, the auditory channel is considered as an alternative or supplement to visual displays. Examples include the presentation of route navigation (Parkes & Coleman, 1990; Streeter et al., 1986) and tracking error information (Forbes, 1946; for a review see Wickens, 1992, pp. 480-481). However, the auditory channel is heading for the same sensory overload scenario (Spence & Read, 2003; Brown, Tickner, & Simmonds, 1969; Ramsey & Simmons, 1993; Strayer & Johnston, 2001; Strayer, Drews & Johnston, 2003). Again looking at car driving as an example, the user's auditory channel is typically loaded with radio and traffic information messages, phone calls, warning signals, or simply engaged in conversation with other passengers. Therefore, designers of human machine interfaces are also increasingly keen on applying the sense of touch in man-machine interfaces (e.g., Spence & Driver, 1997; Wood, 1998). Because the sense of touch is a relatively underutilised modality in human-computer interaction, this is a good candidate to reduce the threat of sensory overload.

Solving the threat of cognitive overload may be accomplished by using the sensation→action shortcut in prenav, thereby bypassing the cognitive ladder. This means that the sensation directly evokes the correct

behaviour. The sensation→action shortcut is open to highly trained or reflexive behaviour. Interestingly, many of our reflexes are based on the sense of touch. An example is the rooting reflex in babies, that is, turning the head in the direction of a tactile stimulus to the cheek. Implementing this sensation→action shortcut in a touch-based display is possible as shown for example by Martens and Van Winsum (2001). They found that drivers react more effectively to warning cues presented to the accelerator pedal via the sense of touch than to speech warning cues, possibly due to the intuitiveness of the tactile signal that automatically initiated the required response. Recently, Ho (2006, see also Ho, Reed & Spence, 2006; Ho, Tan & Spence, 2005) investigated whether positive cueing effects of tactile signals on the torso were caused by response bias or attentional facilitation. She separated both factors by using an orthogonal cueing design (Spence & Driver, 1994) in which the responses are orthogonal to the spatial dimension of interest. Observers had to press a low or high button in reaction to a licence plate colour change of a front or rear car. The location of the car was cued by vibration on the frontal or dorsal side of the torso. In this design, the cueing effect was no longer present indicating that a localized vibration does not necessarily results in a shift of spatial attention in the direction indicated by the cue. This means that positive cueing effects in non-orthogonal situations may be caused by the fact that the presentation of a vibrotactile cue from the appropriate spatial direction on the body surface may elicit an automatic response bias (see Prinzmetal, McCool, & Park, 2005).
The last example illustrates that for vehicle control, a tactile display cannot only release the load on the visual and auditory channels, but may also bypass cognitive resources. The favourable effect occurs without the need for an attention shift and as long as the response bias results in the correct response, positive effects on safety can be found. Investigating whether this ‘automatic response bias’ is also possible for other types of local guidance information is one of the major issues in this thesis. But before discussing the potential of the sense of touch further, We will first introduce the skin in the next section.

1.5 Introducing the skin[9]

The skin is by far our largest organ. The surface in adults is just less than 2 m^2 and it weights about 5 kg. Our skin has numerous functions: protection from mechanical injuries and dangerous substances and organisms, temperature regulation, metabolism of water, salt and fat, and last but not least, as sensory system. The skin senses inform the organism of what is directly adjacent to its own body. The number of axons that terminate in the CNS is in the order of 10^6, comparable to that of the retinas and much higher than that of the cochlea. Based on the fact that people who know Braille can read with their fingertips, one can conclude that the skin and the somatosensory cortices are also able to process large quantities of abstract information. However, like other modalities, the cutaneous system cannot process information with infinite accuracy. Stimulus information is lost in the different stages of processing that act as a spatiotemporal filter upon the stimulus that is applied to the skin.

The skin senses can be divided in the sense of pain, the sense of temperature (hot and cold) and the cutaneous sense. The sense of touch is often defined as the sensation elicited by non-painful stimuli placed against the body surface. Different subdivisions and definitions are used in relation to the sense of touch. In a top-down view, the following descriptions will be used throughout this thesis:

- *proprioception* is related to all the senses that are involved in the perception of oneself in space, including the sense of touch, the vestibular system and the haptic sense;

[9] More details are given in Appendix I.

- *haptics / sense of touch / somatosensation* all refer to the sensory systems related to both active and passive touch, including the mechanoreceptors in the skin and the receptors in muscles and joints;
- *tactile / cutaneous* is related to stimuli that evoke a response in the mechanoreceptors in the skin only, thus excluding receptors in joints and muscles, and excluding noxious stimuli that evoke a pain sensation and temperature stimuli that evoke a sensation of cold or warmth;
- *vibrotactile* is related to vibrating stimuli, thus excluding for example pressure stimuli;
- *mechanical vibration* is related to stimuli that physically move the skin (usually by a periodic movement), thus excluding electro-cutaneous stimuli.

The skin contains several different types of mechanoreceptors (see Figure 1.8). Generally, stimuli will evoke a response in multiple types, and the tactile experience will be based on the combined response in mechanoreceptors (e.g., Johansson, 1978; Johansson & Birznieks, 2004). The four main types that are more thoroughly studied are the Meisner and Pacinian corpuscles, the Merkel disks and the Ruffini endings. Thought to be less important for cutaneous perception are the hair follicles and the bare nerve endings. The Meisner corpuscles (only found in glabrous or hairless skin[10]) react to light touch and lower frequency vibrations (resulting in a perceptual quality described as light touch or flutter). The Meisner corpuscles play an important role in forming the two-dimensional representation of stimulus form, and in detecting slip and motion. The Pacinian corpuscles (found in both hairy and hairless skin) react to gross pressure changes and higher frequencies and result in a flutter or vibration percept. The Ruffini endings (also found in both hairy and hairless skin) enable pressure perception while the Merkel disks (mainly found in hairless skin although Merkel disks with a slightly different organisation are found in hairy skin) are thought to be involved in tactile form and roughness perception and are especially sensitive to local spatial features such as edges and curves. The Merkel disks also differentiate between the form of the indentation (e.g., sharp versus flat surfaces) and are used for high resolution tactile discrimination. Finally, hair follicles respond to hair displacement, and the unspecialised free nerve endings are responsible for detecting stretch stimuli and other mechanical stimulations such as pressure.

The functions of the sense of touch can be considered at different levels, starting with sensation and through perception to complex behavioural aspects that are dependent on, or mediated by the skin's sensory function. The significance of the sene of touch is apparent at all these levels as is described below.

There is a biological principle that states that the earlier a function develops the more fundamental it is likely to be. The sense of touch is the earliest sense to develop in a human embryo (Gottlieb, 1971). Within eight weeks, an embryo shows reflexes based on touch. In that stage, it has no eyes and ears yet. The significance of touch is eminent directly after birth. Most of the major reflexes of full-term neonates are based on the sense of touch (Shaffer, 1989), for instance: the rooting reflex (turning the head in the direction of a tactile stimulus to the cheek) and the sucking reflex (sucking on objects placed or taken into the mouth), the Babinski reflex (fanning and then curling the toes when the bottom of the foot is stroked), the grasping reflex (curling of the fingers around objects (such as a finger) that touch the baby's palm) and the swimming reflex (immersed in water, an infant will hold his or her breath and will display active movement of arms and legs). Streri and Pecheux (1986) showed that in the first year of their life, humans are already able to discriminate objects solely on the basis of touch.

[10] Glabrous skin is non-hairy skin and mainly found in the palms of the hands and on the sole of the feet. Most other skin areas are hairy skin.

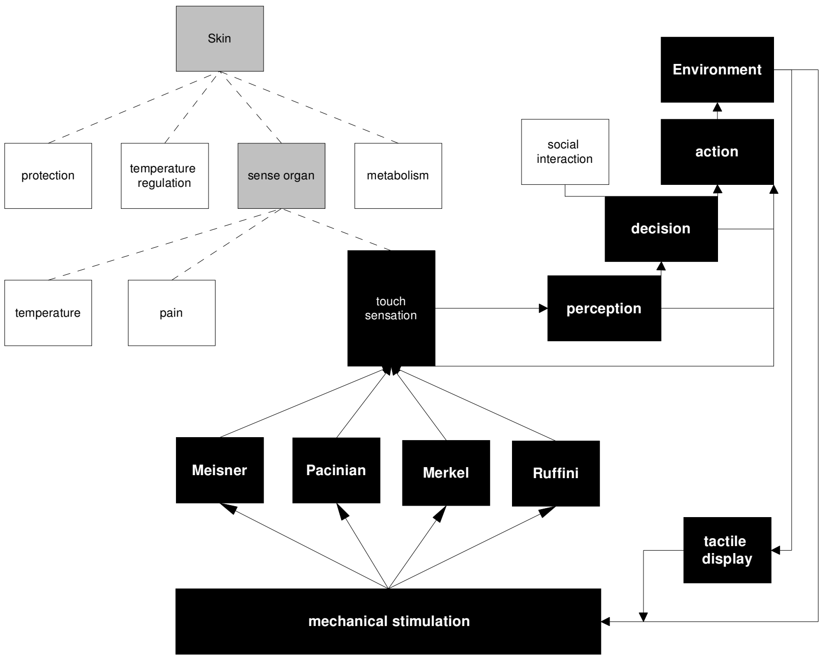

Figure 1.8. The sense of touch can be considered as a subfunction of the skin as sensory organ, which is one of the many functions the human skin has. The black marked cells relate to the prenav model. Mechanical stimulation of the skin may evoke responses in one or more of the four main types of mechanoreceptors: the Meisner and Pacinian corpuscles, the Merkel disks, and the Ruffini endings. The brain will turn this raw sensory data into a percept, guiding for instance social interaction.

Later in life, tactile sensation is essential as feedback mechanism in motor control. It provides guidance in, for example, the exploration of objects and the environment (illustrated by the ease with which we can find the light switch in the dark). Touch is essential in all our motor behaviour. It is for example difficult to walk with a numb leg, to control equipment, button a shirt, or even light a match with numb fingers or to chew and talk after local anaesthesia (Cole & Paillard, 1995; Johansson, Hger & Backstrom, 1992; Monzee, Lamarre & Smith, 2003; Augurelle, Smith, Lejeune, & Thonnard, 2003; Bosbach, Cole, Prinz, & Knoblich, 2005). Local guidance can thus be considered as one of the ecological functions of touch.
The importance of the skin senses in early development is also eminent at a level above sensation and automated responses. Bushnell and colleagues (Bushnell, Shaw & Strauss, 1985) stated that temperature is an important dimension of reality for infants, even more important than colour. In her experiments, babies payed more attention to objects that differed in temperature only than to objects that differed in colour only. Furthermore, the brain uses tactile sensations to develop awareness of the body in space, and to perceive space, time, shape, form, depth, texture and all other kinds of (mechanical) object properties. Tactile perception is indispensable in building a complete picture of the world around us as we know it. Although people are inclined to think that only vision and audition can shape our mind and enable us to understand the world, the case of Helen Keller who became deaf and blind in infancy and learnt to communicate solely on the basis of touch shows that this is not true. When vision and audition fail, the skin can to an extraordinary degree compensate for their deficiencies. There are numerous other examples

of the general ability of tactile perception to compensate for deficiencies in other sensory systems, including aids for people with a hearing, vision or vestibular disability (see Borg, Rönnberg & Neovius, 2001; Bach-y-Rita & Kercel, 2003; and Kentala, Vivas & Wall, 2003, respectively). These compensations will often be accompanied by measurable psychophysical and neurophysiological effects. For example, in an experiment of Zubek, Flye and Aftanas (1964), subjects showed increased sensitivity for tactile and pain stimuli after being in a dark room for a week.

Touch is not only critical in the interaction with objects, but also between individuals, that is in social relationships. The sense of touch is one of the first mediums of communication between newborns and parents. The critical importance of this tactile communication was shown by Harlow and Zimmermann (1959). In their experiment, infant monkeys that were separated from their group showed a large preference for a surrogate mother consisting of wires and cloths that resembled the feel of a real mother ape over a surrogate mother consisting of wires only. This preference was also prevalent if the wire surrogate mother provided food and the cloth mother did not. Based on the licking, tooth-combing and grooming behaviour of mammals towards their young, it is concluded that tactile experiences play a fundamentally important role in growth and development. After a thorough study of the literature on the critical role of tactile experiences required in order to develop as a healthy human being, Montagu (1972, p. 332) even stated that touch or cutaneous stimulation is a basic need which must be satisfied for the organism to survive, therewith classifying it as importantly as sleep, food, rest and oxygen. Throughout the rest of our life, the sense of touch remains important in social interaction: in greetings (shaking hands, embracing, kissing, backslapping, and cheek-tweaking), in intimate communication (holding hands, cuddling, stroking, back scratching, massaging), in corrections (punishment, spank on the bottom), and of course in sexual relationships. All these complex social interactions are based on touch.

Finally, imagine what it would be like to live without touch. Even if you survived as a newborn without many basic reflexes, it would be doubtful if you could grow up into a normal functioning human being, it would be difficult to stand, walk, and talk, to interact socially with others, to find your way in dusk or down, to hold a glass without breaking it, to eat nuts without dropping some, to enjoy the feel of smooth silk, to interpret the back patting of an acquaintance, the stroking of a friend and the tender loving care of your lover, to turn pages one by one, to find your keys in your pocket, to relieve your headache by stroking and so on and so forth. The importance of touch in our complicated society is therefore also reflected in language when we talk about the finishing touch, rubbing people the wrong way or stroking them the right way, someone's happy, soft, or human touch, one's thick or thin skin, getting under one's skin, getting in touch, being touched, losing touch, the master's touch...........

1.6 The skin as an information channel for local guidance

The examples above subscribe to the importance of the sense of touch. Maybe without being aware, the skin senses continuously process information, including local guidance information. For example, we can easily guide ourselves just by holding on to a handrail or by lightly touching the walls. Also, already in early development, we can identify objects by the sense of touch. These observations point up to the potential of the skin as an information channel. The potential of active tactile displays that use the skin as an information channel was already recognized more than 40 years ago (e.g., Geldard, 1961; Bliss, 1970)[11], but many applications remained unexplored at that time, amongst others because of technological

[11] The first known application of a tactile (passive) information display is that of reading by raised dots, introduced by Barbier de la Serre more than 200 years ago. His concept was later optimised by Louis Braille into the Braille system as is still used today.

limitations. Table 1.1 lists some of the pros and cons of using the skin as an information channel. The rest of this section explores the issues with respect to tactile navigation displays in more detail.

Table 1.1. The pros and cons of using the skin as information channel in man-machine interaction.

The pros include:	The cons include:
the potential to lower the visual and auditory load	the fact that the skin can get adapted to prolonged stimulation, and prolonged stimulation may even be harmful, as seems to be the case with children that extensively play with vibrating game controllers (Cleary, McKendrick & Sills, 2002)
the potential to lower the cognitive workload because tactile displays may present specific information more intuitively than visual and auditory displays	the fact that people are not used to tactile displays in general (let alone in man-machine interaction) so it may take users time to learn to manage this way of information presentation
the potential to draw and direct attention. For example, if somebody taps your arm during a cocktail party, there is a reasonable chance that you will notice it and will direct your attention to the person	that the mechanical stimulation can interfere with other tasks (imagine a wildly vibrating steering wheel or other controls)
the fact that the skin is always ready to process stimuli. This is a plain advantage compared to the visual channel. If we don't look and focus on a visual display, we won't receive the information. To perceive information via the skin the observer does not have to make head or eye movements	that the display technology is not as sophisticated as for instance visual display technology. The 1 million pixel resolution of an ordinary visual monitor is many orders of magnitude larger than that of the most advanced tactile displays
the fact that stimulus locations on the body are directly mapped in an egocentric reference frame which may make the skin an interesting channel for information requiring an egocentric view	the fact that the most (spatially) sensitive areas are the fingertips but a display on the fingers will often not be practical because the user needs to hold tools, controls, etc.
the fact that a tactile display allows distal attribution or externalisation (Epstein, Hughes, Schneider & Bach-Y-Rita, 1986). This means that our bodily experience extends beyond the limits of the 'skin-bag' (Clarks, 2003) and we can attribute a stimulus on the skin to an object or event in the outside world (e.g., when using a walking cane or tools)	that tactile displays have to be in contact with the skin which places strict requirements on the design and placement of the display

Implementing an intuitive tactile local guidance display

Two critical choices in designing a tactile local guidance display are which body location to use and which actuator technology to apply. The functional requirements for an intuitive tactile local guidance display may help to solve these issues. These are the following:

- intuitive, which translates to:
    - the display should automatically evoke the correct response
    - the display should require little mental effort

    - the display should make local guidance performance independent of the presence of external stressors and the level of the mental workload
- optimised for local guidance, which translates to:
    - egocentric or actually body-centric and preferably three dimensional[12]
    - the display should not result in detrimental effects on manual control tasks
- general requirements for tactile displays:
    - safe to wear on the body, possibly directly on the skin (including avoiding heat burns, electrical shock and skin irritation)
    - comfortable to wear, including aspects such as fit, pressure and weight
    - wearable (e.g., not wired to power supplies, sensors or systems in the environment)
    - operate ample above the detection threshold (but still at comfortable levels) and within the spatial resolution for all potential users
    - and depending on the application and/or user group: not conspicuous and built from cheap, readily available elements.

Traditionally, many of the tactile displays are designed for the fingers and hands because these body loci have the lowest thresholds and the highest spatial resolution. However, they do not comply with many of the requirements as listed above. For example, they are not egocentric, they may interfere with manual control tasks and they are quite conspicuous. Furthermore, the hands are often not even available, for example because they are needed to shake hands with an acquaintance or to carry the groceries. This effectively disqualifies the hands as location for the display. Other important aspects with respect to the choice of body location are that the display should be egocentric and possibly 3D, and evoke the correct response as an automated reflex. Based on the rooting reflex in neonates (i.e., turning the head in the direction of a tactile stimulus to the cheek), the cheeks are an interesting location to present spatial information, but the cheeks are neither body-centred nor three-dimensional. The trunk, however, is body-centred, is a highly stable factor in our perception of space (see Chapter 4 for more details), and has a three-dimensional form. People's reaction to a tap on the shoulder indicates that it is not so unlikely that the rooting reflex has an equivalent on the torso. The trunk also complies with the other requirements. It is not in use for other displays or controls, one can easily and not conspicuously wear a display under normal clothing, and it has a large surface allowing larger vibrating elements that are cheap and result in a stimulus that is ample above the detection threshold and spatial resolution.

With respect to actuator technology: wearability, comfort and safety issues are critical. For wearables, only two main actuator types are available: electrical and mechanical (for more exotic technologies, see Van Erp & Van den Dobbelsteen, 1998). Electrotactile actuators can present a sensation of vibration by electrodes that are attached directly onto the skin. This technology has several disadvantages that need to be solved before it can be applied. Apart from the obtrusive and complicated way to mount the display, the sensation is not stable over individuals and even not for the same individual over days. This means that an electrical charge that is comfortable on one day may be painful on another. Mechanical actuators that produce mechanical vibration don't have these disadvantages. There are three major actuator principles: pneumatic, DC-motor based and coil based. Pneumatic actuators use pressurised air and valves to mechanically move a membrane that touches the skin. Although the display itself is easily wearable, the system is not because of the need for pressurised air. DC-motor based actuators are based on an eccentric

[12] as Montello, Richardson, Hegarty, and Provenza (1999) stated: "*A central issue for researchers of human spatial knowledge, whether focussed on perceptually guided action or cognitive-map acquisition, is knowledge of egocentric directions, directions from the body to objects and places*".

weight mounted on the shaft of a small DC motor. This technology is widely applied in wearables such as pagers and mobile phones. The disadvantage of this technology is that the vibration is not purely along one direction, and amplitude and frequency of the vibration are coupled. Coil based actuators can be seen as small loudspeakers. This technology is also applied in wearables but not at such a large scale as DC motors. Coil based actuators vibrate along one axis only, and allow to control amplitude and frequency independently (although many types have a very small amplitude when the frequency is more than 10-20 Hz off their resonance frequency).

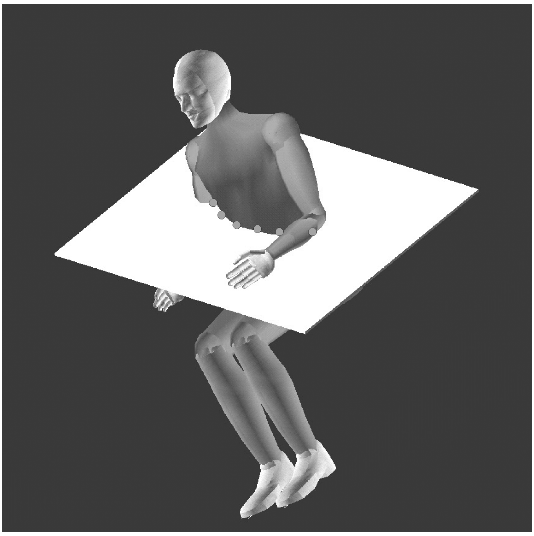

Figure 1.9. An example of local guidance information presented by a tactile torso display: an artificial horizon indicated by a slanted ring of vibrating elements.

Putting all arguments together, an intuitive tactile navigation display may be implemented as a matrix display of vibrating elements covering the torso (e.g., see Figure 1.1), similar to the concept that was introduced in the nineties by Rupert and colleagues (Rupert, Guedry & Reschke, 1993). An examples of local guidance information displayed by such a display is given in Figure 1.9.

1.7 Crossmodal tactile-visual perception

Although there is clear evidence for crossmodal links in visual-tactile information processing, it is not clear whether extra costs are involved in crossmodal comparisons compared to intramodal comparisons. This thesis is primarily about tactile local guidance displays, often as an alternative or additional display to solve the risk of visual overload. Therefore, tactile displays should be considered in a broader perspective of user interfaces. Multimodality becomes increasingly important in user interface design and it is unlikely that a tactile display will be implemented as stand-alone display. Rather, optimal integration of a tactile display in a multimodal setting will be an important issue. Therefore, We will investigate the crossmodal visual-tactile comparisons of time and space in Chapter 5.

There are several strategies to combine the visual and tactile modality in a multimodal setting. For example, the same information can be presented to both modalities making them redundant. Also, different attributes of an object or event may be presented to the different modalities, making them complementary. A third strategy is to present related objects or events to the different modalities. In this latter multimodal setting, stimulation from several sensory channels must be congruent informationally as well as temporally (Kolers & Brewster, 1985) since comparisons made by the user can be crossmodal. An important issue in this respect is whether there is a difference between the quality of crossmodal and intramodal comparisons (Davidson & Mather, 1966). To be able to compare visual and tactile information in a crossmodal setting, there must be a common representation of the information from both senses. Several mechanisms for crossmodal visual-haptic comparisons have been suggested, based on two fundamentally different models (for an overview see Summers & Lederman, 1990). The first (see Figure 1.10, left) is based on modality specific representations that are used for uni-modal comparisons (e.g., see Lederman, Klatzky, Chataway & Summers, 1990). These modality specific representations must be translated into a common representation for crossmodal comparisons. This implies that crossmodal comparisons require an extra translation as compared to uni-modal comparisons. Based on the assumption that this extra translation increases the variability in the judgements, this model predicts a lower sensitivity for crossmodal comparisons than for uni-modal comparisons.

The second model (Ernst, 2001, p. 88, see also Ernst & Banks, 2002) states that information from the different modalities is directly processed and translated into a common representation (see Figure 1.10 right). This representation is used for both unimodal and crossmodal comparisons. In the latter model, unimodal and crossmodal comparisons are based on the same representation and are therefore hypothesized to have the same sensitivity.

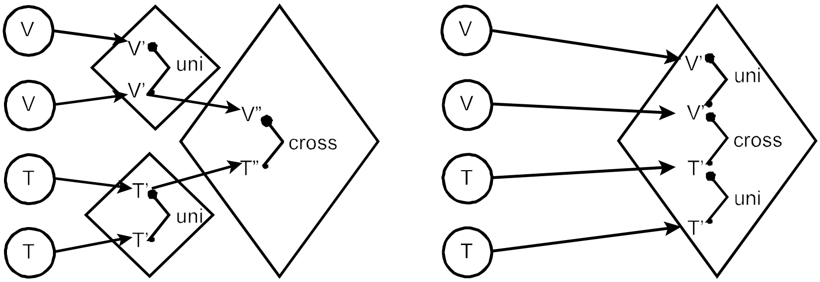

Figure 1.10. Two models for unimodal and crossmodal comparisons of visual (V) and tactile (T) information. The model on the left has a modality specific representation in which the unimodal comparisons are made. Crossmodal comparisons can only be made after the unimodal representations are translated into a common representation. The model on the right has only one (common) representation in which both the unimodal and the crossmodal comparisons are made.

1.8 Critical research issues and outline of this thesis

The three main issues of this thesis about tactile torso displays for navigation and orientation can be summarised as follows: 1) do they work?, 2) can they lessen visual overload?, and 3) are they intuitive?. To answer these questions, we face challenges at the sensation, perception, cognition and action level.

Sensation

At the sensation level, the processing of vibratory stimuli on the torso is relevant. The first set of questions at the sensation level concerns the detection threshold and the spatial resolution for vibrotactile stimuli as a function of location on the torso. Although the detection threshold of the torso may be higher than that

of other body parts, it is still extremely low (4 microns or lower) and therefore no potential bottlenecks are expected since simple pager motor technology can easily reach amplitudes that are far above this detection threshold. Spatial acuity of the skin has been investigated by several methods, but many studies use pressure and not vibratory stimuli to measure spatial acuity. This lack in the literature was confirmed by Cholewiak and Collins (2003). Also, most studies investigated the finger (tips) as body locus. Because vibratory stimuli act upon different sensory receptors and result in both longitudinal and shear waves that may degrade spatial resolution (depending on the tactor - skin contact; see Vos, Isarin and Berkhoff (2005) for wave propagation models for the skin), it is doubtful whether pressure data may be generalised to vibration stimuli.
Also, no extensive data are available on the absolute localization of stimuli on the torso (a possible exception being the work of Cholewiak and colleagues (Cholewiak, Brill & Schwab, 2004), see Chapter 3). For a display that maps external events on a specific location on the body, absolute localization is at least as important as relative localization. With absolute localization, we refer to the ability to localize a stimulus on the body or in 3D space. The methods to measure spatial resolution are based on relative localization of two stimuli, or the difference between two stimuli, but do not measure where on the body the stimuli are perceived to be located. Principally, both measures can be independent, like a darter that throws the darts close together (i.e., a high spatial resolution), but in the wrong number (bad absolute localization).

The second set of questions at the sensation level concerns the preferred secondary parameter. Besides location on the body, many local guidance applications may require a secondary parameter to code for information such as distance, priority, amount of deviation, etc. Looking at the three secondary parameters subjective magnitude, frequency, and timing, we can conclude the following (for details, see Appendix I). With respect to coding information by subjective magnitude, the number of levels an observer can distinguish or identify is limited (Sherrick, 1985). Boff and Lincoln (1988) advice not to use more than four levels. For coding information by frequency, the number of levels is larger than for subjective magnitude, but still limited. Boff and Lincoln (1988) advice to employ not more than nine frequency levels. Coding information by temporal patterns seems more promising. The temporal sensitivity of the skin is very high (close to that of the auditory system and larger than that of the visual system). A single actuator of a tactile display can encode information with time slots as small as 10 ms, that is 10 ms pulses and 10 ms gaps can be detected. This means that many different rhythms can be constructed to encode the value of the secondary parameter. Based on the available data (more details can be found in Appendix I and in Van Erp, 2002a), the preferred secondary parameter is timing (or actually temporal rhythm). However, the skin has a tendency to integrate place and time. Stimuli that are presented closely in time and space can alter the percept and may even result in a completely new percept (such as apparent motion, the percept of smooth motion elicited by the sequential activation of discrete point vibrations). Important parameters in spatiotemporal interactions are burst duration and the stimulus onset asynchrony (see Appendix I). These parameters may also affect the spatial acuity of the torso, which has not been investigated yet.

The above leads to the following three main questions at the sensation level:

Q1. What is the spatial resolution of the torso for vibratory stimuli, and is it uniformly distributed across the torso?

Q2. What are the effects of timing parameters on the spatial resolution?

Q3. How well can observers determine the absolute location of vibratory stimuli?

These questions will be studied in Chapters 2 and 3. The hypotheses for the first three questions are:

H1. Since there are no relevant data available we must look at the data for pressure stimuli to formulate our hypothesis (although pressure stimuli are processed differently than vibratory stimuli). The spatial resolution is in the order of 4 cm and is evenly distributed across the torso, vertically as well as horizontally,

H2. Timing parameters will affect performance, resulting in decreased resolution when either the burst duration is very short or the stimulus onset asynchrony is very short,

H3. Since we are able to hit a mosquito on our torso without looking, observers are able to determine the absolute location of a stimulus with a resolution of half the width of a hand, i.e., with a resolution of 5 cm or better.

Perception

At the perception level, the following questions will be investigated:

Q4. Are observers able to perceive an external direction based on a localized vibration, and what is the accuracy (and bias) in this direction perception?

Q5. How do people extract a direction from a ('dimensionless') point stimulus?

Q6. Which model can describe the crossmodal tactile-visual perception of time and space?

These questions will be studied in Chapters 4 and 5. We have the following hypotheses:

H4. Since the sense of touch is used to externalise stimuli, we expect that people can easily externalise a localized vibration to a direction in the outside world. We expect an accuracy in the order of the 12 hours of the clock (i.e., 30°) with no bias,

H5. We hypothesise that people use an internal egocentre to extract the direction of a point stimulus in the horizontal plane, comparable to the cyclopean eye for visually perceived directions, and the cyclopean ear for auditory stimuli. For the torso, this egocentre is located on the body midaxis,

H6. The recent interest in crossmodal perception has revealed links between vision and touch on several processing levels. For example, using positron emission tomography, Hadjikhani and Roland (1998) positively identified areas that were hypothesized to be involved in the crossmodal transfer of information. Overt and covert crossmodal links in attention were shown by, amongst others, Spence et al. (1998), Driver and Spence (1998), and Lloyd et al. (1999). Driver and Spence (1998) assumed pre-attentive integration of multi-sensory spatial information to produce internal spatial representations in which attention can be directed. Therefore and because the world is multimodal, we hypothesise that a model based on a common representation can accurately describe crossmodal visual-tactile perception. This means that crossmodal comparisons are as good as intramodal comparisons.

Cognition

At the cognition level, the following questions are important.

Q7. Can local guidance displays lower subjective mental effort ratings compared to a visual display?

Q8. Is objective performance with a tactile local guidance display independent of cognitive workload or external stressors?

Q7 and Q8 are linked but still independent. If Q7 is answered in the negative, Q8 is no longer of interest. However, if Q7 is answered in the positive, the answer of Q8 can be either yes or no. It should also be noted that Q7 refers to a difference in absolute workload ratings (independent on the level of cognitive processing, that is the location on the cognitive ladder), while Q8 refers to a difference in performance as function of the workload (or actually: does the information processing require the cognitive ladder or not?). These questions are tackled in Chapters 6-10. The tactile display is expected to be intuitive, even up to the level that the stimulus can reflectively evoke the correct action, thus closing the sensation→action shortcut directly. Hence, we hypothesise the following.

H7. The mental effort ratings with a tactile display are lower than with a visual display.

H8. The information on the tactile display can be processed without involving the cognitive ladder making the user immune to high mental workload situations. With a tactile display present, adding additional mental tasks and/or external stressors will not affect performance.

Action

At the action level, we have to investigate whether tactile displays are effective across the local guidance task space (see Figure 1.6), in other words:

Q9 In comparison to a visual display as baseline, can (adding) a tactile display result in better performance?

We test tactile local guidance displays in tasks like staying in a virtual corridor, maintaining a stable helicopter hover, navigating waypoints, maintaining stable flight, intercepting targets, and determining one's spatial orientation in Chapters 6-10. The experimental situations are chosen to be able to test the following more specific hypothesis.

H9. In a direct comparison, we don't expect an advantage of a tactile display over a visual display. However, a tactile display will improve performance when the user suffers from a) sensory overload, for instance a high visual load or reduced visual information (e.g., when flying with night vision goggles), and/or b) cognitive overload, for instance when other tasks have to be performed in parallel.

To summarise the questions and hypotheses:
1) Do they work? Yes.
2) Can they lessen sensory overload? Yes.
3) Are they intuitive to the degree that they lessen the effects of a high cognitive load? Yes.

In Chapter 11, We will summarise and integrate the results and hypotheses and give hints for further research.

Chapter 2. Vibrotactile spatial resolution on the torso: Effects of location and timing parameters[13]

Abstract

The processing of spatiotemporal vibrotactile patterns by the torso was examined in two experiments. The first experiment investigated the spatial resolution as a function of the location on the torso. A uniform acuity of 3-4 cm was found, except on the body midline where the acuity was 1-2 cm. This favourable effect is hypothesized to be caused by specific processing characteristics of the central nervous system which makes the body midline an anchorpoint for location. The second experiment focussed on the effect of timing parameters on the spatial resolution. The results indicate that performance was closely related to both temporal ordering and apparent motion. The data show that there is a tradeoff between speed of presentation and the required spatial separation, but in general we conclude that the torso's spatiotemporal information processing capacities are larger than required by currently available tactile local guidance displays. Therefore, we expect no bottleneck in the step from display to sensation, the first step in the prenav model.

[13] Parts of this chapter have been published as:
Van Erp, J.B.F. (2005b). *Vibrotactile spatial acuity on the torso: effects of location and timing parameters*. Proceedings of Worldhaptics, pp. 80-85. Los Alamitos, CA: IEEE Computer Society.

2.1 Introduction

The first psychophysical research on spatial acuity was done in the nineteenth century by Weber (1834) and Vierodt (1870). It was Weber who introduced the point localization test and the accompanying measures: the two-point limen and the localization error. Mapping of the whole body revealed large differences in spatial acuity between different parts of the body. Vierodt generalized this to the 'law of mobility', which states that the two-point limen improves with the mobility of the body part.
After the work of Weber and Vierodt, little attention was given to this field until the 1950s and 1960s. In a classical study Weinstein (1968) measured thresholds of two-point discrimination and tactile point localization on several body loci (see also Stevens & Choo, 1996). Both measures were highly correlated. Acuity found with two-point discrimination was three to four times lower than with point localization. Furthermore, Weinstein found significant effects of body locus. Lowest thresholds were found for the fingertips: 2.5 mm and 1.5 mm for two-point discrimination and point localization, respectively. Thresholds for the trunk were approximately 40 mm and 10 mm, respectively. Sensitivity decreased from distal to proximal regions: fingers, face, feet, trunk, upper and lower extremities, and thresholds inversely correlated with the relative size of cortical areas subserving a body part. Another important observation was that good two-point discrimination did not necessarily mean good sensitivity to pressure, that is a low detection threshold.
Vierck and Jones (Vierck & Jones, 1969; Jones & Vierck, 1973) stated that the method of the two-point limen leads to an underestimation of the skin's actual spatial sensitivity. They showed that the discrimination of for example stimulus length is about ten times better. In the 1970s, Loomis and Collins (1978) found comparable results when the stimulus was a gradual shift in the locus of stimulation. Johnson and Phillips (1981) introduced alternative methods, and measured two-point thresholds, gap detection and discrimination of grating orientation for the fingertips. They found thresholds of 0.87 mm and 0.84 mm, respectively. These results show that the ability of participants to discriminate stimuli is much finer than is indicated by the two-point threshold of Weinstein (1968). More details on psychophysical studies are presented in Appendix I.

In Chapter 1, we described how a display consisting of a linear array or a matrix of vibrating elements could support local guidance tasks. The information transfer with such a display is realised by presenting specific spatiotemporal patterns to indicate for instance the direction of drift in a helicopter hover task or the direction of the next waypoint in a navigation task. To be able to adjust the display design to the perceptual characteristics of the torso, knowledge on the spatial resolution and on the processing of spatiotemporal patterns is required. Recently, Cholewiak and Collins (2003) concluded that, although tactile acuity has been extensively investigated for pressure stimuli, *vibro*tactile resolution of the skin has not. To fill this gap, this chapter reports two experiments investigating the spatiotemporal processing of vibrotactile stimuli on the torso to answer the first two questions that were put forward in Chapter 1:

Q1. What is the spatial resolution of the torso for vibratory stimuli, and is it uniformly distributed across the torso?

Q2. What are the effects of timing parameters on the spatial resolution?

Spatial resolution in this thesis refers to the ability of observers to sense the relative location of two vibrotactile stimuli on the skin, operationally defined as the distance on the skin between two stimuli (cm) for which the observer senses the relative position of the second stimulus correctly in 84% of the presentations[14] (see the time - place diagram depicted in Figure 2.1). The intention of this Chapter is to investigate the relevant issues for the foreseen applications and display layout, including its limitations.

[14] Please note that the 84% threshold is more strict than the also often used t_{75} threshold.

Experiment 1 focusses on the first question and investigates the spatial resolution as function of location on the torso. Experiment 2 focusses on the second question and investigates the timing parameters of the stimulus presentation and their effect of on performance [15].

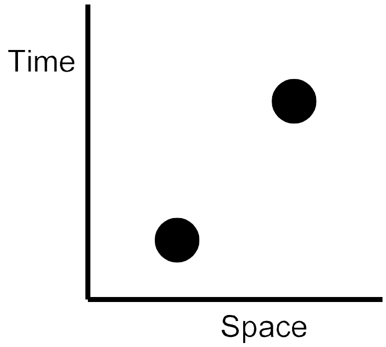

Figure 2.1. Time - Space diagram of the spatial resolution experiments.

2.2 Experiment 1: Spatial resolution as function of location on the torso

In Experiment 1, the spatial resolution for vibrotactile stimuli as a function of location on the torso was measured. In Chapter 1, We hypothesised that the spatial resolution is in the order of 4 cm and is evenly distributed across the torso, vertically as well as horizontally.

2.2.1 Method

Experiment 1 in a nutshell[16].

- Four observers performed a spatial discrimination task. After the presentation of two vibrations they responded whether the second was left or right from the first. The stimuli were located all over the torso.
- The independent variable was the location on the torso.
- The dependent variable was the spatial acuity, defined as the 84% threshold of the fitted curve.

[15] Over the years, we were able to gather an extensive data set (Van Erp, 2001b, 2002b, 2004; Van Erp & Werkhoven, 1999) to answer the given and related questions. This Chapter presents a selection of two experiments from this data set, focussing on the relevant issues for local guidance tactile displays. However, the results presented are representative for the larger set.

[16] These nutshell boxes are provided as a service to the reader for quick reference of the experimental method. Appendix IV gives the nutshell boxes of all 14 experiments.

Participants

Four male researchers participated voluntarily in the study. They were familiar with psychophysical studies and with studies on tactile perception, but not involved in the research project. Their ages were 27, 28, 32, and 34 years.

Apparatus

The tactile stimuli were delivered to the skin by means of MiniVib-4 tactors of Special Instrument Development Cooperation, Sweden. The tactors were matched on amplitude and were attached to the skin of the torso by thin double-sided sticky tape (see Figure 2.2). The contact area of the tactors is 16 by 22 mm. More details on the tactors can be found in Appendix II. The participants wore noise-reducing headphones to block the faint humming sound of the tactors and an oversized T-shirt to block any visual cues. The participant was seated on a stool without a backrest in a dimly lit room.
The tactors were driven by a 250 Hz sine wave with a burst duration (BD) of 28 ms. Each presentation consisted of the sequential activation of two tactors with an inter stimulus interval (ISI) of 196 or 980 ms, which equals Stimulus Onset Asynchronies (SOAs) of 224, and 1008 ms, respectively[17]. The task of the observer was to indicate whether the second tactor was to the left or to the right of the first (a 2 AFC task) by pressing the left of right button on a standard computer mouse, respectively. For the vertical arrays, the mouse was rotated 90° and the observer indicated whether the second stimulus was below or above the first. Stimulus combination and the observer's response were stored for later analysis. No feedback on performance was given. The next presentation started automatically 2 s after the response was given. The experiment was run in three sessions with different locations of the tactor array.

Placement of the tactors

In the first session, 14 tactors were placed in a horizontal array on the back with a spacing of 4 mm, resulting in a centre to centre distance of 2 cm (see Figure 2.2). The array had a total length of 28 cm. The ninth tactor was placed exactly on the spine just below the shoulder bone. The array covered an area from 17 cm to the left of the spine to 11 cm to the right. In the second session, 11 tactors were placed in a horizontal array on the belly with the middle one on the midline about 5 cm above the navel. In the third session, two vertical arrays were placed on the belly, each consisting of five tactors. One array was on the midline with the lower tactor just above the navel. The other array was placed on the left side of the belly such that each tactor's centre was 6 cm from the midline. In a vibrotactile categorisation task, Cholewiak, Brill and Schwab (2004) showed that height around the waist did not affect vibrotactile performance with a horizontal array. Therefore we did not measure horizontal acuity as function of height.

[17] Because Experiment 1 is focussed on the effect of location, the data are aggregated over SOA levels. The effect of SOA is investigated in detail in Experiment 2.

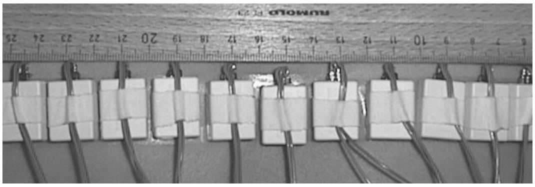

Figure 2.2. Horizontal array of tactors attached to the back with double-sided sticky tape.

Stimuli and data analysis

In the horizontal arrays (sessions 1 and 2), every third tactor was designated as standard (S) location while the remaining ones were used as comparison (C) location. In the two vertical arrays (session 3), the middle tactor was designated S. Each S was paired to four Cs, located two and four cm to the left and to the right of the S in the horizontal or two and four cm above and below the S in the vertical arrays. For each of the two levels of inter stimulus interval (196 and 980 ms), each S-C pair was presented 40 times: 20 times in the order S-C and 20 times in the order C-S. For each S location in the horizontal arrays, the data were analysed by fitting the proportion "to the right" responses as function of the location of the C (-4, -2, +2, +4 cm) to the cumulative normal distribution with the package MATHEMATICA 3.0 (least squares loss function). For the vertical arrays, the same analyses were performed with curve fitting to the proportion “above” responses.

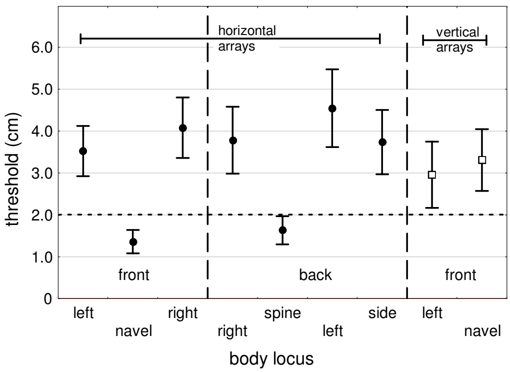

Figure 2.3. Results of Experiment 1: spatial acuity (mean threshold and 95% confidence intervals, with the threshold defined as 84% ‘to the right’ or ‘above’ responses) as function of location on the torso for horizontally (left, filled circles) and vertically oriented arrays (right, open squares). The horizontal line denotes the 2 cm centre-to-centre distance of the tactors.

2.2.2. Results

Data inspection revealed that all observers showed the same response patterns, therefore only the aggregated data are presented here. The spatial resolution thresholds were analysed with an analysis of variance with standard location (9 levels) as independent variable. The analysis resulted in a significant effect, $F(8, 24) = 3.42$, $p < .01$. Figure 2.3 presents the spatial acuity as function of the location on the torso. Please note that the threshold is based on a curve fitting procedure that can result in thresholds smaller than the centre-to-centre distance of the tactors. A post-hoc Tukey test with alpha set at .05 revealed that the navel and spine locations in the horizontal array differed significantly from the other seven locations.

2.2.3. Discussion

The results show a uniform acuity across the torso of 3 - 4 cm, except for locations on the body midline (i.e., the spine and the navel) for horizontally oriented arrays (but not for the vertical arrays) where the resolution is much higher, about 1 - 2 cm. This 'midline effect' will be discussed further below. Apart from this effect, two things can be concluded. First, the resolution of the torso for vibrotactile stimuli is in the same order as the values reported by Weinstein (1968) for pressure stimuli: between 1 and 4 cm (depending on the method). Second, there are no differences between horizontally and vertically oriented arrays. With a torso circumference between 80-100 cm and a horizontal acuity of 3-4 cm, a horizontal display resolution of 24 tactors should be obtainable. A similar calculation would result in a vertical display resolution of 8 tactors. However, these display resolutions are estimated for the current localization task with static stimuli. Although this seems quite low compared to visual displays, it is higher than the most advanced torso displays which presently have a resolution in the order of 100 tactors. Noteworthy is the fact that the torso's spatial resolution is in the same order as the tactor spacing. At first sight, this may reflect an artefact, for example pointing in the direction of individually recognisable tactors. However, recognising individual tactors is not directly relevant in determining the relative localization of two (recognised) tactors, and performance in discrimination tasks is generally better than in identification tasks (Horner & Craig, 1989). Also, the current fitting method would result in a (close to) 0 cm threshold for perfect performance, and not to a threshold in the order of the tactor size. Also Cholewiak, Brill and Schwab (2004) found that only about 7 tactors around the whole torso could be correctly identified. This indicates that identification requires a centre-to-centre spacing of the tactors of 10 cm or more. Therefore, identification could not have set the much better limits as found in the current localization task. Another artefact may be that the torso's resolution is actually better than the present results, but that the tactor size limits the threshold. Further investigating this would require tactors much smaller than the acuity limits found in the current experiment (i.e., in the order of 1 cm for the horizontal arrays at the navel and spine), which are not available in wearable variants.

Midline effect

The midline effect refers to the superior resolution on the midline for horizontally oriented arrays only. Fuchs and Brown (1984) and Weber (1834) already indirectly found the midline effect when they reported that two-point thresholds were dramatically lower when the two points straddled the torso midline compared to the situation in which the two points were near, but on the same side of the midline. Several effects may have caused the midline effect. First, there may be differences in the form, and/or size, and/or density of the receptive fields between the midline and the lateral areas of the torso. Data show that the receptive fields are fairly round on the torso (contrary to for example the limbs where receptive fields are ovally shaped; Johnson & Lamb, 1981; Loe, Whitsel, Dreyer & Metz, 1977). This makes it unlikely that differences in size or density would have resulted in superior acuity for horizontally oriented arrays, but not for vertically oriented ones like the present data show. Second, as mentioned by Adams and Helson (1966), stimuli applied to the spine have a distinctive feel (probably caused by the underlying bony structure). However, this feel is not reported for the ventral side where this bony structure is absent, while the midline effect is also present on the frontal side. Third, with respect to the neural pathways and processing involved, the midline area has two remarkable features. First, peripherally, there are ipsilateral and bilateral cells, dorsal as well as frontal (Conti, Fabri & Mazoni 1986). This means that the signals terminate in both hemispheres and not in the contralateral hemisphere only[18]. Second, there are dense colossal connections between the areas representing the midline area. These connections are present in both the primary and the secondary somatosensory cortex (Mazoni, Barbaresi, Conti & Fabri, 1989; Iwamura, 1998). This means that the midline area is represented in both hemispheres at several levels throughout the processing chain. The hypothesised function of this mechanism is the integration of the phenomenal space of both hemispheres, indicating that the midline serves as an anchorpoint for horizontal position of tactile stimuli. As shown by Cholewiak and Collins (2003), localization performance may improve on or near anchorpoints. This anchorpoint effect reveals an asymmetry for horizontal arrays but not for vertical arrays.

2.3 Experiment 2: Spatial resolution as function of timing parameters

The usefulness of spatiotemporal patterns to display information not only depends on (location dependent) spatial resolution, but also on the temporal parameters. To gain more insight into the processing of simple spatiotemporal patterns on the torso, Experiment 2 is concerned with the timing parameters of the stimuli, namely Burst Duration (BD) and Stimulus Onset Asynchrony (SOA). It has been known for long that localization is dependent on timing parameters. For example, the different effects for simultaneous and successive presentation of two points were already revealed by Weber (1834). The importance of timing parameters is also found in the tau effect (Helson & King, 1931), in sensory saltation (the illusory spatial localization of a stimulus due to its timing; Geldard, 1982), in the cutaneous rabbit (the illusory displacement of a series of taps in-between the stimulated locations; Geldard & Sherrick, 1972), and in the perceived distance between points (Cholewiak, 1999). Details on these effects can be found in Appendix I. In Chapter 1, we hypothesised that timing parameters will affect performance, especially when either the burst duration is very short or the stimulus onset asynchrony is very short.

2.3.1 Method

Experiment 2 in a nutshell.

- Four observers performed a spatial discrimination task. After the presentation of two vibrations they responded whether the second was left or right from the first. The stimuli were located on the dorsal side of the torso.
- The independent variables were the burst duration (BD)and the stimulus onset asynchrony (SOA).
- The dependent variable was the percentage correct responses.

The four participants of Experiment 1 also participated in Experiment 2. The task (i.e., indicate left or right for the second stimulus) and apparatus were the same as in Experiment 1. However, the number and placement of the tactors was different. Four pairs of tactors were attached to the back of the participant. The distance between two tactors was 2.5 cm within a pair (centre-to-centre), and 3.5 cm between two neighbouring pairs. The centre of the pairs was at: -9, -3, +3, and +9 cm with respect to the participant's midline (see Figure 2.4). The stimulus set and data analysis also differed from Experiment 1. The stimulus set consisted of the four pairs of tactors activated with a given BD and SOA. In total, 25 combinations of BD and SOA were presented, see Figure 2.5. Each of these combinations was presented 80 times: for each

[18] Recently, research in macaque monkeys has revealed that the hand representations in area 3b also receives ipsilateral input (Lipton, Fu, Branch & Schroeder, 2006).

pair 10 repetitions in the order left-right and 10 in the order right-left. This resulted in 2000 presentations for each participant, spread over a full day.

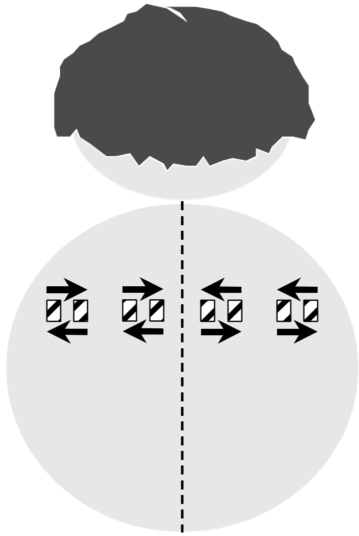

Figure 2.4 Placement of the four pairs of tactors in Experiment 2, with a centre-to-centre distance of 2.5 cm within a pair and 3.5 cm between neighbouring pairs.

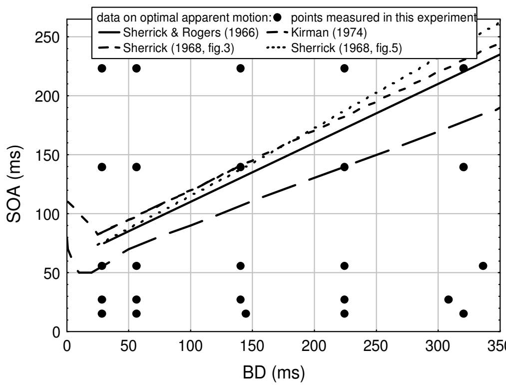

Figure 2.5. Plot depicting the 25 combinations of BD and SOA used in Experiment 2 and the (interpolated) lines of optimal apparent motion found in different studies (see the Discussion section for details).

2.3.2. Results

The data were analysed in an exploratory way as in Cholewiak and Collins (2000). The proportion correct responses was plotted in a contour plot as function of BD and SOA by using a least squares second order nonlinear fit (Statistica 5.5©). Again, since all four observers showed the same pattern, all data were combined. The result is depicted in Figure 2.6.

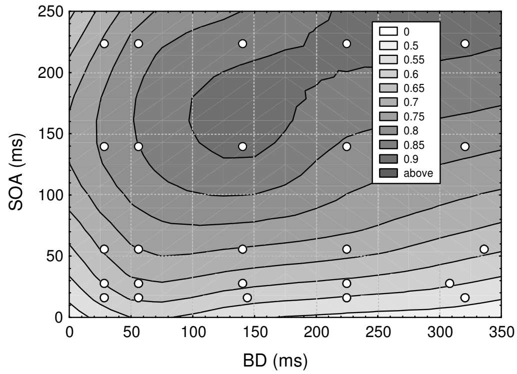

Figure 2.6. Contour plot indicating the proportion correct as function of the burst duration (BD) and de stimulus onset asynchrony (SOA). Darker colours indicate better performance.

2.3.3 Discussion on timing parameters

Figure 2.6 shows that the equal performance lines or contours are slanted, indicating that performance is dependent on both timing parameters. In general, localization performance increases when the SOA increases (especially in the range 0 - 200 ms). For BD, the picture is less clear, but averaged over all data, performance improved for higher BDs. Thus, there is a tradeoff between spatial resolution and presentation duration. This implies that tactile display applications that require high localization accuracy can benefit from longer BDs and SOAs. On the other hand, tactile display applications that require fast presentation of (consecutive) stimuli as in vehicle control applications may require a larger distance between the tactors. A further inspection reveals that SOA has a larger effect on performance than BD. In a large area (the lower part of the graph), the lines are predominantly horizontal, that is, mainly dependent on SOA. Interestingly, the typical pattern of the lines of optimal apparent motion as given in Figure 2.5 (Sherrick & Rogers, 1966; Sherrick, 1968a; Kirman, 1974a) can also be seen in Figure 2.6, including the dip at smaller BDs. This seems to indicate that both phenomena are related.

In the localization task used, three factors can influence performance: a) determining the stimuli's (relative) location (i.e., the *spatial resolution*); b) determining the *temporal order* of the locations[19]; and c) the possible occurrence of *apparent motion*. With respect to the spatial resolution, the centre-to-centre distance was equal for all pairs, and the skin’s spatial resolution was equal over the four locations. With respect to temporal order, an important study was done by Craig and Baihua (1990). They stimulated fingertips with two consecutive 26 ms bursts of 230 Hz vibrations. Thresholds (75% correct) ranged from 67 ms (same finger) to 48 ms (different fingers, same hand) and 36 ms (different hands). These data show that the critical temporal separation for two events at different locations is in the order of 30-70 ms. So, SOAs below 30 ms will result in reduced temporal order performance, eventually leading to being able to determine that there are multiple events at the stimulated locations, but without being able to determine their temporal order. This temporal order effect is reflected by the horizontally oriented contours (marked ‘temporal order’in the lower part of Figure 2.7), indicating (close to) chance performance. With respect to apparent motion, a correct percept of motion direction unambiguously indicates the location of the

[19] This would not have been the case when the task was to indicate whether the two stimuli were at the same or at different locations.

second stimulus. Essick and colleagues (Essick et al, 1991; Essick, 1998) showed that judgments of the direction of apparent motion induced by dense arrays of tactors are much better than predicted on the basis of local spatial resolution. The occurrence of apparent motion may explain the good performance in the slanted area where apparent motion percepts can occur (marked 'apparent motion' in Figure 2.7, cref Figure 2.5). The fact that localization performance is enhanced along the lines of optimal apparent motion indicates that the motion cues are additional to place-time performance. Finally, stimuli with a short burst duration (BDs smaller than 30 ms) are supposed to be processed differently by the nervous system (Kirman, 1974b; Sherrick, 1968a). Although there is no psychophysical data available that investigates this directly, several authors come to the same statement. For example, Hill and Bliss (1968a, b) suggest that for small BDs, the sequence of the presentation is lost, not the content. In the data of Kirman (1974b), there is a small hint that there is a larger SOA required for stimuli with smaller BD to be felt as successive instead of simultaneous. This small BD effect is reflected by the dip in the performance for small BDs with a constant SOA (marked 'small BD' in Figure 2.7). It should be noted that according to Sherrick (1968a), movement, simultaneity, unordered duality, and clear successiveness coexist over a range of stimulus intervals. This means that these phenomena are closely related and there are no strict borders between them.

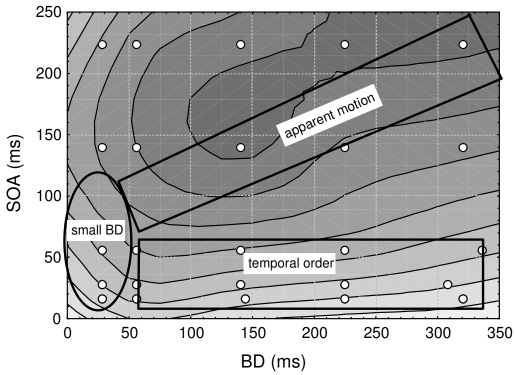

Figure 2.7. The relation between the results of Experiment 2 and three phenomena involved in the processing of spatiotemporal patterns: apparent motion, temporal order judgment, and the deviant processing of stimuli with a small BD. See the discussion section of Experiment 2 for details.

2.4 General discussion and conclusion

To optimally adjust the design of a tactile torso display for local guidance to the perceptual characteristics of the user, fundamental knowledge on how spatiotemporal patterns on the torso are processed is indispensable. In Chapter 1, the following two questions were posed:

Q1. What is the spatial resolution of the torso for vibratory stimuli, and is it uniformly distributed across the torso?

Q2. What are the effects of timing parameters on the spatial resolution?

Experiment 1 investigated the spatial resolution as function of location on the torso. The resolution showed to be quite uniform over the torso and in the order of 3 - 4 cm, both vertically and horizontally, confirming our hypothesis. The exception is that for horizontally oriented arrays, the resolution on the midline is 1 - 2 cm. A plausible explanation is based on the particular way the central nervous system

processes stimuli on the midline and the midline acting as an anchorpoint. An important conclusion of Experiment 1 is that advanced torso displays have not reached the borders of the torso's spatial resolution. Experiment 2 investigated the effect of the major timing parameters of localization: BD and SOA. The effects of temporal ordering, and the occurrence of apparent motion were reflected in the data. The results confirm our hypothesis that lowering the SOA results in decreased performance. However, even very small BDs can result in good performance (provided that the SOA is large enough), contrary our hypothesis. The fact that the skin easily and automatically integrates specific spatiotemporal patterns might be important in designing such patterns. The effect may have positive and negative effects, including spatial and temporal masking. The preferred choice in the tradeoff between speed of presentation (dependent on the timing parameters) and the spatial resolution may be dependent on the application. Those applications requiring a high spatial resolution can benefit from longer presentation times, those requiring a fast presentation require a larger distance between the tactors.
In general, we conclude that the torso's spatiotemporal information processing capacities are larger than required by currently available tactile local guidance displays. Therefore, we expect no bottleneck in the step from display to sensation, the first step in the prenav model (see Figure 1.5).

Chapter 3. Absolute localization of vibrotactile stimuli on the torso

Abstract

Local guidance tactile torso displays present spatial information (like the direction of a waypoint) through a localized vibration on the torso. In the previous chapter, we showed that the processing capacity of the torso's sensory system is sufficient for local guidance displays currently in use. However, using these systems requires the ability to determine the absolute location of the stimulus. Because data are only available on the ability to determine the relative location of 2 stimuli on the torso, the current experiment is an extension of those on spatial resolution. We developed a novel method to measure absolute localization based on triangulation. The results show that there are individual differences among the 15 male observers while each individual is consistent in localizing the stimuli either outside or within the body. All mislocalizations are along the radius originating from the body midaxis. Therefore, the difference between the actual and the perceived direction of a stimulus is small. The results make us believe that stimulus locations on the torso are coded in polar co-ordinates of which the distance is less important because it varies with, among other things, posture and breathing. These data, together with those on spatial resolution, confirm the potential of the tactile modality to process local guidance information from display to sensation (the first phase of the prenav model).

3.1 Introduction to Experiment 3: Absolute localization of tactile stimuli on the torso

The ability to perceive the absolute location of a stimulus on the body is an essential prerequisite to correctly externalise a stimulus. When you have to compare a stimulus with an external location or direction, it is not enough to be able to discriminate its location from that of another stimulus. You have to know its location in 2D space or on the body[20]. Therefore, the ability of observers to discriminate (adjacent) stimulus locations (relative location or spatial resolution) and to determine the precise location (absolute location) of a stimulus are key factors in the successful application of local guidance tactile displays. Figure 3.1 illustrates what happens when an observer mislocalizes a vibration, under the assumption that the observer uses an internal reference point to perceive the direction of the stimulus.

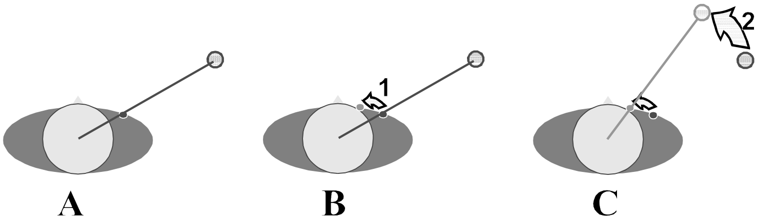

Figure 3.1. The effect of mislocalization of a stimulus on the perceived direction. In part A, the active tactor is for example expected to indicate a threat at 2 o' clock. However, when the observer mislocalizes the tactor as depicted with arrow 1 in part B, the perceived direction of the threat will be 1 o' clock as depicted with arrow 2 in part C.

Absolute localization of stimuli on the torso has not been investigated yet. A high spatial discriminability or resolution does not necessarily imply high absolute localization performance; like a darter that consistently throws the darts close to each other but in the wrong number (Clark, Larwood, Davis & Deffenbacher, 1995; for empirical support see Horner & Craig, 1989). For instance, phenomenal tactile space might be curved or distorted as shown for haptic space (Blumenfeld, 1937; Kappers & Koenderink, 1999). This effect can be independent of the local spatial resolution.

Although daily life experiences suggest that people are quite accurate in determining the absolute location of a stimulus on the body (most people are able to hit a stinging mosquito in a split second without visual guidance), this is not trivial at all. For example, does this ability change when we lose weight or after finishing a good meal. And what about women whose shape changes during pregnancy or people with a disorder of body perception and cognition (Blake et al., 2004; Naito, 2002)?

In the present experiment we investigate not the relative but the absolute localization of tactile stimuli. It extends a recent investigation on identifying vibrotactile stimuli around the torso (Cholewiak, Brill & Schwab, 2004). In the experiments of Cholewiak and colleagues observers were wearing a linear array of 6, 8, or 12 tactors encircling the torso, or a 7 tactors array in a partial ellipse around the frontal part of the torso. They were instructed to indicate as fast and accurate as possible which tactor had been active. The

[20] Absolute localization may also be important for the brain to reconstruct our sense of the body instead of passively perceiving it (Haggard, Taylor-Clarke, Kennett, 2003).

stimulus was a short 200 ms burst of vibration of one of the tactors. The response was a keystroke on a specifically designed three-dimensional keyboard, consisting of a cylinder with the same number of keys in a circle as the number of tactors in the array around the torso. This response system in which the observers could operate the keyboard from an "over the shoulder" perspective was intended to enable observers to map their bodies onto the keyboard. The major results show that the information transmitted in bits calculated from the stimulus/response confusion matrixes (i.e., the amount of information is directly related to the range of possible alternatives available to the observer). This appeared to asymptote close to the theoretical value (the magical number seven; Miller, 1956). Although this psychophysical method measures other aspects than spatial discriminability only, it does not allow to determine the precise location where the observer located the stimulus in comparison with the actual physical location. A second issue is that observers need to project the stimulus array onto a keyboard of which the keys neither correspond in physical layout (the torso is usually shaped like an oval not a circle) nor in direction (the tactors were placed at equal distances over the skin while the buttons on the keyboard were placed at equal angles) with the tactor array. A third issue is that observers received feedback after each response, making it a classification task (in line with the objective to measure information transfer). Also important is that observers can identify a tactor without needing to know it's exact location. For instance, observers can use cues such as the underlying structure (e.g., the tactor somewhere on my lower left rib) and whether a tactor is located at or close to an anchorpoint such as the navel or spine. As Cholewiak and colleagues report: observers are extremely good in identifying the tactors at navel and spine and are also quite confident that other stimuli are not at these anchorpoints. The results of their main experiment (Cholewiak, Brill & Schwab, 2004, Table1) show that of the 3000 non-anchorpoint stimuli only 8 were wrongly classified as an anchorpoint. This 'anchorpoint bias' may also be the explanation for the results they found for the tactors adjacent to the anchorpoints. Because observers will never respond with the navel or spine location, a bias away from the mid-sagittal plane is introduced.

The questions stated above cannot be investigated by the current psychophysical methods for spatial resolution or classification but requires a different psychophysical measuring method. This method should not be based on the assumption that the subjective location of the vibration is on the skin surface, should allow continuous responses instead of a limited number of categories, and must prevent the 'anchorpoint bias'. Based on these preconditions, we developed a method based on triangulation, i.e. determining the co-ordinates and distance of an unknown point by observations from two (or more) known locations in space.

3.2 Method

Experiment 3 in a nutshell.

- 15 observers performed a triangulation task in which they had to line up a cursor with two stimuli of which one was attached to the frontal side of the torso.
- The independent variables were the location and the modality of the torso stimuli. There were 15 stimulus locations and two modalities: visual and tactile.
- The dependent variable was the subjective location of the stimulus (either in x, y co-ordinates or in polar co-ordinates).

Participants

Fifteen male observers participated in the experiment, six were recruited from the scientific staff of TNO Human Factors and nine were undergraduate students. All participated voluntarily, only the students received €50 for their participation. Before the start of the experiment all individuals received written and verbal information on the experiment and read and signed an informed consent. None of the observers reported any conditions that might affect tactile perception of vibration on the torso or a distorted body schema.

Apparatus

Figure 3.2 depicts the experimental setup. The experiment took place in a completely darkened room. The observer was lying on a stretcher with his torso fixated but allowing head rotations. To facilitate viewing the frontal side of the torso, a cushion was placed under the observer's head. A board was placed over the observer, perpendicular to the body midaxis at a level just below the navel. Each trial consisted of the presentation of three stimuli: one on the torso which could be either tactile (a burst of vibration) or visual (an LED), a reference stimulus (which was an LED mounted in the board), and a visual cursor (which was projected on the board). The task of the observer was to position the cursor so that the three stimuli were on a straight line. The cursor was a round dot projected by a focussed light attached to a servo-controlled platform mounted behind the observer. Cursor position resolution and readout accuracy was 0.01°. The observer steered the cursor along an imaginary circle on the board with a handheld rotary dial. When the cursor was subjectively positioned correctly, the observer pushed a button on the rotary dial and the next trial would start. The visual torso stimulus served as control condition.

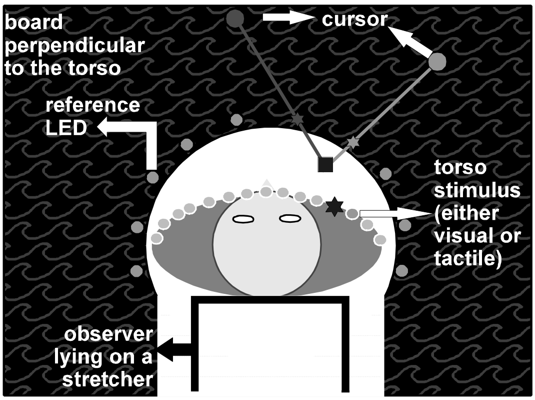

Figure 3.2. Layout of the experimental setup and the triangulation principle. The observer was lying on his back on a stretcher. A board was placed perpendicular to the body midaxis just below the observer's navel. Each trial consisted of three stimuli: a torso stimulus (a vibration or LED), a reference LED mounted in the board and a cursor. The observer's task was to position the cursor with a handheld dial such that the three stimuli were on a straight line (the dots are two examples). By using different reference LEDs for each torso stimulus, the subjective location of the torso stimulus can be calculated using triangulation (the square would be the result based on the two example responses).

All stimuli were located in the same, flat plane. The radius of the circle of red reference LEDs was 0.46 m, that of the cursor was 0.71 cm. The exact location of the torso stimulus in the plane of the board was measured using three accurate thread potentiometers at known locations on the board and the method of trilateration. The torso stimulus and reference LED were activated in a "100 ms on - 200 ms off" rhythm which is both comfortable and prevents tactile adaptation. Each of the fifteen torso stimuli was combined with each of ten reference stimuli resulting in 150 pairs. Each pair was presented three times in one session. Each of the observers completed two sessions of 450 trials: one for the visual torso stimuli and one for the tactile torso stimuli. The 450 trials in each session were randomised with the restriction that successive torso stimuli were at least two positions apart. Eight of the participants started with the tactile torso stimuli, seven with the visual. The tactile stimulus was presented with a MiniVib 4 vibrator with a contact area of 22 by 16 mm (Special Instruments Development Corporation, Sweden) driven with a 250 Hz sine wave. The torso visual stimuli were red LEDs.

Procedures

After reading the instruction and signing the informed consent, the observer laid down on the stretcher. Fifteen pieces of ultra thin double sided sticky tape (Sellotape, Switzerland) were placed at equal distances at the frontal side of the torso and in such a way that the outer ones were located more or less at the left and right side of the observer's torso. With a felt-tip pen, a marker was placed on each piece of sticky tape. At that time, the torso of the observer was fixated by cushions besides the legs and upper body, and the location of each of the 15 felt pen markers was measured. After this measurement, the visual or tactile torso stimuli were attached at the marked locations, and the observer was given the handheld control box. After switching off the room lights, a total of 20 trials was presented in the presence of the experiment leader. When the experiment leader was convinced that the instructions were clearly followed and the participant had no more questions, he left the room and the experiment could start. The experiment leader was able to monitor the participant and setup by means of an infrared light source and a CCTV camera. The experiment was self-paced, but none of the sessions lasted longer than one hour (i.e., a mean response time below 8 s). After completing the 450 trials in the first session, a short break was taken and the torso stimuli were changed (tactile for visual or vv.) without removing the sticky tape. The torso stimuli in the second session were placed at exactly the same locations by using the marked sites, which was checked with the thread potentiometers.

3.3 Results

All data were analysed with a reference frame defined in the plane of the board. We defined the body midaxis as origin, the left-right direction seen from the head of the observer as x-axis and the y-axis as perpendicular to the x-axis and the body midaxis. The subjective location of a torso stimulus was calculated as follows. For each of the 30 trials for a specific torso stimulus, a line was drawn through the reference LED and the cursor position. Next, for the set of 30 lines, the intersection of each of the possible line pairs was calculated (Figure 3.2 depicts one such pair). This resulted in 405 intersections per torso stimulus per observer. The intersections with an x or y co-ordinate smaller than -1 m, or larger than +1 m were removed from further analyses. These intersections were the result of (nearly) parallel lines. The percentage of removed intersections for a torso stimulus never exceeded 10% and was 1.5% on average. The subjective location of the torso stimulus was calculated as the mean x and mean y co-ordinate of the intersections.

Before we looked at localization performance, we calculated the uncertainty intervals around each subjective location, based on the 95% confidence limits of the mean (separately for the x and y co-ordinates). We analysed the uncertainty intervals with a Modality (tactile or visual torso stimulus) × Location (15 torso stimulus locations) × Axis (x-axis, y-axis) design. This analysis revealed main effects of all three independent variables. The effect of Modality: $F(1, 14) = 54.81$, $p < .01$ showed somewhat smaller intervals for the visual stimuli (mean 1.49 cm) than for the tactile stimuli (1.66 cm). The effect of Axis: $F(1, 14) = 1411.06$, $p < .01$ showed that the interval for the y-axis (0.79 cm) was smaller than for the x-axis (2.36 cm). The main effect of Location: $F(14, 196) = 10.63$, $p < .01$ showed that the uncertainty intervals for the torso stimuli near the midline were smaller than for those near 90° left or right. The range between the largest and smallest mean uncertainty interval as function of Location was less than 0.5 cm. Post hoc tests on the two significant interactions with Location: Modality × Location: $F(14, 196) = 8.59$, $p < .01$ and Location × Axis: $F(14, 196) = 12.30$, $p < .01$, revealed no systematic effect other than the main effect of Location.

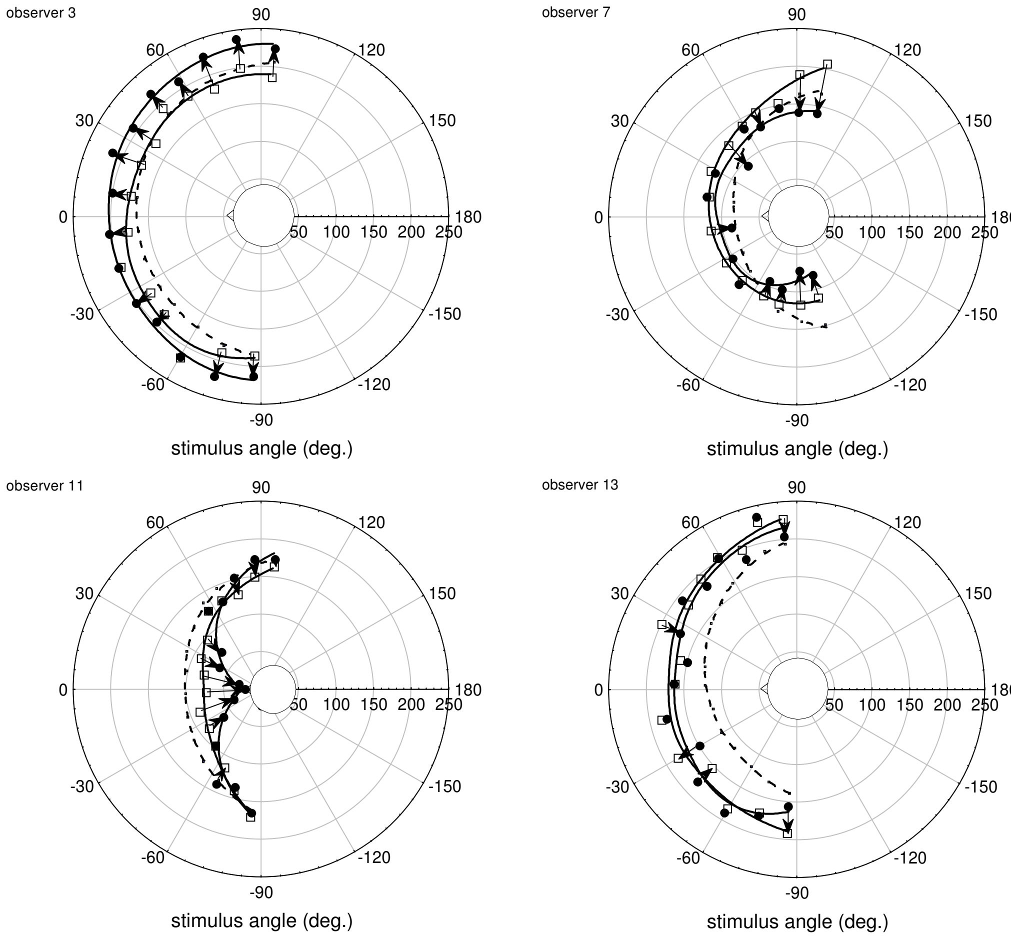

Figure 3.3. Results for four typical observers. The open squares represent the locations of the visual torso stimuli, the filled circles those of the tactile torso stimuli. Corresponding stimuli are connected by arrows. The radius is in mm, the navel and nose are at 0°. The lines are the least squares fit. The dotted line is the fit through the physical location of the stimuli.

The localization data for four typical observers are plotted in Figure 3.3. We compared the subjective location of the tactile torso stimuli with that of the control condition with visual torso stimuli. Each plot depicts the visual torso stimuli (open squares) with arrows to the corresponding tactile torso stimuli (filled circles). The uncertainty intervals are not plotted because their size is in the same order as the size of the symbols in the plot. Observer 3 is typical for a group of three observers for whom the tactile torso stimuli had a somewhat larger radius than the visual torso stimuli. Observer 7 is typical for a group of three observers for whom the torso stimuli were typically observed with a smaller radius than the visual stimuli. Three observers showed a pattern as that of observer 11 in which the tactile torso stimuli near the midline had a smaller radius than the visual stimuli, while this shift was absent for stimuli further away from the midline. Finally, observer 13 is typical for the remaining six observers who showed no or only small differences between the perceived locations of the visual and tactile stimuli. Inspecting the data of all 15 observers, also taking into account the objective or physical location of the torso stimuli, resulted in the following observations. First, for all 15 observers, the sequence or angular order of the subjective locations corresponded to those of the objective locations in both modalities. This indicated that the line-up task was doable and that the triangulation method resulted in meaningful data as was already expected from the small uncertainty intervals. Second, the difference between the subjective location of a tactile torso stimulus compared to its corresponding visual torso stimulus was best described by a shift along the radius, neither shifts purely along the x-axis nor along the y-axis seemed to occur. Third, for most observers, the tactile torso stimuli had a radius that was either smaller or larger than that of the visual torso stimulus, irrespective of the location. We analysed the radius of the torso stimuli with a Modality (2) × Location (15) ANOVA. This analysis resulted only in a significant effect of stimulus Location: $F(14, 196) = 15.97$, $p < .01$, nicely following the oval shape of the torso for both modalities (see Figure 3.4, the interaction was not significant).

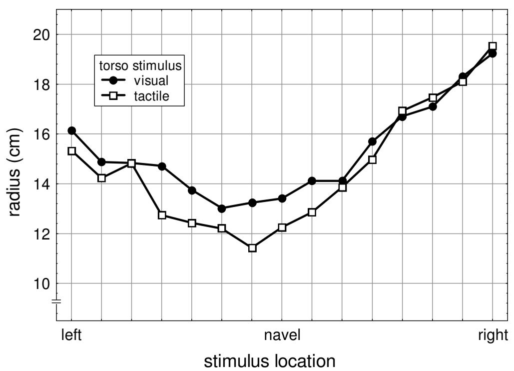

Figure 3.4. The radius of the torso stimuli as function of the location on the torso and the modality of the stimulus.

Finally, because the angles of the localized vibration are important in tactile mobility systems, we analysed the angles of the presented and perceived locations. Figure 3.5 depicts the fit of the subjective angle as function of the objective angle for the visual torso stimuli and the tactile torso stimuli.

For both modalities, the subjective angle corresponded well to the objective angle. For the visual stimuli, there seemed to be an undershoot over the whole range. For 90° left and right the undershoots were 14° and 6°, respectively. This left-right asymmetry might be related to eye and/or hand dominance since the hardware setup is symmetrical. The subjective angles for the tactile torso stimuli equalled the objective ones till about 45° left and right and showed an undershoot for larger objective angles. The undershoots for the left and right sides (i.e., -90° and 90°) were 15°, and 10°, respectively, showing the same left-right asymmetry as the visual stimuli.

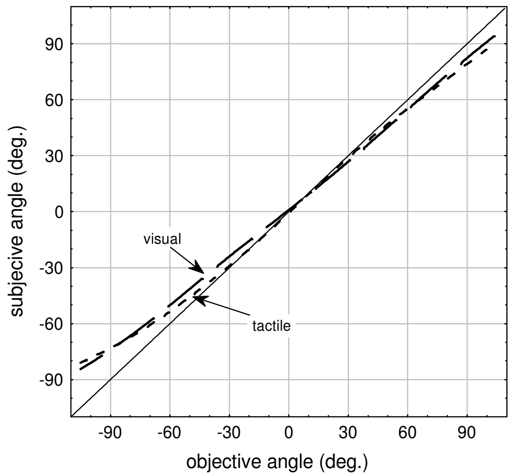

Figure 3.5. The subjective angle as function of the objective angle for the visual and tactile torso stimuli. Each least squares fit is based on the combined data of the 15 observers and the 15 torso stimuli.

3.4 Discussion and conclusion

The triangulation method employed in this experiment resulted in accurate determination of the observed location of torso stimuli. The uncertainty intervals were smaller than 2.5 cm for the x-axis and smaller than 1 cm for the y-axis. There was a small, but significant difference of 0.17 cm in uncertainty interval between the visual and tactile modality. The uncertainty interval for the visual stimuli is 1.49 cm, that for the tactile stimuli is 1.66 cm on average, which is about the same as the contact size of the vibrators. The size of the uncertainty intervals, and the fact that the spatial ordering of the observed location corresponds with that of the physical locations, justifies the conclusion that the triangulation resulted in accurate and meaningful results. The fact that the uncertainty interval in the x-axis is about three times that of the y-axis may be due to the layout of the reference LEDs. The employed method is sensitive to near parallel lines, because the co-ordinates of their intersections approach ±∞. The present layout with reference LEDs near -90° and +90° enlarged the uncertainty in the x-axis, but not in the y-axis for torso stimuli close to -90° and +90°. The comparable situation for the reference LEDs near 0° that would have affected the uncertainty of the torso stimuli close to 0° did not occur since there were no reference LEDs near -180°.

The main question investigated in this Chapter was Q3 at the perception level: How well can observers determine the absolute location of vibratory stimuli on the torso? The results show that shifts of the subjective locations are along the radii of the objective locations and not along the left-right or fore-aft dimension. The net effect of this displacement on the subjective direction of the stimuli is close to zero, especially in the forward 90° cone. Outside this cone, the subjective angle is closer to the body midline. To compensate for a potential effect of eye or hand dominance resulting in a larger angle undershoot for locations left or right of the body midline, we can correct the tactile data with the results of the visual data. Doing so leaves a small tactile undershoot of 1° left and 4° right. Interestingly, although there are large differences between the observers, they are all quite consistent in locating stimuli with either a shorter or longer radius than their actual radius. Even when there are large shifts between the objective and subjective location (5 cm or more, e.g. see Figure 3.3, observer 11), the shift is always along the radius, both for visual and tactile stimuli. This may indicate that (stimuli on) the skin of the torso are coded in polar co-ordinates (i.e., an angle and distance). The present results indicate that angles are the perceptual invariant for torso stimuli. Apparently, distance is either less relevant in localizing torso stimuli or the sensory system required to adjust the distance for posture, breathing, pregnancy or a copious meal is not worth the effort. As long as we move our hand along the radius, we will hit that stinging mosquito sooner or later.

All in all, the data show that observers are able to localize a vibratory stimulus close to its actual location, a prerequisite for the successful development of tactile mobility displays on the torso. The results are in accordance with our hypothesis that people can determine the absolute location of a tactile stimulus with a resolution of 5 cm or better. When the objective and subjective locations do not coalesce, the shifts are mainly along the radius, which has no effect on the perceived direction of the stimulus. We can conclude that these data, together with those of Chapter 1 on spatial resolution, confirm the potential of the tactile modality to process local guidance information from display to sensation (the first phase of the prenav model).

Chapter 4. Direction perception[21]

Abstract

Chapters 2 and 3 explored how well people can discern neighbouring stimulus sites on the torso (spatial resolution) and perceive the location of a torso stimulus (absolute localization), both related with the first step in prenav from display to sensation. The next step in prenav is from sensation to perception, i.e. translating the stimulus into meaningful information. Important prerequisite for local guidance tactile displays is that the user can externalise the stimulus: the vibration does not indicate an event on the body but points into the direction of an object or event in the external world. The present study investigated the direction in the horizontal plane to which a specific torso location is mapped using a 15 tactor linear display. Participants indicated the observed external direction of a localized vibration by positioning a remotely controlled cursor. The results show that the observed direction is toward the midsagittal plane (i.e., the navel or the spine) compared to the tactor direction. This bias is consistent over the observers tested, and up to 10° for the oblique directions. Inspection of the response patterns revealed that observers did not use the body midaxis as origin for the observed direction, but used two spatially separated internal reference points, one for each body half. The variability of the responses also depends on the tactor direction. It is higher for the left-right direction and lower for the fore-aft direction, which may be caused by the spine and navel acting as anchor points.

[21] Parts of this Chapter have been published as:
Van Erp, J.B.F. (2005a). Presenting Directions with a Vibro-Tactile Torso Display. *Ergonomics*, *48*, 302-313.

4.1 Introduction to Experiment 4: Direction perception

A simple local guidance tactile display may consist of a small number of tactors on, for instance, the legs or wrists. Successful applications include the studies done by Rochlis and Newman (2000) who presented direction information during simulated extra vehicular activity in space by tactors on the torso and the neck, and by Dobbins and Samway (2002a) who presented a virtual corridor by tactors on both thighs of a blind individual who set the blind world water speed record at 117 km/h. More complex displays, however, consist of many more tactors that may cover the complete torso of the user. These displays present not simply left or right, but map external directions in the horizontal plane directly to a specific location on the torso.

For a complex torso display that uses a direct mapping between an external direction and a location on the torso, two issues are relevant. The first issue is concerned with *the bias and accuracy*, that is, which direction is experienced for a specific torso location and how accurate are observers? In other words, it seems logical that a vibration at the navel is experienced as a direction straight ahead. But what about a location 10 cm to the right, is this determined as for example 1, 2, or 3 o'clock, and how consistent is this determination? The second issue is which *reference mechanism* observers use. How are observers able to determine a direction based on a single point stimulus on the skin? The applications that are currently under investigation make the implicit assumption that observers perceive direction as the line from an internal reference point (assumed to be the body midaxis) through the location of the tactor on the torso's skin. The location of this internal reference point is important because it is correlates phenomenal and physical space. The strategy of using an internal reference point resembles the perceptual ego-centres that are postulated for vision (also called the cyclopean eye, e.g. Roelofs, 1959; Ono et al., 2002), for kinaesthesis (Blumenfeld, 1936; Rubin, 1936; Hunter, 1954; Davidson, 1972; Shimono et al., 2001), and for audition (Cox, 1999). An important difference between direction determination with a tactile torso display and the perceptual ego-centre theory is that the latter includes perceived direction and perceived distance. Since vibrotactile displays require physical contact between the stimulus and the observer's skin, perceived distance as function of physical distance cannot be investigated. An alternative strategy to determine the direction of a localized vibration is that the location of stimulation contains direction information through the skin's local curvature. More specific, an observer may determine the direction for a specific location as perpendicular to the skin at the specific location, that is, as the “normal vector”.

This study investigates both issues mentioned above for tactile direction determination in a transversal plane through the torso (i.e. the horizontal plane when standing). By having observers make repeated direction determinations for the same stimulus location, insight can be gained in the variability of the indications. Also, by accurately measuring the physical location of the vibrotactile stimuli and the observer's body form, it is possible to investigate whether observers indeed use the body midaxis as internal reference point or use the torso's curvature. To characterize body form, the eccentricity of observers was calculated by dividing the torso width by the torso depth. Figure 4.1 shows the predicted response patterns as function of eccentricity. For observers with a circular torso, the predicted response patterns for both strategies will be indistinguishable. However, for observers with a more oval shaped body form, the strategy of using local curvature predicts a correlation between response pattern and body form (imagine that an infinitely slim individual will feel a stimulus either from the front or from the back) while the directions perceived using the strategy of an internal reference point are independent of the local curvature.

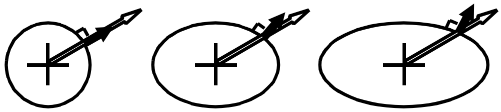

Figure 4.1. Hypothesised effect of body form on the direction determination. The open arrow gives the predicted response when the observer uses the body midaxis as internal reference point, the filled arrow gives the predicted response when the observer uses the local body curvature as cue. The three hypothetical observers each have a tactor at a direction 60° right from the midsagittal plane. The left observer has a circular body form (an eccentricity of 1.0) and both response patterns are indistinguishable. Both other observers have an eccentricity of 1.5 and 2.0, respectively and show an increasing difference between both response patterns.

4.2 Method[22]

Experiment 4 in a nutshell.

- Ten observers performed a direction perception task, in which they positioned a cursor on a table surrounding them such that it indicated the direction of a vibration on the torso.
- The independent variable was the angle of the tactor (there were 15 tactors in a belt around the torso), calculated from the body midaxis.
- The dependent variables were the bias (calculated as the difference between the angle of the tactor and the indicated direction), and the consistency (calculated as the standard deviation over multiple responses given to the same tactor).

Participants

Ten male researchers of TNO Human Factors voluntarily participated. They were all right-handed and familiar with experiments on tactile perception. The experiment was approved by the institute's human participants committee. After the explanation of the experiment, the participants signed an informed consent. Table 4.1 gives an overview of relevant participant data.

[22] Please note that all participants did the experiment twice: with tactile stimuli on the torso and with visual stimuli located in a circle just adjacent to the torso. Only the results of the tactile stimuli are reported here in detail. See Van Erp (2000) for further information.

Table 4.1. Data of the ten participants. The torso circumference was measured by a tape measure and used to determine the inter tactor distance. The outer tactor angle gives the angle of the angular range of the tactors clockwise and counter clockwise from straight ahead. The torso width and depth were calculated based on the data of a 3D bodyscan of the participant. The torso measures were taken just above the navel, that is at the position of the tactors. The eccentricity was defined as the torso width divided by the torso depth.

participant	age	torso circumference (cm)	inter tactor distance (cm)	outer tactor angle (°)	torso width (cm)	torso depth (cm)	eccentricity
1	30.1	83	5	151	28.1	23	1.22
2	29	82	5	154	28.1	21.8	1.29
3	33.6	96	6	158	30.4	24.3	1.25
4	31.8	88	5	143	29.2	23.5	1.24
5	32	108	6	140	34.8	30.9	1.13
6	29.6	84	5	150	29.7	21.9	1.36
7	34.9	97	6	156	32.9	26.2	1.26
8	33.8	88	5	143	30.2	22.5	1.34
9	25.6	93	5	135	31.1	25.1	1.24
10	25.7	81	5	156	28	21.1	133

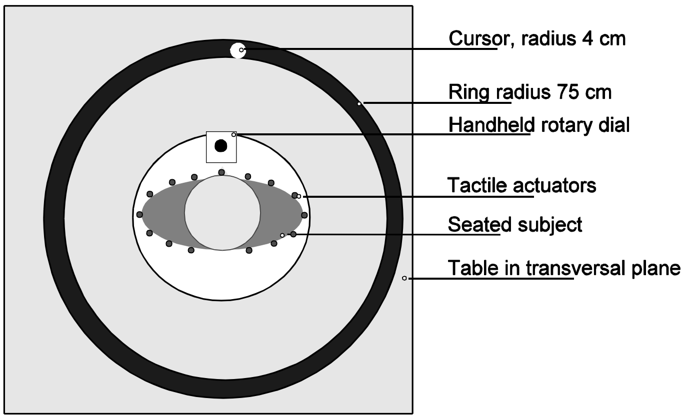

Figure 4.2. Schematic top view of the experimental setup (not to scale).

Apparatus

The participant sat straight on a stool in the middle of a circular gap in a horizontally positioned square table (see Figure 4.2). The stool was adjusted so that the participant's midaxis was in the middle of the table. The stool allowed maintenance of a fixed and comfortable position. The table was just above navel

level of the participant. Fifteen tactors were placed at equi-distances on the participant's torso. The distance between tactors was 5 cm when the torso circumference was smaller than 96 cm and 6 cm when the circumference was 96 cm or larger. The middle tactor was placed just above the navel, exactly at the level of the table. With respect to the body midaxis, the outermost tactors were placed at about 150° to the left and the right of the middle tactor, forming a partial circle in the transversal or horizontal plane. Because the tactors were placed equidistantly, the exact tactor angle depended on the body form (see also Table 4.1). The tactors were held in place by two-sided sticky tape. The tactors were minivib-4 vibrators of Special Instruments Development Corporation, Sweden (see Appendix II for details). After placing the tactors, each participant was scanned using a Vitronic VIRO-3D 1600 body scanning system. The raw data from the scans were cleaned and transformed using the software packages Polyworks and Integrate. The latter resulted in a cross section of the torso with calibrated x- and y-co-ordinates (error estimation smaller than 2 mm). This scan allowed exact localization of the tactors in the transversal plane.
The input device was a handheld rotary dial (position control). The participant could steer a cursor along a white circle drawn on the table (radius 75 cm). The cursor was a light spot with a radius of 4 cm that was produced by a focussed light attached to a servo controlled platform mounted on the ceiling. Cursor position resolution and readout accuracy was 0.01°. This method was preferred to pointing with the arm or hand which may force the observers to move their torso. The 75-cm radius allowed to see the cursor by making eye and head movements only.

Procedures

The experiment was run in a closed, dimly lit room. The participant wore a headset with white noise to prevent localization of the tactile stimulus based on the faint humming sound. An oversized T-shirt was worn over the tactors to prevent visual localization. The participants were instructed to keep a fixed position on the stool and to keep their torso still. The experimenter checked this via a closed circuit television system.
In each trial, one stimulus was activated in a ‘100 ms on - 200 ms off' pattern. The participant was asked to position the cursor on the circle, such that it indicated the direction of the vibration. The participant pushed a button near the rotary dial after positioning the cursor. Maximum duration of stimulation was 6 s, followed by another 4 s period to respond. However, the participants could give the response as soon as they felt that the cursor was correctly positioned after which the stimulation was terminated. After pressing the button, the next presentation began without repositioning the cursor. Participants were allowed to work in their own preferred pace (however, maximum response time for each trial was 10 s). A short practice session of 20 trials was given before the start of the experiment. The experiment was run in five blocks with two-minutes breaks in between. A block consisted of seven repetitions of each of the 15 tactors. Successive presentations were in randomized order, but differed at least two tactor positions in the array. Including instruction and body scanning, the experiment took less than two hours. The participants received no feedback on performance neither during the practice nor during the experimental trials. Two sessions were run: one with tactile stimuli as described above and one with visual stimuli. The visual stimuli were mounted in the board with a radius of 35 cm. The latter data will not be presented here, but will only be used to cancel out possible effects of the visual system that are reflected in the tactile data.

4.3 Results

First, the location of each tactor and of the body midaxis on the basis of the 3D body scan was calculated. This allowed the creation of a visual representation of the data for each observer. The results of a typical observer are given in Figure 4.3 (the results of the visual data are given as illustration). In this figure, lines were drawn between each stimulus and its mean indicated direction.

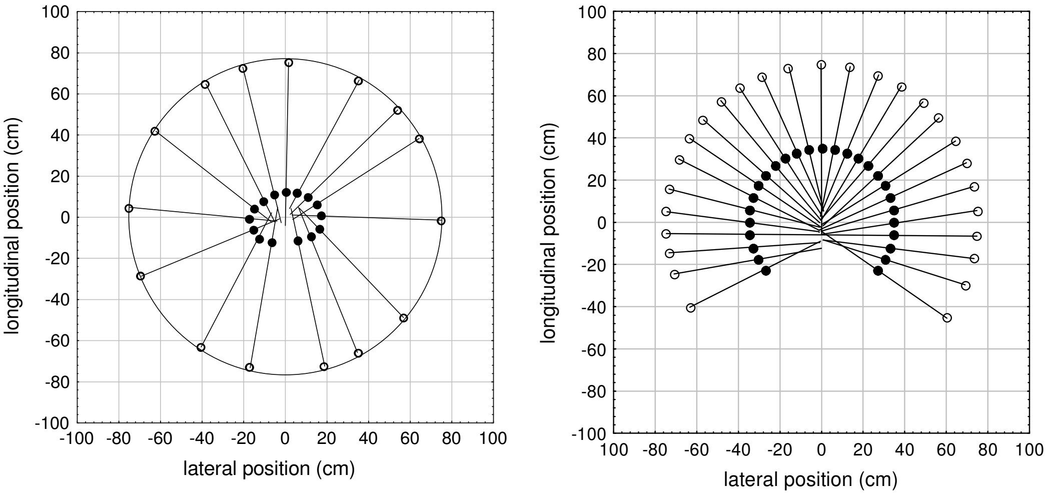

Figure 4.3. Typical response patterns (top view) for the tactile stimuli (left) and visual stimuli (right). The filled circles in the left panel are the locations of the vibrotactile tactors on the torso as measured by the body scan. The lines connect each stimulus with the mean of the responses (open circles).

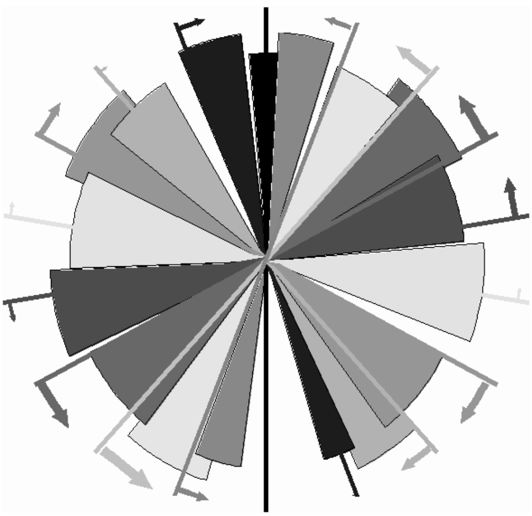

Figure 4.4. Graphical depiction of the mean response and the response variability over all participants. The difference between the tactor angle (lines) and the responses (arcs covering the mean response ± 1 standard deviation) are indicated by the arrows. The angular size of the arc represents the variability, the size of the arrow represents the bias.

Since all observers showed a similar response pattern, it was decided to combine the data. To that end the data were expressed in polar co-ordinates with the body midaxis as origin (ahead was defined as 0° with positive angles clockwise). Because the tactors were located equidistantly for each observer, the polar angle of each tactor differed between individuals. Therefore, the angles were grouped in 20° intervals. It should be noted that this means that an individual observer is not necessarily represented in each interval (e.g. an observer with successive tactors at 27° and 52° is not represented in the [30°, 50°] interval). The combined results are depicted in Figure 4.4. In this figure, the mean tactor angle is represented by the line, the arcs summarise the responses (mean response ± 1 standard deviation). The arrows indicate the difference between the mean tactor angle and the mean response angle. Figure 4.4 gives both an indication of the relation between torso location and determined direction and of the variability of the responses. For most tactor angles, there was a difference between the tactor angle and the average response angle. If observers use the body midaxis as internal reference point, this difference should be close to zero. Inspecting Figure 4.3 reveals that it is not likely that this typical observer used the body midaxis as internal reference point.

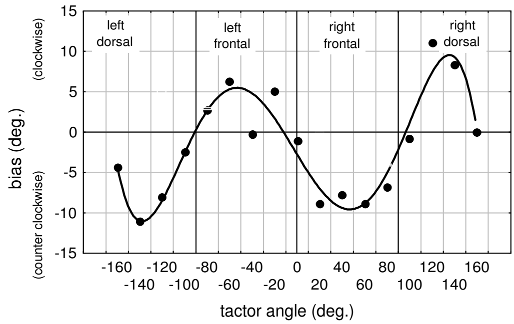

Figure 4.5. Bias (the difference between tactor angle and determined direction) as function of the tactor angle. The quadrants of the torso are given in the upper part of the graph.

A more numerical way of plotting the data is used in Figure 4.5 which shows that the difference between the tactor angle and the response angle varied between -10° and +10° (the visual results showed a different pattern with a systematic undershoot in estimated direction of 5%). The direction of the difference (clockwise (positive values) or counter clockwise) was dependent on the quadrant of the tactor (the quadrants are named in the upper part of the figure). Summarising, the responses were toward the midsagittal plane compared to the tactor directions, that is toward the navel for the frontal side of the torso and toward the spine for the dorsal side. It should be noted that this difference would be the bias in direction determination for those applications that present direction in relation to the body midaxis as origin as is common practice.

A similar plot can be made for the variability as function of the tactor angle. This is depicted in Figure 4.6. The lowest variability was found on the midsagittal plane with a SD of 4° and was systematically higher to the sides (SDs rising to 14°). The variability lowered again on the dorsal side. The visual results show a different pattern with low variability at 0° (< 2°) that systematically rises to the sides and further to the dorsal side (5°).

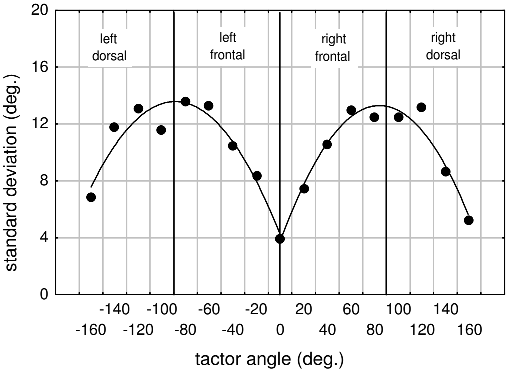

Figure 4.6. Variability (standard deviation over repetitions) of the direction determination as a function of the tactor angle. The quadrants of the torso are given in the upper part of the graph.

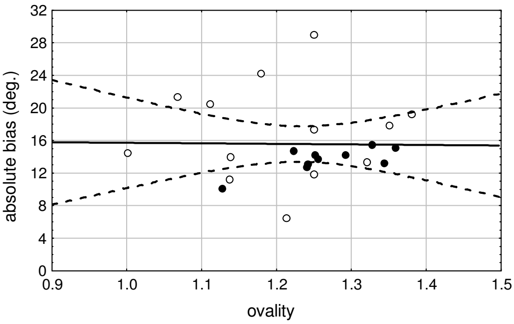

Figure 4.7. Correlation (regression line and 95% confidence interval) between the eccentricity of observers and the size of their absolute bias. The filled circles represent the data of the present experiment, the open circles represent data from former experiments. A significant correlation would have indicated that observers might have used body curvature as cue in direction determination.

Because the data do not seem to fit with a strategy of using the body midaxis as internal reference point, the second suggested strategy was investigated, namely using the body curvature. Bias was defined as the difference between the tactor angle and the response angle, and eccentricity as the body width divided by the body depth. When observers used their local curvature of the skin as cue, the bias would increase for increasing eccentricity. In other words: An observer with a perfectly circular torso (i.e. an eccentricity of 1.0) would have no bias, while very slim observers would have a large eccentricity and a large bias (see also Figure 4.1). To test this, the correlation between eccentricity and the absolute bias was calculated. To achieve a more reliable analysis, the present data were combined with an older experiment (Van Erp, 2000), bringing the total number of observers to 23. This older experiment differed from the present experiment on the following two aspects: the tactors were placed at every 20° instead of equidistantly and a body scan was not taken. However, torso depth and width were measured. The correlation between eccentricity and absolute bias was found to be -.01, see also Figure 4.7. This means that it is also unlikely that observers used local body curvature to determine the direction of a vibrotactile point stimulus. The data did not fit well with both suggested strategies, and the individual data plots (see Figure 4.3 for an example) showed a pattern in which the lines from response to tactor seemed to intersect in two points:

in the right torso half for tactors on the right and in the left torso half for tactors on the left. Therefore, we performed an additional analysis in which we calculated these internal reference points as the point of intersection of the line crossings of a chosen set of tactors. The two sets were for the left and right body half (the tactor on the midline was left out). The results showed that for all observers, the two internal reference points are laterally displaced with a mean distance of 6.0 cm between both points, see Figure 4.8.

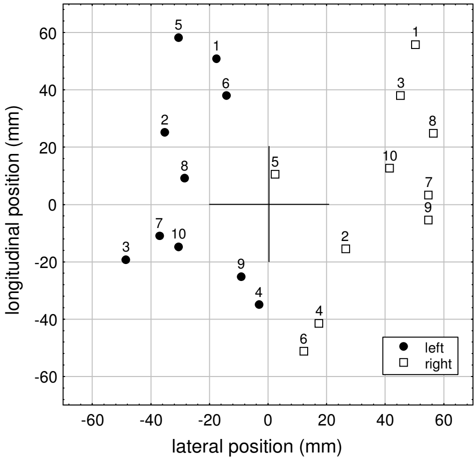

Figure 4.8. The internal reference points for the ten observers (numbered 1-10) calculated separately for the tactors on the left body side (filled circles) and the right body side (open squares).

4.4 Discussion and conclusion

Chapters 2 and 3 explored how well people can discern neighbouring stimulus sites on the torso (spatial resolution) and perceive the location of a torso stimulus (absolute localization), both related with the first step in prenav from display to sensation. The next step in prenav is from sensation to perception, i.e. translating the stimulus into meaningful information. We investigated two questions at the perception level: Q4 (are observers able to perceive an external direction based on a localized vibration, and what is the accuracy (and bias) in this direction perception?) and Q5 (How do people extract a direction from a (‘dimensionless') point stimulus?). We measured perceived direction as function of the direction of a point stimulus. The experiment was run with tactile and visual stimuli. The latter served as control to be able to investigate whether patterns in the tactile data were caused by the visual system. Although the effects found in the tactile data are partly caused by the visual system, the patterns of the visual bias and variability as function of stimulus direction is so different that it could not have caused the effects found in the tactile data. The results indicate that the accuracy of direction perception is high for directions straight ahead and straight behind, but lower for the directions left and right. There is also a general bias in the perceived direction toward the midsagittal plane. This bias seems to contradict the study of Cholewiak, Brill and Schwab (2004) who investigated localization around the torso and found a bias away from the midsagittal plane (see Section 3.1 for a more thorough discussion on their experiment). As argued in Section 3.1, this bias may have been caused by the fact that observers are very well able to identify their midline and will not easily identify a nearby stimulus as being located on their midline. However, when the navel and the spine are considered as anchorpoints (cref. Chapter 2), the bias toward the midsagittal plane is in accordance with the bias found by Cholewiak and Collins (2003) for linear arrays on the arm.

The present experiment confirms that people are able to indicate an external direction that matches a vibrotactile point stimulus on the torso. Since a single point stimulus does not contain direction information, observers need to use additional information. Two alternatives were postulated. The first is that observers experience direction as perpendicular to the skin surface at the location of stimulation. However, the lack of a correlation between body form and the response patterns shows that this is not very likely. The second is that observers use a second (internal) reference point. Although the data did not seem to fit with the existence of a single internal reference point located at the body midaxis as hypothesised in the introduction (H5), the response patterns did fit with the existence of an internal reference point for each body half. This observation is consistent over observers, and results in a mean lateral distance between both reference points of 6.0 cm across participants. In the previous experiment on absolute localization, we found a response pattern that fitted with polar co-ordinates with the body midaxis as origin. However, the stimulus presentation in the triangulation task consisted of three points and was thus independent of the use or exact location of an egocentre.

The conclusion that there are two internal reference points may be related to the way vibrotactile stimuli are processed in the central nervous system (cref. Appendix I). Stimuli presented to a specific location on the torso are processed by the contralateral hemisphere. Just as each body part has its own kinaesthetic internal reference point (e.g. Soechting &Flanders, 1982, 1992), the two torso halves can be seen as different body parts, each having its own internal reference point. There is no a-priori reason to expect that both are exactly co-located. The fact that the response to a stimulus on the observer's midline is a direction that relates neither to the left nor to the right reference point is the consequence of the fact that tactile stimuli presented to the torso midline (i.e., within a band of about 6 cm width) are processed in both hemispheres (Conti et al., 1986; Fabri, Polonara, Salvolini & Manzoni, 2005; Manzoni et al, 1989; Iwamura, 1998). The function of this mechanism is hypothesised to be the integration of the phenomenal space of both body halves into one coherent percept, in this case a direction that is somewhat in between that indicated by the left and the right hemisphere.

Coupling direction to location: implications for spatial guidance applications

Currently applied tactile torso displays calculate the tactor direction with the body midaxis as origin. The present data show that doing so results in a systematic bias between the tactor direction and the experienced direction, while we expected no bias (according to H4). This bias is toward the midsagittal plane, that is, experienced directions are toward the navel for tactors on the frontal side, and toward the spine for tactors on the dorsal side.

This may have consequences for the design and applications of tactile displays that use a direct mapping between stimulus location and external direction. The bias in the direction perception for the oblique directions is up to 10°. Although this may be acceptable for many applications (for example, the 12 hours of the clock used in military environments to indicate directions (e.g., "bogey at 2 o'clock") have a 30° resolution), some applications may require a larger resolution. Those situations may ask for an individual calibration of the mapping of external directions on skin locations, that is, constructing a "torso related transfer function, or TRTF". The TRTF would map each direction to a unique location on the torso and vice versa. Although an individual TRTF will optimally reduce the difference between presented and determined direction, a general TRTF may be sufficient. This general TRTF will at least compensate for the bias toward the midsagittal plane.

Assuming that a TRTF results in a correct mean direction perception, variability is the only relevant performance measure. The results show that the variability is dependent on the stimulus location, but much better than the hypothesised value of 30° (H4). The variability is lower on and near the midsagittal plane (SD of 4° for the direction straight ahead) than on the sides of the torso (SD 10-14°). The variability is in the same order of the angular size of the tactors (with a mean abdomen circumference of about 90 cm, the 2 cm size of the tactors results in a mean angular size of 8°). As discussed in Chapter 2, the tactor size may have played a role in restricting performance, although -similar to the results of Chapter 2- best performance (i.e., lowest variability) is about a factor two better than the tactor size. Two factors may have contributed to the effect of stimulus location. First, the midsagittal plane (on the frontal and the dorsal side, 0° and 180°, respectively) may act as anchor point. Anchor points are characteristic body locations, such as Vierodt's mobility points (e.g. the shoulders, elbows and wrists; Vierodt 1870, Lederman and Taylor 1969, Lederman et al. 1987, cref. Chapter 3). The role of anchor points in vibrotactile localization performance on the arm and trunk was investigated by Cholewiak and colleagues (Cholewiak & Collins, 2000, 2003). On the trunk, they found that near optimal performance occurred at the navel and the spine which they defined as anchor points. The present data show that the further away from these anchor points, the less accurate the direction determination becomes, with lowest performance around 90° left and right. A second factor is related to spatial accuracy. A higher spatial resolution may result in less uncertainty in the determination of the stimulus location, and thus in less variance in the determined direction. Chapter 2 showed that the vibrotactile spatial resolution near the midsagittal plane (frontal as well as dorsal) is higher than more to the side of the torso. The results imply that optimal performance may be expected for tasks that require the perception of directions straight ahead or straight behind. This is for example the case in a situation in which a visually disabled individual wants to walk to the next waypoint in a preprogrammed route, or a fighter pilot flying towards a target. This also implies that tactile direction perception can be complementary to 3D sound, in the sense that 3D sound is optimal to present lateral directions but has a relatively high occurrence of front - back reversals.

Chapter 5. Crossmodal visual-tactile perception of time and space[23]

Abstract

Tactile displays are often introduced as alternative or additional display to reduce the incidences of visual overload. An important issue in introducing a multimodal visual-tactile interface is whether there is a difference between the quality of crossmodal and intramodal comparisons. In the prenav model, this process is part of the cognitive ladder. This chapter therefore tackles the following question: Which of the models presented in Section 1.7 can describe the crossmodal tactile-visual perception of time (Experiment 5) and space (Experiment 6)? The first experiment investigated the consistency between tactually and visually designated empty time intervals. In a forced-choice discrimination task, participants judged whether the second of two intervals was shorter or longer than the first interval. Two pulses defined the intervals. The pulse was either a vibrotactile burst presented to the fingertip or a foveally presented white square. The comparisons were made for unimodal and crossmodal intervals. We used four levels of standard interval durations in the range of 100 - 800 ms. The results showed that tactile empty intervals must be 8.5% shorter to be perceived as long as visual intervals. This crossmodal bias is larger for small intervals and decreases with increasing standard intervals. The Weber fractions are consistent over uni- and crossmodal comparisons, which indicates that there is no additional noise involved in the crossmodal comparisons of temporal intervals. The second experiment investigated spatial tracking performance with tactile and/or visual presentation of target and cursor. The tactile display consisted of vibrators in a horizontal linear array on the torso, the visual display consisted of dots projected on a horizontal plane surrounding the observer. Participants performed two different tracking tasks with target and cursor presented to the same modality (either visual or tactile) or to different modalities (a visual target and a tactile cursor or vice versa). The errors in both crossmodal settings were well predicted by the unimodal errors. This indicates that no additional costs are involved in crossmodal visual-vibrotactile tracking. The results of both experiments indicate that cross- and intramodal comparisons of space and time are based on the same representation. This would mean that there are no additional costs involved in combining the visual and tactile modality in a multimodal interface.

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[23] Parts of this Chapter have been published as:

Van Erp, J.B.F. & Werkhoven, P.J. (2004). Vibro-tactile and visual asynchronies: Sensitivity and consistency. *Perception*, *33*, 103 -111.

Van Erp, J.B.F. & Verschoor, M.H. (2004). Cross-Modal Visual and Vibro-Tactile Tracking. *Applied Ergonomics*, *35*, 105-112.

5.1 Introduction

Due to the increasing complexity of visual interfaces, system designers are increasingly looking towards the auditory and/or tactile channels to provide an alternative or supplementary means of information transfer (Spence & Driver, 1997; Van Erp, 2002a). Effective multimodal interfaces require that stimulation from several sensory channels be coordinated and made congruent informationally as well as spatially and temporally (Kolers & Brewster, 1985). In case the information is not presented redundantly to multiple modalities, but instead spread over the sensory modalities, the user must be able to compare information crossmodally (Van Erp et al. 2006). In one of the two models for crossmodal comparison, there is an additional processing step required to be able to make crossmodal comparisons compared to intramodal comparisons (see Section 1.7). If this additional step is indeed required, the potential costs (e.g., in terms of additional processing time, added workload, or additional noise in the comparisons) may reduce the expected improvements. These costs are especially relevant when two or more events are presented to different modalities and the task requires the user to make crossmodal comparisons. Therefore, we investigate the uni- and crossmodal visual-tactile perception of time and space, and focus on the question whether crossmodal comparisons can be predicted on the basis of unimodal comparisons. In Experiment 5, we do this for the perception of empty time intervals of durations between 100 and 800 ms, the range that is relevant for the current applications. In Experiment 6, we do this for pursuit and compensatory tracking, the two relevant local guidance tasks at the steering and control level, respectively (cref. Chapter 1, prenav model).

5.2 Experiment 5: Crossmodal visual-tactile perception of temporal intervals

5.2.1 Introduction

An interesting question is how empty interval length is internally represented. For empty intervals it is tempting to assume that internal interval length is measured as the time between a particular feature of the response function (e.g., its onset, point of maximum curvature, or peak) of the first pulse and that same feature of the second pulse (e.g., the onset of both pulses). In this case, the internal representation of interval length is independent of the shape of the response function or the particular feature used and therefore independent of the modality, as long as the first marker does not affect the timing of the second. Such internal representation should not yield biases between modalities. However, an alternative assumption (see also Grondin's internal marker hypothesis; Grondin, 1993) is that the internal representation is the time between one feature of the response function to the first pulse and another feature of the response function to the second pulse (e.g. the end of the first pulse and the onset of the second). In this case, internal interval length becomes dependent on the shape of the response functions and thus the modality of stimulation. First of all, response functions may be asymmetric in that the steepness of the response function at the onset of a pulse differs from its steepness at the offset. Second, the width of the response functions may differ for different modalities. This will result in a bias in crossmodal comparisons.
The relationship between the auditory, visual, and tactile channels regarding temporal duration has not been studied extensively. Only the perceived duration of visual and auditory time intervals have been compared. For filled temporal intervals in the order of one second, visual intervals had to be set longer than auditory intervals to be judged as equal in duration (Behar & Bevan, 1961; Goldstone & Goldfarb, 1963; Goldstone, Boardman & Lhamon, 1959; Goldstone & Lhamon, 1972; Wearden, Edwards, Fakhri & Percival, 1998). The same crossmodal bias is present for empty intervals. The intervals bounded by light flashes appear shorter than those bounded by brief auditory stimuli (Goldstone & Lhamon, 1971; Sebel & Wilconsoncroft, 1983; Walker & Scott, 1981). Modality differences have also been reported for

other time related measures and tasks, for example in duration discrimination (Lhamon & Goldstone, 1974), temporal order judgement (Kanabus, Szelag, Rojek & Poppel, 2002), stimulus sequence identification (Garner & Gottwald, 1968; Handel & Buffardi, 1969), in the perception of temporal rhythms (Gault & Goodfellow, 1938), and in a temporal tracking and continuation tapping task (Kolers & Brewster, 1985). We know of only two studies that have addressed auditory-tactile interval duration comparisons. Both Ehrensing and Lhamon (1966) and Hawkes, Deardorff, and Ray (1977) found perceived tactile durations to equal auditory ones. To our knowledge, no data are available for tactile-visual comparisons.

As manual interactions with the environment are often controlled using visual feedback it may be expected that the perception of time intervals for the eye and for the finger tips has evolved to be consistent. Evidence for this comes from the development of visual-haptic interactions in children (Birch & Lefford 1963, 1967; see also Freides, 1974). However, based on the biassed auditory-visual relation and the unbiassed auditory-tactile relation, we expected a bias in tactile-visual comparisons: visual intervals will be set longer than tactile intervals to be judged as equal in duration.

Crossmodal temporal sensitivity

Unimodal threshold studies have shown that the temporal resolution of the skin lies between those of hearing and vision (Kirman, 1973). This relation goes for numerous time related measures and tasks, including discrimination of duration (Goodfellow, 1934); synchronization of finger taps (Kolers & Brewster, 1985), and adjusting empty intervals to equal pulse duration (Craig, 1973). However, in their classical temporal order study, Hirsh and Sherrick (1961) found that the thresholds (75% correct) for the visual, auditory, and tactile modality were the same and in the order of 20 ms. Although the temporal resolution of the skin has been investigated in several ways (e.g., with the fusion threshold (Geldard & Sherrick, 1971; Gescheider, 1966, 1967, 1974) and the gap detection performance (Van Doren, Gescheider & Verillo, 1990; Formby, Morgan, Forrest & Raney, 1992)), tactile interval discrimination has not yet been systematically studied as a function of interval length (cref. Appendix I). Only Goodfellow (Goodfellow, 1934; see also p. 219 in Fraisse, 1978) reported a difference threshold for interval duration of 9.5% (averaged across various methods used) for a standard interval of 1 s.

5.2.2 Method

Experiment 5 in a nutshell.

- Eight observers performed an interval discrimination task, in which they responded wether the second of two intervals was shorter or longer than the first. The two open intervals had different lengths. An interval was marked with either two visual flashes or two tactile bursts. The two intervals could be of the same modality or of two different modalities.
- The independent variables were the combination of interval modality and the interval length.
- The dependent variables were the bias and the sensitivity.

Participants

Eight male, right-handed volunteers between 21 and 25 years old participated. They all reported normal vision and a normal sense of touch. They were paid € 40 for their participation.

Stimulus and apparatus

An empty interval is defined as the time between the onsets of two pulses of equal duration (33.3 ms). A visual pulse was a white square (subtending 5.1 × 5.1° of visual angle) drawn on a monitor (Iiyama CRT with short persistence phosphor P22) against a dark background (see Wearden et al. (1998) for comparable stimuli). The tactile pulse was presented by a Special Instruments Minivib 4 vibrator with a contact area of 22 × 16 mm attached to the skin with sticky tape and driven by a 250 Hz sine wave signal (see Appendix II). The intensities of the tactile and visual stimuli were subjectively matched by a simple procedure (method of adjustment). Three observers adjusted the brightness of the visual stimulus (5 ascending and 5 descending trials per observer) so that the intensities were judged to be equal to the tactile stimulus. Since intensity of the markers does not affect crossmodal interval discrimination (Grondin, Irvy, Franz, Perrault, & Metthe, 1996), the intensity of the visual stimulus was fixed at the mean value for these three observers.
The Visual interval (V) was always presented foveally to both eyes. The Tactile interval (T) was presented to the tip of the left index finger. The participants wore headsets with white noise that attenuated the sound of the vibrator to a sub-threshold level during all conditions. On each trial two intervals were presented: a standard interval (S) and a comparison interval (C). Standard and comparison intervals were presented in random order. The pause between the presentation of the two intervals was 2 s. Participants were asked to indicate whether the second interval was shorter or longer than the first interval by pushing the left or right mouse button. No feedback was given. The standard interval was 100, 200, 400, or 800 ms. The range of comparison intervals was chosen on the basis of pilot data, so that the percentage of trials to which the comparison interval was judged 'longer' than the standard ranged from 0 to 100%. For each standard (except for the 100 ms standard), we choose to measure five longer comparison intervals and five shorter intervals. Using equal step sizes between the comparisons and taking into account the 60 Hz refresh rate of the monitor, this resulted in step sizes of 16.7, 16.7, 33.3, and 67.7 ms for the 100, 200, 400, and 800 ms standard intervals, respectively. The values of standard and comparison intervals are given in Table 5.1.

Table 5.1. Range and stepsize of the comparison intervals as function of the standard interval length in Experiment 5.

Standard interval length (ms)	range of the comparison intervals (ms)	stepsize (ms)
100	50.0 - 150.0	16,7
200	116.7 - 283.3	16,7
400	233.3 - 566.7	33,3
800	466.7 - 1133.3	667

Marker-type conditions

We tested temporal interval discrimination for four marker-type conditions: Unimodal: T-T and V-V, as well as crossmodal discrimination: T-V (a standard tactile interval with a varying visual interval) and V-T (a standard visual interval with a varying tactile interval). Please note that a single interval is always defined by markers of the same modality.

Data fitting

A method of constant stimuli was used testing 30 repetitions for each S - C interval combination. We fitted a cumulative normal function to the fractions of 'longer' responses for range of comparison intervals, by MATHEMATICA® 3.0. The fit resulted in the point of subjective equality (PSE), and the threshold, defined as the increment of the comparison value relative to PSE for which the percentage of trials to which the comparison interval is judged 'longer' than the standard is 75%. The difference between the PSE and the standard interval is called bias.

Design and statistical analyses

The experiment consisted of four sessions. Each session tested a single standard interval length. The four marker-type conditions were blocked within the session. The order of the sessions and the order of the marker-types within a session were semi-balanced across participants. For each comparison interval, 30 repetitions were recorded. Before analysis the bias and threshold were standardized by dividing them by the standard interval. For the threshold, this results in the Weber fraction (Fechner, 1860; Luce & Galanter, 1963). The results were analysed using a repeated measures analysis of variance (ANOVA): Marker-type condition (4) × Standard interval (4). Significant effects were further analysed by a post-hoc Tukey HSD test with alpha set at .05.

Procedure

The participants were seated 90 cm in front of a monitor in a dimly lit room with their right-hand on a mouse. They wore a sound-attenuating headset with white noise during all sessions to prevent hearing the faint humming sound of the vibrator. At each trial, participants were asked to compare the length of two empty intervals and indicate whether the second interval was 'shorter' or 'longer' (forced choice) by pressing the left or right mouse-button, respectively. The participant started every next trial by pressing the middle mouse-button. There were four sessions, each one testing a specific standard interval. There were pauses in between sessions. Each participant completed the experiment on a single day.

5.2.3 Results

Standardized bias

The ANOVA on the standardized bias resulted in three significant effects: Marker-type condition, $F(3, 21) = 14.59$, $p < .001$, Standard interval, $F(3, 21) = 3.17$, $p < .05$, and the interaction between Marker-type condition and Standard interval, $F(9, 63) = 4.82$, $p < .001$.

The interaction of Marker-type condition and Standard interval is depicted in Figure 5.1 (aggregated over participants). A positive bias is the result of observers judging the second marker-type condition as longer than the first. The post-hoc test on the interaction can best be summarized as follows. The standardized bias in the crossmodal conditions with the smaller standard intervals (100 and 200 ms, i.e. four means in total) is significantly higher than and the other conditions (12 means).

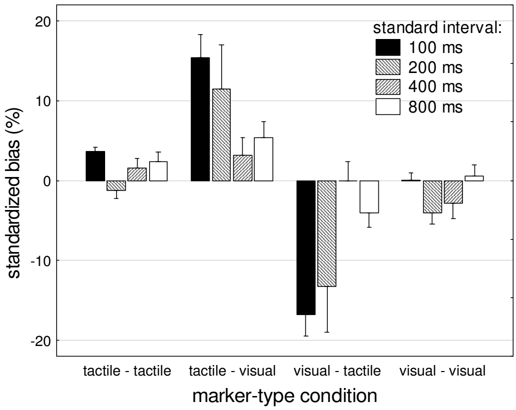

Figure 5.1. The interaction between Marker-type condition and Standard interval length on the standardized bias. Marker-type conditions indicate the modalities of the standard interval and the comparison interval, respectively. Positive values indicate that the comparison interval is set longer than the standard interval. Bars indicate the Standard Error.

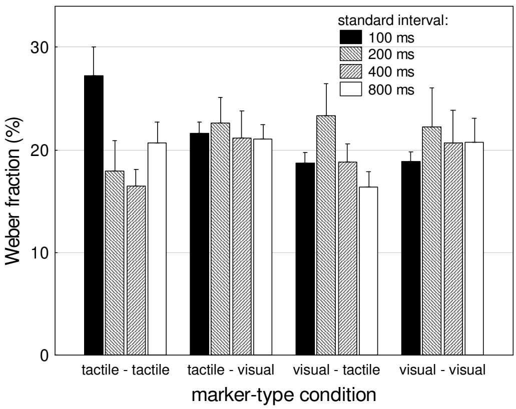

Figure 5.2. The interaction between Marker-type condition and Standard interval length on the Weber fraction. Marker-type conditions indicate the modalities of the standard interval and the comparison interval, respectively. Bars indicate the Standard Error.

Weber-fractions

The ANOVA on the Weber fraction resulted in one significant effect: the interaction between Marker-type condition and Standard interval, $F(9, 63) = 4.61$, $p < .001$. This interaction is depicted in Figure 5.2. The post-hoc analysis of this effect showed no specific pattern of significant differences.

5.2.4 Discussion

Bias

In principle, no bias is expected when the two intervals to be compared are of the same type, that is, presented in the same modality (T-T and V-V). The two intervals to be compared differ only in their interval length, not in any other stimulus dimension. Further, because the order of presentation was randomised, any preference for judging the second interval as shorter or longer will have an effect on the threshold, but not on the bias. However, the data show a small bias for these same marker type discriminations. In order to perceive the comparison interval as equally long as the standard interval, the comparison interval has to be 2.3 % longer on average (independent of interval length). This is probably due to the fact that the stimulus dimension 'interval length' is not symmetric, but stretches from 0 to infinity. In contrast, the cumulative normal distribution that is fitted along this stimulus dimension stretches from -infinity to +infinity. When a symmetric curve is fitted to such asymmetric data, the PSEs will be systematically raised relative to the standard value (a positive bias) as observed in this experiment. We also fitted the data after a log transform of the time parameter. Although this resulted in a smaller bias, the improvement was not statistically significant.
Of course, the same effect may bias the PSEs in positive direction for marker-type conditions where intervals of different type (presented in different modalities) have to be discriminated. Applying the 2.3% correction to the T-V and V-T data results in a bias of 8.8 and 8.5%, respectively. This suggests that the length of a visual interval is systematically underestimated compared to a tactile interval, and/or that the length of a tactile interval is systematically overestimated compared to a visual interval. This confirms our hypothesis, based on the biassed auditory-visual relation and the unbiased auditory-tactile relation. The interaction of Marker-type condition and Standard interval length shows that this bias is only present for short intervals. We will discuss two hypotheses for this bias.

Internal marker hypothesis

Grondin's internal marker hypothesis (Grondin, 1993) is that the internal representation is the time between one feature of the response function to the first pulse and another feature of the response function to the second pulse. Consequently, a comparison between tactile and visual intervals may yield biases caused by the differences in response functions. For example, tactile response functions in the fingertip may ascend more steeply, and/or descend faster in comparison with visual response functions. In that case, the time between the internal representations of the offset of the first pulse and the onset of the second is longer for a tactile interval than for a visual interval. Consequently, tactile intervals will be overestimated in length compared to visual intervals. This hypothesis predicts that a crossmodal bias is dependent on the response functions only and independent of the interval length. To test this, we performed an ANOVA on the raw (not standardized) bias. This analysis showed a highly significant effect of Standard interval: $F(3, 21) = 11686.94$, $p < .001$. The means were 6.2, 12.1, 24.7, and 49.6 ms for a Standard interval of 100, 200, 400, and 800 ms, respectively. This result argues against the internal marker hypothesis that predicts a constant bias that is independent of the length of the interval.

Directed attention hypothesis

A second explanation for the crossmodal bias is based on the effect of directed attention on time related tasks. For instance, Stelmach and Herdman (1991), Carver and Brown (1997), and Spence, Shore and Klein (2001) showed the effect of directed attention on the perception of temporal order and simultaneity. The attended stimulus appears to occur before the unattended stimulus when both are presented simultaneously. Data indicate that directed attention also has an effect on the perceived duration of a brief stimulus (i.e., filled intervals). Mattes and Ulrich (1998) found that stimuli (stimulus durations between 70 and 270 ms) in the attended modality (either visual or auditory) were rated as longer than stimuli in the unattended modality. This effect of attention on brief stimuli was confirmed by Chen and O'Neill (2001). If, in a crossmodal condition, there is an asymmetry in the capture of attention or in the shifting of attention between the modalities, biases in perceived duration may occur. The interval presented in the modality that captures or holds attention will be judged as longer. Spence and McGlone (2001) showed that tactile spatial attention can be reflexively directed towards peripheral tactile stimuli. Comparisons between the costs involved (in terms of required time) when switching attention between modalities (auditory, visual and tactile) were made by Spence and Driver (1997). They indeed found consistently higher costs of shifting from the tactile to the visual modality than vice versa. These asymmetrical effects between the visual and tactile channel combined with the effect of attention on duration perception (especially for brief stimuli) may explain the crossmodal bias and the effect of an increased bias for smaller interval lengths. Both effects must be investigated further, for example by using a directed attention paradigm. However, these investigations on bias are outside the scope of this thesis in which crossmodal sensitivity is an important issue.

Sensitivities

The sensitivities (i.e., the 75% correct threshold of interval discrimination) are easiest discussed in terms of Weber-fractions since the results show that these are invariant with standard intervals. A Weber-law (the sensitivity is a constant fraction of the interval length) seems to hold for the range of standard intervals tested (100 - 800 ms). Our Weber fractions (20%) seem to be in-between the results reported by Grondin (1993, p. 386 on 250-ms empty visual interval discrimination) (t_{75} =23%) and those of Grondin (1998) and McKee and Taylor (1984) who reported Weber fractions around 10% for the visual modality.

Consistency of crossmodal sensitivities

Participants estimated only two types of intervals: visual presentation in the fovea and tactile on the fingertip. The Weber fraction is 20.6% in the unimodal marker-type conditions, and 20.5% in the crossmodal marker-type conditions. This confirms the predictions of a crossmodal comparison model in which the same (common) representation is used for both the unimodal and crossmodal comparisons.

5.2.5 Conclusions

The present experiment on tactile and visual discrimination of empty temporal intervals can be summarized as follows. The length of tactile intervals is systematically overestimated compared to visually presented intervals, and/or the length of visual intervals is underestimated compared to tactile intervals. This bias decreases for larger interval lengths. Within the range 100 - 800 ms, Weber-fractions for empty interval discrimination (tactile, visual, and crossmodal) are in the order of 20%. The Weber-fractions are constant over the interval range tested (i.e., the Weber law holds), and the Weber fractions are consistent over the uni- and crossmodal marker-type conditions. Despite the bias in tactile - visual interval length perception, there is no additional noise introduced in crossmodal comparisons compared to unimodal comparisons. This fits with a crossmodal model based on a common representation for both unimodal and crossmodal comparisons but not with a model based on two different representations for unimodal and crossmodal comparisons.

5.3 Experiment 6: Crossmodal visual-tactile perception of space

5.3.1 Introduction

Because of the goal of this thesis to study local guidance tactile displays (in a multimodal setting), using a crossmodal tracking task is a good option to study the crossmodal perception of spatial information (such as directions). For instance, the direction of an incoming threat in a fighter aircraft may be presented on a tactile torso display, while the visor of the aircraft's weapon system may simultaneously be presented visually. As described in Chapter 1, tracking tasks are important at the local guidance level. At the control level, the majority of the tasks (e.g., compensating for side wind, maintaining our balance) are compensatory tracking tasks. At the steering level, the majority of the tasks (e.g., maintaining a constant distance to a lead vehicle, intercepting enemy aircraft) are pursuit tracking tasks. The application of crossmodal visual and tactile tracking displays has never been investigated (contrary to visual and auditory tracking, e.g., Tsang & Vidulich, 1987). Therefore, we investigated performance in two tracking tasks in crossmodal visual-vibrotactile conditions, and compared performance with intra-modal conditions. To ensure that the visual display and the tactile torso display presented qualitatively equivalent information, we used a set-up in which both modalities indicated a direction in a horizontal plane around the observer's torso, similar to the setup in Chapter 4. The tactile display consisted of vibrators attached to the torso, while the visual display consisted of dots projected onto a table surrounding the observer.

5.3.2 Method

Experiment 6 in a nutshell.

- 12 participants performed several tracking tasks in which the error between a target and a cursor had to be minimised. The cursor and target were displayed either on a visual display (dots presented on a table surrounding the participant) or on a tactile display (a belt with tactors around the torso).
- The independent variables were the modality of the cursor and target (visual and/or tactile) and the tracking task (compensatory or pursuit).
- The dependent variable was the RMS tracking error.

Participants

Twelve right–handed male students (between 20 and 27 years old, median 22.9 years) participated voluntarily. They received €40 for their co–operation. All had normal or corrected to normal vision. They had no previous experience with tactile displays.

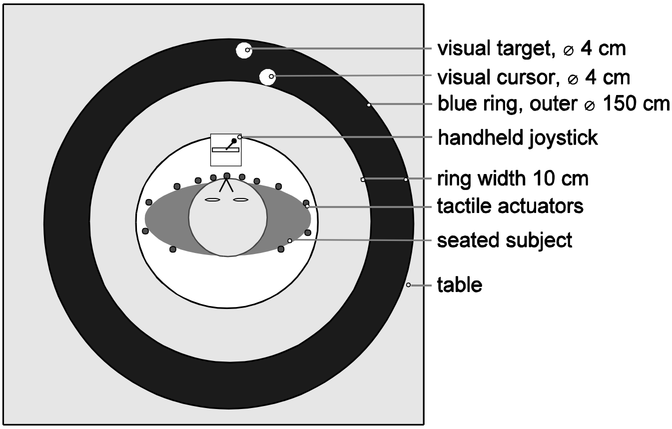

Figure 5.3. Schematic top view of the experimental set-up in Experiment 5 (not to scale).

Apparatus

Figure 5.3 shows a schematic top view of the setup. The participant was seated on a stool and surrounded by a square table with an open circle in the middle. Two displays were used, one visual and one tactile. The visual display was generated with an update rate of 30 Hz by a PC which was linked to an LCD projector (320 × 200 pixels). The projector was mounted on the ceiling above the participant and projected onto the table. The projected image consisted of a small blue ring with a width of 10 cm. The visual target and cursor (white dots with a diameter of 4 cm) moved along the outer and inner edge of the ring, respectively. The outer diameter of the projected ring was 150 cm, with the participant positioned in the centre. The resolution of the visual display was 1 pixel, which was roughly equivalent to 0.40°. The vibrotactile display consisted of 26 Special Instruments Minivib 4 vibrators (see Appendix II). These 250 Hz vibrators, with a contactor area of 22 by 16 mm, were attached to the skin with double sided sticky tape. The vibration had a 100% duty cycle. The participant was wearing noise reducing headphones in order to exclude localization of the vibrators on the basis of their faint humming sound. The vibrators were attached to the participant's trunk in two partial circles in the transversal plane (called upper and lower belt), ranging from 120° left to 120° right of the ventral midline, defined as -120° to +120°. It was verified that the visual and tactile display were calibrated by projecting radiants of the ring of the visual display at 20° intervals during the attachment of the tactors (see Figure 5.4). Note that, because the human trunk is usually oval, this procedure leads to variable inter–vibrator distances, with smaller distances near the midsagittal plane. The vibrators were placed such that the lower belt was in the plane of the table's surface, approximately 5 cm above the participant's umbilicus. The upper belt was located between the navel and the nipples, 8 cm above the lower belt.
The skin tends to integrate spatiotemporal vibrotactile patterns into a coherent percept. For example, sequentially activated vibrators at adjacent locations are not felt as static stimuli but are integrated into a percept of smooth motion, also known as apparent motion (For details on tactile apparent motion and the dependency on spatiotemporal parameters see for example Kirman, 1974a; Lakatos & Shepard, 1997; Sherrick, 1968a, b; cref. Appendix I). This means that the sensation of movement (or a dynamic stimulus) can be created by static stimulation. Each vibration was emitted either by a single vibrator, or by two adjacent vibrators activated simultaneously, eliciting the sensation of 'apparent location' (for details on

tactile apparent location, see for example Cholewiak, 1988; cref. Appendix I). By using this phenomenon, the static resolution of the tactile display was doubled to 10°.
Participants controlled the cursor (i.e., the vibrotactile pulse in the upper belt or the visual dot on the inner side of the circle), whereas the pulse in the lower belt or the dot on the outer side served as target. The range of the cursor was from -120° to 120°. The range of the target was from -90° to 90°. Because the display ranged from -120° to 120°, this allowed for a cursor overshoot of 30°. The participants used a handheld one-dimensional joystick to control the cursor. The joystick controlled the cursor's angular velocity, yielding a first order control system and allowed following the target stimulus with perfect fidelity. A rightward position of the joystick resulted in a clockwise motion of the cursor. A PC controlled the experiment and registered the target and cursor data.

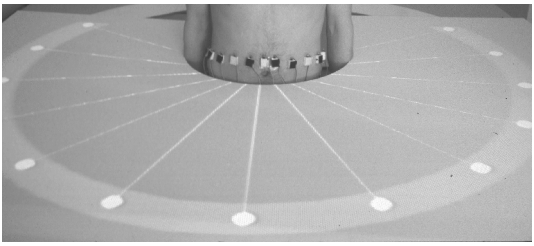

Figure 5.4. The method to attach the elements at 20° angles and calibrate the tactile and visual display. The rays were projected from above and only used during the attachment of the tactors.

Tasks, stimuli and design

Each participant performed two tracking tasks: a pursuit tracking task and a compensatory tracking task (see Van Erp & Oving, 2002). In both tasks, the instruction was to minimize the angular error between the direction indicated by the cursor and the direction indicated by the target. The main difference between the two tasks was that the external error acted on the direction of the target in the pursuit tracking task and on the direction of the cursor in the compensatory tracking task. Thus, in the pursuit tracking task target motion was the result of the disturbance trace and cursor motion of control input. In the compensatory tracking task, the target was stationary and the motion of the cursor was the result of control input and external error displacement. These two tracking tasks can be considered as instances of steering and control tasks, respectively, e.g.: tracking a moving element (e.g., a hostile aircraft) in an environment, and keeping an object in a fixed position despite external disturbances (e.g., hovering a helicopter with side wind). Each participant had three target directions in the compensatory tracking task. Six participants had the centre (0°), left ahead (- 40°) and on the right (+ 80°), the other six had the centre (0°), right ahead (+ 40°) and on the left (- 80°). Eight 150 s disturbance traces were constructed, with more than 90% of the power below 0.5 Hz. The end and beginning of each trace connected smoothly, making it possible to use different starting points in the trace. Participants were allowed to intercept the signal in the first 10 s of each trial, followed by 150 s of effective tracking. Since the duration of the total disturbance trace was only 150 s, the first 10 s of the trace was repeated at the end of the effective trial.
In the unimodal conditions, the target and cursor were both visual (VV) or both tactile (TT). In the crossmodal condition the target was visual and the cursor tactile (VT) or vice versa (TV). Participants performed both tracking tasks in all four uni- and crossmodal conditions, leading to a total of eight conditions. Each participant completed three traces in each condition, resulting in a total of 24 trials. The traces were randomly chosen from the set of eight available traces, and had a random starting point. The order of the conditions was balanced across participants, using a digram–balanced Latin square

(Wagenaar, 1969). The RMS (root mean square) angular tracking error (°) was calculated as performance measure.

Procedure

Prior to the start of the experiment, participants were asked to read and sign an informed consent, which stated that they could end the experiment at any time without consequences. Participants were seated statically in a dimly lit room. They were allowed to rotate their head, but were instructed not to move their body. Body position during the experiment was monitored by the experimenter through two surveillance cameras. After attachment of the vibrators, one training trial for each of the eight conditions was given. These training trials were presented in random order. Participants received no explicit feedback on their performance on either the training or the experimental trials.
The 24 trials for each participant were presented in eight blocks of three trials each. The condition changed after each block. Between two blocks, participants were allowed a one minute pause. There was a 15 minute break after four blocks. A complete session lasted approximately two hours.

5.3.3 Results

The RMS tracking error was analysed using a repeated measures analysis of variance (ANOVA) with the following independent variables: Task (pursuit/compensatory) × Target (visual/tactile) × Cursor (visual/tactile) × Repetition (3). When appropriate, significant effects were further analysed by a post hoc Tukey test with alpha set at .05. The 4–way ANOVA revealed highly significant main effects of Task $F(1, 11) = 93.23$, $p < .001$, indicating a larger tracking error in the pursuit tracking task than in the compensatory tracking task; Target $F(1, 11) = 394.30$, $p < .001$, indicating a larger error with a tactile target than with a visual target; and Cursor $F(1, 11) = 111.26$, $p < .001$, indicating a larger error with a tactile cursor than with a visual cursor. There were no effects of Repetition. All means and standard errors are depicted in Figure 5.5. Apart from the main effects, two interactions were present. The interaction between Task and Target, $F(1, 11) = 179.76$, $p < .001$, showed that the main effect of Task (higher errors in the pursuit tracking task, present when the open bar is larger than the filled bar) is present for tactile targets only, but is absent for visual targets. The interaction between Target and Cursor, $F(1, 11) = 10.19$, $p < .01$ showed that performance is best in the visual–visual conditions, followed by the crossmodal conditions and finally the tactile–tactile conditions.

5.3.4 Discussion

The interaction between target modality and task shows the following two effects. Firstly, performance degradation is predominantly present for tracking dynamic tactile targets in the pursuit tracking task. This is visible in Figure 5.5 as the open bars marked [1] and [2] with a mean tracking error of 29° and 42°, respectively. Secondly, there is a low tracking error for the compensatory tracking task with a tactile target and a visual cursor, marked [3] (i.e., apart from the superior performance in the unimodal visual condition). In this condition, the tactile target is static. These effects indicate that tracking errors increase when there is an external disturbance signal present in the tactile signal. In the present experiment, this is the case for tactile targets in the pursuit tracking task and the tactile cursors in the compensatory tracking task. These cases are marked with an arrow in Figure 5.5.

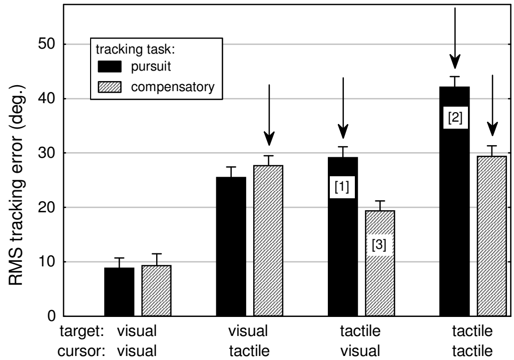

Figure 5.5. Mean tracking error as function of tracking task and target and cursor modality. In the pursuit tracking task the disturbance affects the target, whereas in the compensatory tracking task disturbance affects the cursor. The bars marked with arrows indicate situations in which the disturbance affects the tactile signal. The numbers are explained in the text.

Crossmodal tracking requires the integration of the spatial information from the visual and the tactile sensory channels. Although there is clear evidence for crossmodal links in visual-tactile information processing, it is not clear whether extra costs are involved in crossmodal comparisons compared to intra-modal comparisons. Regarding spatial tasks, the evidence is divided. For example, Fishbein et al.(1977) found no differences between crossmodal and intra-modal comparisons in a task that required the perception of object locations. Lecheld and Verenka (1980) found only small errors in crossmodal conditions in stimulus orientation judgments, while the intra-modal differences were large. Ernst and colleagues (Ernst, 2001; Ernst et al., 1998) found crossmodal size perception thresholds to be higher than unimodal errors for specific experimental procedures only.

Crossmodal Effects

To investigate the possible additional costs involved in crossmodal visual-vibrotactile tracking, we employed a model based on the unimodal results, that is a statistical equation that describes the result of combining two distributions. The model predicts the value in a crossmodal condition on the basis of the standard deviation of the performance measures for the two corresponding normally distributed unimodal conditions. The following formula describes the predicted crossmodal RMS error with no additional noise (formula 1).

$$RMS_{VT\ pred.} = RMS_{TV\ pred.} = \sqrt{RMS_V^{\ 2} + RMS_T^{\ 2}} = \sqrt{\left(\frac{RMS_{VV}}{\sqrt{2}}\right)^2 + \left(\frac{RMS_{TT}}{\sqrt{2}}\right)^2} \quad \{1\}$$

For the obtained data, the thus predicted crossmodal RMS error is 26.0° while the mean observed RMS error is 25.4°. It appears that this additive model indeed fits the data which indicates that there are no additional costs involved in crossmodal visual and tactile tracking. This confirms the predictions of a crossmodal comparison model in which the same (common) representation is used for both the unimodal and crossmodal comparisons. This indicates that tactile and visual displays can coexist in a multimodal setting.

Unimodal effects

The present results support earlier unimodal comparisons between visual and tactile tracking displays. These comparisons have revealed several differences between both modalities, including differences in absolute performance (Hahn, 1965; Triggs et al., 1974) and in the transfer functions (Seeley & Bliss, 1966; Bliss et al., 1967). Two things should be noted though. Firstly, the participants received no training, while eye-hand coordination is a process that is trained for years (also eye-joystick coordination). One might expect performance to improve when skin-hand coordination is trained. This does not contradict the intuitiveness of the display: the response is evoked sheer automatically, but the skin-hand coordination can probably be further fine-tuned. This aspect is not within the scope of this thesis. Secondly, the display resolution of the visual display is larger than that of the tactile display. The tracking error with the visual display will increase when its resolution is reduced (see Van Erp & Verschoor, 2004).

5.3.7 Conclusions of Experiment 6

Regarding crossmodal effects, the good fit of an additive model to the data indicates that there are no costs involved with respect to tracking performance when target and cursor are presented to different modalities (although best performance is found with the unimodal visual display). This indicates that the visual and tactile channel can be combined in a multimodal tracking display when both modalities contain qualitatively equal information. Regarding the unimodal conditions, tracking performance with a tactile display is worse than with a qualitatively equal visual display in the present set-up. Part of the difference is caused by the quantitative difference between the displays: The visual display resolution in the present experiment is larger than that of the tactile display. However, when the visual data are corrected for this, performance with the visual display is still superior (data not presented here, see the control experiment in Van Erp & Verschoor, 2004). Therefore, the transfer function of the tactile channel must be further investigated. Inspecting the data more closely, we find that performance is degraded when external disturbances are presented to the tactile modality. However, the data also indicate that the tactile modality is better suited to present information that does not contain external disturbances, that is, the cursor in the pursuit tracking task and the target in the compensatory tracking task.

5.4 General discussion and conclusion

This Chapter reports two experiments that investigated the crossmodal perception of time and space. These aspects are important in applying tactile displays in a multimodal setup, and knowledge about possible biases and effects on crossmodal comparisons are prerequisites for the optimal integration of display modalities in man-machine interaction. Like the direction perception experiment in Chapter 4 showed that for spatial data, vision and touch are not always 'calibrated', the temporal interval judgment task of Experiment 5 showed the same effect for temporal data. For smaller intervals, two physically equal tactile and visual intervals are not judged to have the same duration. Besides this bias (which display applications could easily adjust for when known), we were mainly interested in the quality of cross-modal comparisons, or whether there are additional costs involved in crossmodal comparisons compared to unimodal comparisons. In Section 1.7, two models for crossmodal comparisons were introduced (see Figure 5.6). We hypothesised (H6) that the crossmodal comparison of time (or actually empty intervals) and of space (or actually direction) would follow the model in which there is one common representation of the visual and tactile information that is used for the unimodal and for the crossmodal comparisons. This hypothesis is confirmed by the data of both experiments.

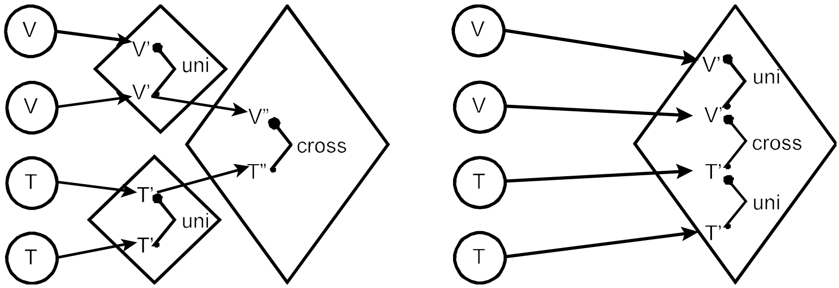

Figure 5.6. Two models for unimodal and crossmodal comparisons of visual (V) and tactile (T) information. The model on the right fits the crossmodal visual-tactile comparison of place and time.

Chapter 6. Navigation in 2D[24]

Abstract

This Chapter is the first in a series of four that investigate tactile displays in local guidance tasks. This Chapter presents three experiments on waypoint navigation in 2D. Experiment 7 investigates different ways of coding the distance to the waypoint. Apart from the direction, coded by the location of vibration, users may benefit from information about the distance to the waypoint, for example to facilitate identification of the waypoint or to enable anticipation for actions to be taken upon arrival at the waypoint. However, the results of Experiment 7 show that this parameter is of minor importance. In Experiment 8 we investigate navigation in a driving simulator. The messages are either presented on a visual display, a tactile display, or simultaneous on both. We measured performance and subjective mental effort for two experimental groups: a normal workload group and a high workload group. The results show that the bimodal presentation of navigation cues resulted in faster reactions to the navigation messages and lower mental effort ratings. With the tactile display, there is no performance difference between the workload groups, while with a visual display only, the high workload group shows decreased performance. These results confirm three important hypotheses we formulated in Chapter 1. In Experiment 9, we take a tactile local guidance display out of the laboratory to test it onboard two platforms: a helicopter and a fast boat. Especially relevant is to investigate whether the concept is still effective and intuitive when applied in high performance platforms and under conditions of whole body vibration. In two case studies, we show that the tactile navigation display is successful in these operational environments, supporting the conclusion of Experiment 8 that the display can be used for vehicle waypoint navigation and is not necessarily affected by external stressors and whole body vibration. Because the boat driver and helicopter pilot received no training with the display we can conclude that the display is easy to learn and can be used without extensive practice. The operators' reactions were direct and adequate. The performance of the helicopter pilot showed a fast learning effect, that of the boat driver showed no room for improvement, confirming the intuitive character of the display.

[24] Parts of this Chapter have been published as:
Van Erp, J.B.F. & Van Veen, H.A.H.C. (2004). Vibrotactile in-vehicle navigation system. *Transportation Research part F: Human Factors*, *7*, 247-256.
Van Erp, J.B.F., Van Veen, H.A.H.C., Jansen, C. & Dobbins, T. (2005). Waypoint Navigation with a Vibrotactile Waist Belt. *Transactions on Applied Perception*, *2 (2)*, 106-117.

6.1 Introduction

Based on the results of the experiments described in Chapters 2-5, we can conclude that the prerequisites for the concept of tactile local guidance displays have been fulfilled. The spatial resolution of the torso's skin is at least sufficient to be able to distinguish the 12 hours of the clock, an important standard in platform navigation. Also, observers are able to externalise a vibration on the skin to a direction in the outside world, and do this with adequate precision. The Standard Deviation of repeated determinations is 16° or better, again within the 12 hours of the clock standard[25]. Finally, the previous chapter has shown that tactile torso displays can be used in combination with visual displays in a multimodal setting, and that tactile torso displays can be employed in pursuit and compensatory tracking tasks. This chapter is the first in a series of four in which the concept is tested in operational tasks. In two experiments, we test waypoint navigation in 2D with the classical steering and control tasks: driving (Experiment 8), sailing, and flying (Experiment 9). Besides demonstrating the proof-of-concept, we explore the two questions at the cognitive level (see Section 1.7): Q7: Can local guidance tactile displays lower cognitive effort ratings compared to a visual display? And Q8: Is performance with a local guidance tactile displays independent of cognitive workload or external stressors?

Distance information in waypoint navigation

In waypoint navigation, two parameters are important: direction of the next waypoint and the distance to this waypoint (e.g., Burnett & Porter, 2002). Although direction information alone would be sufficient to go from one waypoint to the next, in specific situations distance information may be beneficial and improve performance. Distance information can for instance aid in identifying the waypoint before reaching it, and help to prepare for actions to be taken just before or after reaching the waypoint (as in car driving). To investigate this matter we did a pilot study (Experiment 7) with pedestrians to investigate four schemes to code for distance.

Since a vibrotactile display has to be in contact with the skin to be perceived, distance is not a parameter that can be manipulated directly. Also, the preferred display parameter to code distance is not a priori clear. Therefore, a 'possibly arbitrary' parameter has to be chosen (for example intensity) and a scheme describing how this parameter should reflect distance has to be devised (e.g., the intensity increases when distance decreases). On the basis of psychophysical data, we chose to use on-off rhythm (see Appendix I and Van Erp (2002a) for a discussion on secondary parameters). This choice is also supported by examples of best practices. Chiasson et al. (2002) used three different rhythms to enlarge the 90° display resolution to indicate 30° segments, Dobbins and Samways (2002a) used rhythm to code the seriousness of passing the imaginary lines of a virtual corridor in speedboat driving, McGrath et al. (2004) used rhythm to indicate the amount of drift or the airspeed in their helicopter hover displays, and Bosman et al. (2003) found that length of pulse trains is a better coding than intensities as a distance to waypoint coding.

[25] Please note that the tactile belt display in the field experiments described in this chapter (Experiments 7 and 9) only consists of 8 tactors due to hardware limitations.

6.2 Experiment 7: Pilot study on distance coding schemes

6.2.1 Introduction

To test the importance of distance coding in waypoint navigation, and the preferred coding scheme, we did a study with pedestrians. The participants walked predefined routes along several waypoints with the aid of a tactile torso display. Direction to the waypoint was coded by the location of vibration (8 locations), distance was coded by on-off rhythm. Each participant walked five routes, each with a different distance coding scheme.

Figure 6.1. The tactile navigation system during a test in Fort Benning, Georgia, with dismounted soldiers. The same system was used in the distance coding schemes experiment.

6.2.2 Method

> Experiment 7 in a nutshell.
>
> - 12 participants walked several routes on an open terrain (each consisting of six waypoints), while waypoint information was presented on a belt with 8 tactors around the torso. The location of the vibration indicated the direction of the next waypoint. The rhythm of the vibration displayed information on the remaining distance.
> - The independent variable was the scheme to code for the remaining distance.
> - The dependent variable was the effective walking speed calculated as the distance between two waypoints divided by the walking time.

Participants

Twelve participants were tested: 6 females and 6 males, ranging in age between 18 and 24. All were in good condition. They were paid for their participation and had signed an informed-consent agreement after extensive written and verbal instructions of the procedures.

Apparatus

The experiment was run with a wearable stand-alone system consisting of a minicomputer (486 DX Tiqit matchbox PC), a digital compass (Honeywell HMR2300), batteries, a GPS receiver (Garmin GPS 35-HVS), and the tactile display (see Figure 6.1). The system, except for the display and the sensor pack, was placed inside a backpack. Information about current position and compass angle were sampled with 1 Hz. The system calculated the direction of and the distance to the next waypoint, and translated the data into a tactile picture. This picture was displayed using eight tactors, placed at adjustable distances on an elastic band worn around the waist over the participant's own T-shirt. The elastic band was adjustable to enable a tight but comfortable fit. The location of the eight tactors was adjusted to the participant's body size so that they covered the cardinal and oblique directions, see Figure 6.2. The tactors were based on pager motors (JinLong Industries), such as those used in mobile phones, which were housed in PVC boxes. The tactors had a contact area of 1.5 by 2 cm and vibrated at 160 Hz. They were activated in one-second pulses, the pause between subsequent pulses depended on the distance to the next waypoint and the coding scheme, see below. Reaching a waypoint (i.e., being within 15 m of the waypoint's GPS co-ordinates) was communicated to the user by making all eight tactors vibrate for one second.

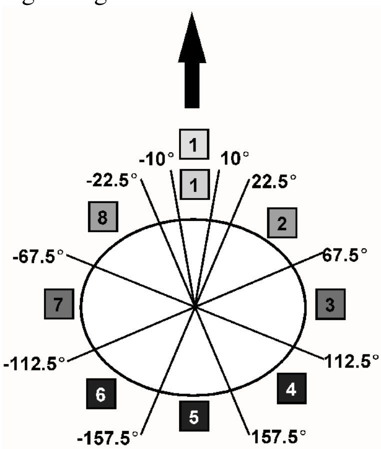

Figure 6.2. Schematic picture of the vibrator positions and numbering. The arrow indicates the forward direction. A vibrator is active when the waypoint direction is within its range as indicated by the lines and angles. The grey scale coding will also be used in the results section. The -10°, 10° cone is only used in Experiment 9.

Statistical design

We used a within-subjects approach with ten different routes and five different distance coding schemes, and created random sequences of the schemes to balance any learning effect. Each participant walked the ten routes in the same sequence, while combinations of routes and schemes differed between participants. The same sequence of conditions was used within each participant for the first five routes (practice) and the last five routes (test). All routes were between 360 and 390 m in length, and all used the same start location. Each route consisted of 6 waypoints (imaginary circles with a 15 m diameter) located on an open field of grass of about 110 × 90 m, surrounded by bushes. The waypoints could not be identified visually. Based on the logged data, we calculated the effective walking speed as the leg distance (distance along a straight line between two waypoints) divided by the walking time.

Display coding

Waypoint direction was coded by the location of the vibration; each of the eight vibrators covered a 45° cone with borders as depicted in Figure 6.2. For example, tactor 5 would indicate that the waypoint is behind. Two approaches were used to design the distance coding schemes. The first is a 1-phase model with a monotonic relation between distance and rhythm, in general: the smaller the distance, the faster the rhythm. In this approach, the rhythm has a fixed relation to the remaining distance, in which remaining distance could be either absolute (i.e., the number of metres) or relative with total leg length as reference (a leg is the stretch between two consecutive waypoints). The second is to apply a 3-phase model. Navigating a leg consists of: phase 1: setting the desired course, phase 2: cover the distance (roughly) maintaining the desired direction, and phase 3: accurately homing-in on the waypoint. During phase 1, the new heading must be set, which requires frequent feedback from the system. In the second phase, the user requires less feedback, and possibly merely needs a confirmation that he or she is still on track. Finally, when the user closes in on the waypoint (phase 3), again information is needed frequently. In the 3-phase approach, the temporal density of the information depends on the navigation phase, and not monotonously on the remaining distance. Based on the above considerations, the following distance to coding schemes were used:

1. 3-phase model in absolute mode. The pause between two 1 s pulses was as follows: phase 1 (within 15 m of the start point): pause 2 s. Phase 2: pause 6 s. Phase 3 (within 20 m of the endpoint): pause 1 s.
2. 3-phase model in relative mode. Phase 1 (within 10% of the leg length from the start point): pause 2 s. Phase 2: pause 6 s. Phase 3 (within 10% of the leg length from the endpoint): pause 1 s.
3. 1-phase model in absolute mode. The pause was 1/10th of the number of metres left to the next waypoint (i.e., every second of pause signalled 10 m of distance). However, within 15 m of the starting point, a signal was given every 2 s, otherwise the pause would have been too long to pick up the new heading. Formally this could be considered a two-phase model.
4. 1-phase model in relative mode. The pause started at 10 s and was reduced with 1 s for every 10% closer to the waypoint. However, within 15 m of the starting point, a signal was given every 2 s,
5. Control condition. Pause duration was fixed at 2 s.

Procedures

The procedures were as follows. After reading the written instructions, the participant and experimenter walked to an open field of grass. During this walk and during the training, participants were told which condition was coming next and what they could expect (e.g., 'the vibration-rate will increase as you come nearer to your target waypoint'). Participants were instructed to finish the experiment as fast as possible, while maintaining a normal walking speed. The participants had unrestricted vision, but the waypoints could not be visually identified. During the training, the experimenter was allowed to correct unwanted behaviour such as running and walking into the bushes. After the last condition, the experimenter interviewed the participant on issues such as usability and points for improvement using an open interview protocol.

6.2.3 Results

All participants were able to complete all routes without problems. The mean effective walking speed for the distance coding conditions is presented in Figure 6.3, averaged over legs and participants. An analysis of variance with coding scheme as independent and effective walking speed as dependent variable did not reach significance ($F(4, 44) = 1.55$, $p > .20$).

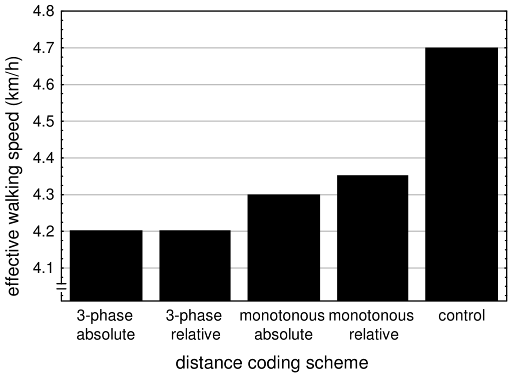

Figure 6.3. Results of Experiment 7. Effective walking speed does not depend on the distance coding scheme.

6.2.4 Discussion

The tactile waist belt proved to be an effective navigation display. After approximately 30 minutes (5 routes) the participants could walk a route based on tactile information only, and demonstrated acceptable effective walking speeds (4.2 - 4.7 km/h) which are somewhat below normal walking speeds (please note that effective walking speeds do not compensate for 'zigzagging', meaning that a detour reduces the effective walking speed). The display is thus quickly learned.

In general, the differences between the coding alternatives were small, and were not significant. Highest effective walking speeds were reached with the coding scheme in which participants received feedback unrelated to the distance to next waypoint (i.e., the control condition). This could be caused by the fact that distance information (as presented in this experiment) is simply not needed in waypoint navigation on foot, that the experiment had not enough statistical power to reveal an effect, or that the participants were not able to interpret the information. The first may be related to the fact that the waypoints were not actual landmarks that could be identified when approximated close enough. In other words: Since the waypoints were just GPS co-ordinates, the benefit of knowing the distance is reduced compared to a landmark as waypoint that could be identified when direction and distance are known. The latter can be due to the fact that participants were not able to perceive the rhythm changes at all, which is not very likely since the Weber fraction for tactile intervals is about 20% (see Experiment 5 in Chapter 5), or were not able to translate the rhythm into the required behaviour leading to performance improvements. This may be because the participants received too little training in translating the distance coding.

The drawback of the present coding schemes is that they affect the direction information as well. By manipulating the pause between pulses, the temporal resolution of the direction information is also manipulated. In the distance-related feedback schemes direction updates came with intervals up to 8 seconds while the latency in the control condition was relatively short: always 2 seconds.

The post experiment debriefing confirmed that the direction indication was directly clear and very useful, but that the distance indication was more difficult to interpret. Participants also indicated that distance information was not critical to come to a higher walking speed, but that a pre-warning a short distance before reaching the next waypoint would be convenient to focus attention and to prepare for a course change.

6.3 Experiment 8: Tactile in-vehicle navigation system

6.3.1 Introduction

There is a general conviction that driver overload and distraction resulting from the actions of in-vehicle support systems can form a threat to the positive effects expected from these systems (e.g. Carsten & Nilsson, 2001; ECMT, 1995; Rumar, 1990). Warnings and procedures have been issued to avoid this, starting with the system's design stage (European Commission, 2000; ISO, 1999). The threat could manifest itself in two ways: (a) in an overload of the traditional sensory channels (vision and audition) because in-vehicle support systems present additional messages to them, next to the everyday messages already arising from the traffic scene itself and (b) in an overload of the cognitive capacities that drivers have at their disposal. The prenav model predicts that an intuitive tactile display can counteract both threats.

Driver support systems and other information systems in automobiles rarely use the driver's tactile information processing capacities, but rely on the visual and to a lesser extent on the auditory channel. However, evaluation of visual in-vehicle information systems has shown that they may negatively influence the drivers' scanning behaviour and attention allocation, and may therefore ultimately reduce traffic safety. Altered scanning behaviour induced by visual navigation displays is a common finding (Fairclough & Maternaghan, 1993; Wierwille, Hulse, Fischer, & Dingus, 1991), although the visual demands may be comparable to that of conventional tasks using dashboard instrumentation (Dingus, Antin, Hulse, & Wierwille, 1989; Wierwille, Antin, Dingus, & Hulse, 1988). It should be noted that visual in-vehicle navigation and/or traffic information displays have been shown to have negative effects on traffic safety (Janssen, Kaptein, & Claessens, 2000; Liu, 2001; Pohlmann & Traenkle, 1994).

In the present study, we investigate the feasibility of an in-vehicle tactile navigation display. The navigation information was presented either via a tactile display, a visual display, or both (bimodal condition). Performance and workload were compared in normal and high workload conditions. With this design, we can investigate the following questions listed in Section 1.8:

Q7: Can local guidance tactile displays lower cognitive effort ratings compared to a visual display?

Q8: Is performance with a local guidance tactile displays independent of cognitive workload or external stressors?

Q9: In comparison to a visual display as baseline, can (adding) a tactile display result in better performance?

6.3.2 Method

Participants

Sixteen volunteer drivers participated in the study and were paid €50. They were divided in a normal and a high workload group, each consisting of six male and two female drivers. Their ages ranged from 23 to 51 years. All participants were experienced drivers, had normal vision, and had experience with driving simulators.

Experiment 8 in a nutshell.

- 16 drivers completed 12 routes through a town in a driving simulator. Route navigation information was displayed on a visual display (an arrow for direction, and a number for distance information) and/or on a tactile display (vibration on the left or right leg for direction, and different rhythms for distance). The drivers were instructed to use their turn indicator as soon as they received the navigation message. During navigation a peripheral detection task PDT) was presented. The rating scale mental effort (RSME) was completed after a block of four routes.
- The between subjects independent variable was workload (normal, high), the within subjects independent variable was display modality (visual, tactile, bimodal).
- The dependent variables were reaction time to the navigation message, RSME score, reaction time and errors in the PDT.

Apparatus and task

The experiment was run in a driving simulator. The simulator had a 180° × 30° field of view, rear-view mirrors, haptic feedback in the controls, automatic gear change, and interactive traffic. The gain of the steering wheel was adjustable. In the high workload condition, the gain of the steering wheel was half that of the normal gain. This allowed proper vehicle control, but made lane keeping and cornering more demanding. The database chosen for the present experiment was an urbanised area, measuring 3 × 3km. Included within the environment were roads, traffic signs, interactive traffic lights, interactive traffic, intersections with different priority situations, and roundabouts. Twelve different routes were completed; the distance travelled during each route was approximately 7 km and each route included 6 or 7 course changes. The minimum and maximum distance between course changes were 300m and 1.5km. Each route took approximately 10 min to complete. Primary data (including position, heading and steering wheel angle) were recorded at a frequency of 60 Hz. The tactors used were Special Instrument MiniVib 4 vibrators, activated in 60 ms bursts. The tactors were mounted in the seat (four under each thigh, in a straight line from front to rear of the seat base) with a centre-to-centre distance of 4 cm. Based on the distance to the next course change, the appropriate navigation symbol was presented (see below for the design of the navigation symbols). Each symbol was presented until the next symbol appeared or the waypoint was reached. The drivers were instructed to use the direction indicator as soon as they received the navigation message. During each run, a Peripheral Detection Task (PDT) was presented. The PDT is based on the narrowing of the attended visual field as a function of workload (Miura, 1986; Williams, 1985, 1995). The PDT is able to measure workload during driving and to measure workload peaks of short duration (Martens & Van Winsum, 2000). The PDT presented red squares in the left periphery of the visual field (between 11–23° laterally, and 2–4° above the horizon) for 1 s. The stimuli were presented with a random interval between 3 and 5 s. The participant's task was to react as fast as possible to the PDT stimulus by pressing a finger switch, attached to the index finger of the right hand.

Experimental design

Workload (normal and high) was a between-subjects variable. Each participant completed 12 runs along the 12 different routes. The 12 runs were divided in three blocks of four runs, one block for each level of modality (i.e., the modality in which the navigation symbols were presented: visual, tactile, and bimodal). After each block, the participant completed the RSME (Rating Scale Mental Effort), a standardised subjective mental effort rating (Zijlstra & Van Doorn, 1985) with an interval scale. Three other performance measures were calculated for each run: the mean reaction time to the PDT stimuli (defined as the time between the onset of the PDT stimulus and the pressing of the finger switch), the percentage of missed PDT stimuli, and the mean reaction time to the navigation cues (defined as the time between the onset of the navigation cue and the activation of the direction indicator). The order of the conditions was semi-balanced over the participants, and the different routes were balanced over the conditions.

Design of the visual and tactile navigation symbols

Contemporary in-vehicle navigation displays present relatively simple visual symbols. Information is typically presented when a course change is required. The information consists of two parts: the direction of the oncoming (course) change (e.g., left, right) and the remaining distance to this change (Burnett & Porter, 2002). This simple symbology was also used in the present experiment. Visual and tactile symbols were made for three distances: 250, 150, and 50 m. Distance was indicated alphanumerically for the visual symbol, and by vibration rhythm for the tactile symbol (see Appendix I on the discussion of using secondary tactile parameters). The visual symbols (arrow plus distance) were presented on an LCD display located 45° left of the steering wheel. The symbols had a resolution of 64 × 64 pixels. In a similar way, the tactile symbols were developed. Based on a pilot study, we coded the direction of the course change by location (i.e., a vibration under the left or the right thigh), and the distance to the next waypoint by rhythm (i.e., smaller distances to the waypoint were indicated by presenting the course change patterns at closer temporal intervals). The symbols always consisted of multiple bursts of vibration with a burst length of 60 ms. The 250 m symbol consisted of three bursts separated 270 ms in time. The 150 m and 50 m symbols were designed as sweeps, that is multiple bursts separated by decreasing intervals. The 150 m symbol consisted of six bursts with intervals decreasing from 270 ms to 60 ms. the 50 m symbol consisted of five bursts with intervals decreasing from 60 to 10 ms.

Procedures

The participants received written instructions describing the experiment and were asked to read and sign an informed consent. The experiment started with a 10 minute familiarisation run. During this run, the drivers could get used to the simulator, the driving environment, the navigation symbols, and the instructions. The instructions were: (a) to employ a normal driving style, including obeying the priority rules and the applicable speed limit (50 km/h), (b) to follow the messages of the navigation system, (c) to use the direction indicator on the steering wheel (i.e., left/right) directly after receiving the navigation message, and (d) to react directly to the stimuli of the PDT by pressing the finger switch. After the familiarisation run, the 12 experimental runs were driven. Before each of the experimental runs, the participant was informed on the modality that the navigation messages were presented in. After each modality (four runs), the participant completed the RSME. There was a 1-minute break between the experimental runs.

6.3.3 Results

Prior to analysis, the data were inspected to ensure that each run was successfully completed (i.e. there were no wrong turns etc.). Each dependent variable was analysed using an analysis of variance (ANOVA) in a Workload (normal, high) × Modality (visual, tactile, bimodal) design. Post hoc analyses were completed using the Tukey HSD test with the alpha level set at .05. We found a significant main effect of Modality on the mental effort rating; $F(2, 28) = 6.15$, $p < .01$ and on the reaction time to the navigation message (there were no wrong responses or missed messages), $F(2, 28) = 4.09$, $p < .05$. The mean values and the post-hoc results are depicted in Figures 6.4 and 6.5, respectively. The analysis of the mental effort demonstrated that the ratings in the visual condition were approximately 25% higher than for the tactile condition. The ratings in the bimodal condition were in between both ratings, and significantly lower than in the visual condition. The mean values for the RT to the navigation messages demonstrated best performance in the bimodal condition. Compared to the visual condition, the RT was approximately 15% faster. A performance gain in choice reaction times for integrated redundant sources is a common finding (e.g., Selcon, Taylor, & Shadrake, 1992). Selcon and colleagues hypothesised that part of the gain in the bimodal conditions was due to the reduction in workload. The RT in the tactile condition was in between the visual and bimodal conditions, but did not significantly differ from both. However, the absolute difference between the visual and tactile conditions was in the order of 100 ms. Since the instructions effectively made the task a choice reaction time task, the difference might indicate a potential advantage in tasks that are time critical, such as responding to (directional) collision warnings. With respect to the PDT, there was no effect on the percentage missed PDT stimuli. For the PDT reaction time, the Workload × Modality interaction almost reached significance; $F(2, 28) = 2.86$, $p < .08$. The mean values of this effect are presented in Figure 6.6. The interaction demonstrated that performance in the two workload conditions that included the tactile modality were insensitive to workload level. However, this was not the case for the visual only condition: the RT increased by 63 ms (10%) in the high workload conditions.

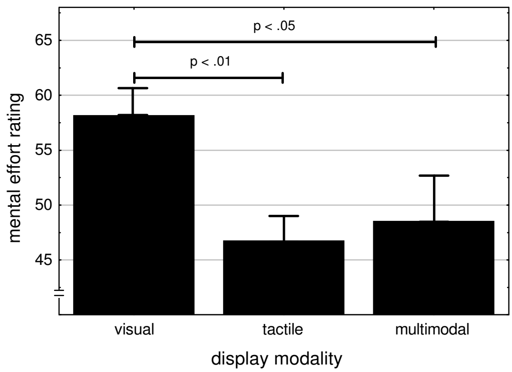

Figure 6.4. Effect of display modality on the mental effort rating. Higher scores indicate a higher subjective workload.

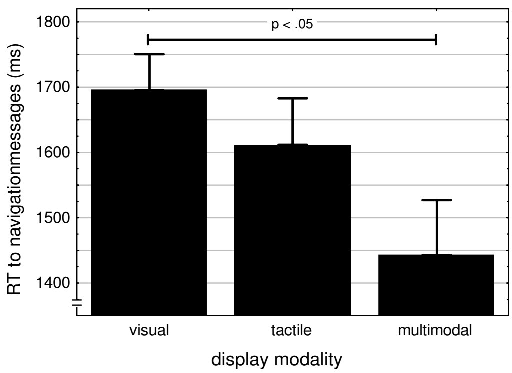

Figure 6.5. Effect of display modality on the Reaction Time to the navigation messages. Drivers had to use the direction indicator as fast as possible after receiving the navigation symbol was presented.

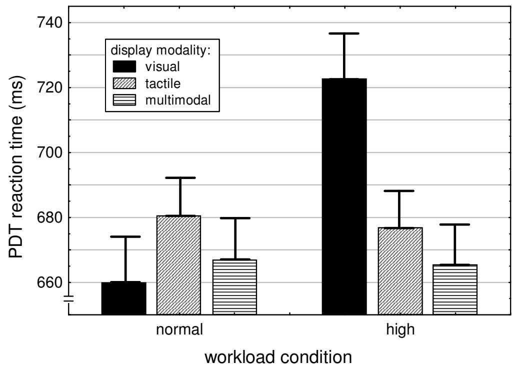

Figure 6.6. The Reaction Time in the Peripheral Detection Task as function of display modality for the normal and high workload groups. The drivers were instructed to react as fast as possible to stimuli presented in the left peripheral field of view. The stimuli were presented during the route at random intervals of 3-5 s.

6.3.4 Discussion and conclusions

The results of the study illustrate the advantages of employing the tactile modality in an in-vehicle navigation system. Employing the tactile modality appears to be a valuable solution to the demands of the automotive industry to improve the man-machine interfaces within cars. When the tactile display was added to the visual navigation display, the bimodal presentation of navigation cues resulted in faster reactions to the navigation messages, lower mental effort ratings and no performance decline when workload increased. With the visual display, performance in the high workload group was lower than in the normal workload group. Also, employing the tactile display instead of the visual display resulted in a lower mental effort rating, and no performance decline when workload increased. Herewith, the present results confirm our hypotheses on Q7, Q8, and Q9.

The results are an indication that using the tactile modality in automobiles may improve the quality and safety of the man-machine-interface and adds to the growing body of evidence in this field (Ho, Tan & Spence, 2005; Tan, Gray, Young & Traylor, 2003). These effects are evident in a bimodal setting but may also be expected in a tactile-only setting under high workload conditions. It should be noted that the workload levels experienced in the simulator may not have approached those experienced in real driving. In a study where vibration was presented to the accelerator pedal, Martens and Van Winsum (2001) found that tactile warning cues were more effective than speech warning cues. This reveals a potential advantage for employing tactile displays for time critical tasks in car driving such as reacting to collision warnings. In the present choice reaction time, the difference between the visual and tactile modality did not reach statistical significance. There are several reasons to expect that the positive effect of using the tactile modality in real driving may be more pronounced than in this simulator study. Some of the participants indicated that it took more (training) time for them to learn to trust the tactile messages than the single familiarisation run. This indicates that the positive effects of the tactile display may potentially become greater after prolonged periods of usage. Also, in a real world setting, several disadvantages of the visual display may arise. In the driving simulator, the navigation display and the outer scene are presented at roughly the same focal distance and with equal intensity. On the road, the driver must adjust to different light levels and focal distances when switching between the navigation display and the outer scene. Furthermore, the visual display in this experiment contained much less visual information (and clutter) than the current commercial navigation displays may contain. Moreover, in the present set-up, the PDT stimuli were presented on the same side (left) as the visual navigation messages. With the visual display located on the opposite side, the effects of a narrowing field of view will be stronger for the visual condition. On the other hand, these disadvantages of a visual display located on or near the dashboard may be solved by employing a head-up display but this would involve other design and safety issues. To investigate the effect on driver behaviour and traffic safety, field studies with an instrumented vehicle and expert judgements are a necessary next step[26]. Future studies should also address the issue of tactile perception within the vibrating environment that automobiles can subject the driver to. A second issue that deserves attention is the (im-) possibility to present more complex navigation messages via a tactile display such as “take the left lane immediately after a right turn 100 m ahead”. The best solution in this kind of complex situations is to use a tactile cue to direct the driver’s attention to a visual or auditory display.

Based on the present study, two beneficial application areas of tactile displays in automobiles can be identified. The first is to use the intuitiveness of localized tactile cues with respect to spatial information such as navigation information, and warnings for line crossings. An important advantage is that the tactile channel has an unlimited field-of-regard, while the visual system has a restricted field of view. This means that vision extracts spatial information from the 180° forward view only, which can result in missing relevant objects (e.g., cars in blind spots and crossing pedestrians). The second potential application for tactile displays lies in the indication of unexpected or time critical events such as collision warnings (Tan, Gray, Young & Traylor, 2003).

6.4 Experiment 9: Waypoint navigation at sea and in the air[27]

6.4.1 Introduction

In Experiment 8 we found profitable effects of a relatively simple tactile display indicating a restricted number of directions in concordance with the ‘simple’ layout of the environment requiring only two direction indications: left and right. In Experiment 9 we expand this to environments that don’t restrict the number of directions, but allow an infinite number of directions to be taken. The first is in the air, flying a helicopter, the second is at sea, driving a fast boat. These two case studies are also relevant because we take the concept out of the laboratory to test it onboard real platforms, which has several consequences. For example, the cockpit of an aircraft is a working environment in which visual workload may be even higher than in a passenger car, and may compromise safety and performance. In a fast boat, visual displays are of little use because of the (whole body) vibration that makes reading the display impossible unless the boat slows down. Whole body vibration can be seen as an external stressor. Although whole body vibration is not a major topic in this thesis, it is relevant to show that a tactile torso display is usable under such conditions.

We employed the same 8-tactor belt as in Experiment 7. Based on the results of Experiment 7, we made two changes. We decided not to code for distance but only to indicate when a waypoint was reached by a 1 s pulse on all eight tactors as in Experiment 7. And we enlarged the directional resolution in the frontal direction using a different rhythm for the front tactor when the waypoint was within the forward 20° cone.

[26] These studies have been done but will not be reported in this thesis (see De Vries et al., 2004).

[27] This study was performed in co-operation with the Royal Marines, Poole, UK and the Royal Army, Middle Wallop, UK.

Figure 6.7. A 500 HP Rigid Inflatable Boat as used during the experiments.

6.4.2 Method

Experiment 9 in a nutshell.

- One boat driver and one helicopter pilot navigated their vehicle along a triangular course marked by three waypoints. The direction of the waypoints was indicated on a tactile display consisting of 8 tactors in a belt around the torso.
- We gathered descriptive (vehicle location) data during the runs and gathered subjective comments from the participants.

Participants and apparatus

In each case study we tested one operator. They were both very experienced in waypoint navigation and in controlling their vehicles. The helicopter pilot had some experience with tactile displays, the boat driver had none. They both participated voluntarily and were not paid. We used the same navigation equipment as in Experiment 7, except for the mini computer that was replaced by a laptop. We used two platforms: a UK Royal Army Gazelle helicopter, and a 500 HP rigid inflatable boat of the UK Royal Marines (see Figure 6.7). The platforms were not modified in any way. Both vehicles resulted in whole body vibrations with main components in the range up to 15 Hz. The exact profile is dependent on the vehicle manoeuvres, posture of the participant and contact points between the participant and vehicle (e.g., seat, feet and hands; see also ANSI S3.18-1979(R1999)).

Routes

The pilot flew a triangular course clockwise (see also Figure 6.8). He started by flying towards waypoint 1, the starting point. Thereafter, about 22 km to waypoint 2, 15 km to waypoint 3 and 10 km to waypoint 1. The boat operator drove a triangular course counter clockwise at open sea. Starting close to waypoint 3, he drove about 6 km to waypoint 1, 7 km to waypoint 2 and 4.5 km to waypoint 3. The radius of the waypoints (the waypoints were circular areas) in the helicopter trials was 50 m, in the boat trials 100 m. Both environments were chosen such that there were no landmarks or reference points and the waypoints could not be visually identified.

The instruction for both operators was the same: Follow the direction indicated by the vibration. When reaching the waypoint, all tactors will vibrate, directly followed by the direction to the next waypoint. The pilot received additional instructions after the second trial. His behaviour revealed that he expected to be on course as soon as the middle tactor fired. Therefore, the experimenter explained that the transition from vibrator 2 to vibrator 1 indicated a course error of 22.5° and not 0°. The participants knew that they should follow a triangular course. The speed was fixed beforehand in consultation with the drivers: 100 mph for the pilot (≈160 km/h), 35 mph (≈56 km/h) for the boat driver.

Procedures

The procedures were as follows. The first test was done with the helicopter. After a verbal explanation of the goals of the experiment, the operation of the tactile display and the interpretation of the signals, the pilot tried the display driving around in a normal passenger car. The pilot drove along a number of waypoints without knowing their location. This familiarization run clarified the operation of the display, but also showed that training was not really necessary. In the helicopter, the first run was without the tactile display but on commands of the onboard navigator. Directly thereafter, the pilot flew two runs with the tactile display and no instructions from the navigator. The waypoints were originally in British National Grid co-ordinates and were translated into Garmin GPS co-ordinates for the tactile trials only. As can be seen from the data plots, the co-ordinates of waypoint 2 were translated incorrectly. The pilot was instructed not to use any reference points on the ground. For the boat trial, the driver also received instructions on the goals of the experiment and the operation of the display, but not the familiarization run with the passenger car. Two trials with the tactile display were run. To familiarize the driver with the tactile signals, he was instructed to sway the vehicle at the start of the first run. After the experiment the participants were interviewed using an open interview protocol.

6.4.3 Results

Figure 6.8 presents the helicopter flight paths in combination with the activation pattern of the tactile display for the three helicopter trials (see Figure 6.2 for the grey scale coding). The mean and standard deviation of the heading error were -2.9 (4.6), 16.7 (10.0), and 4.8 (5.3)°, for the three trials, respectively.

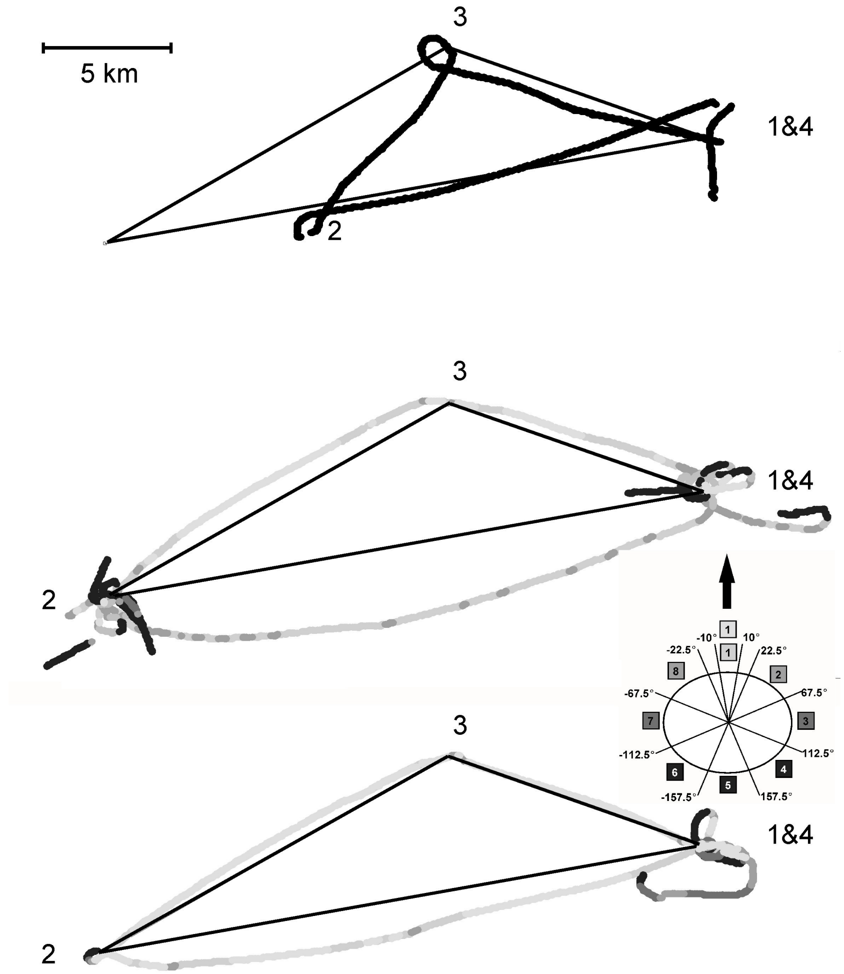

Figure 6.8. The flight paths for the three helicopter trials. In trial 1 (upper panel), the pilot flew on instructions of the navigator, in trials 2 (middle panel) and 3 (lower panel) with the tactile display only. The coding corresponds to the active vibrator (see also Figure 6.2). Gaps in the data are caused by GPS loss.

Inspection of Figure 6.8 shows that:

- The pilot had no trouble with perceiving the displayed information in the helicopter environment,
- The pilot could easily fly into the direction of the waypoints,
- Performance in the third trial is better than in the second trial. Larger parts of each leg are coloured light grey, indicating a course deviation smaller than 10°. The figure shows that in the second trial, the pilot corrects the heading error till the transition to the middle vibrator and not till 0°. In the third trial, performance was as good as the first trial with instructions from the navigator.
- Contrary to the second trial, waypoint 2 is passed adequately in the third trial (see details in Figure 6.9).

- Noteworthy is the fact that the strategy to pass the waypoint is different for the different conditions: the pilot chooses for a more efficient path when supported by the tactile display than when flying on instructions of the navigator,
- The noisy behaviour near waypoints 1 and 2 in the second trial and near waypoint 1 in the third trial had two causes. First, the rotor blades resulted in a loss of GPS reception, and second, the radius of the waypoints appeared too small in relation to the airspeed and turning rate of the helicopter. The right panel of Figure 6.9 shows that the waypoint could only be reached by first flying away from it.

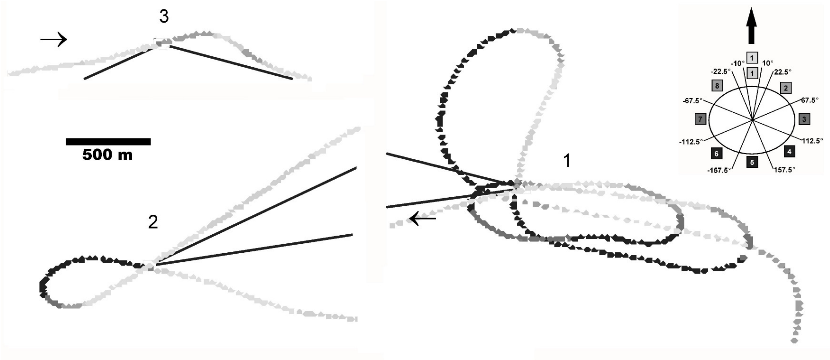

Figure 6.9. Details of flight trial 3 (with tactile display). The arrow indicates the flying direction, the numbers the waypoints, and the grey scale coding the active tactor; see Figure 6.2.

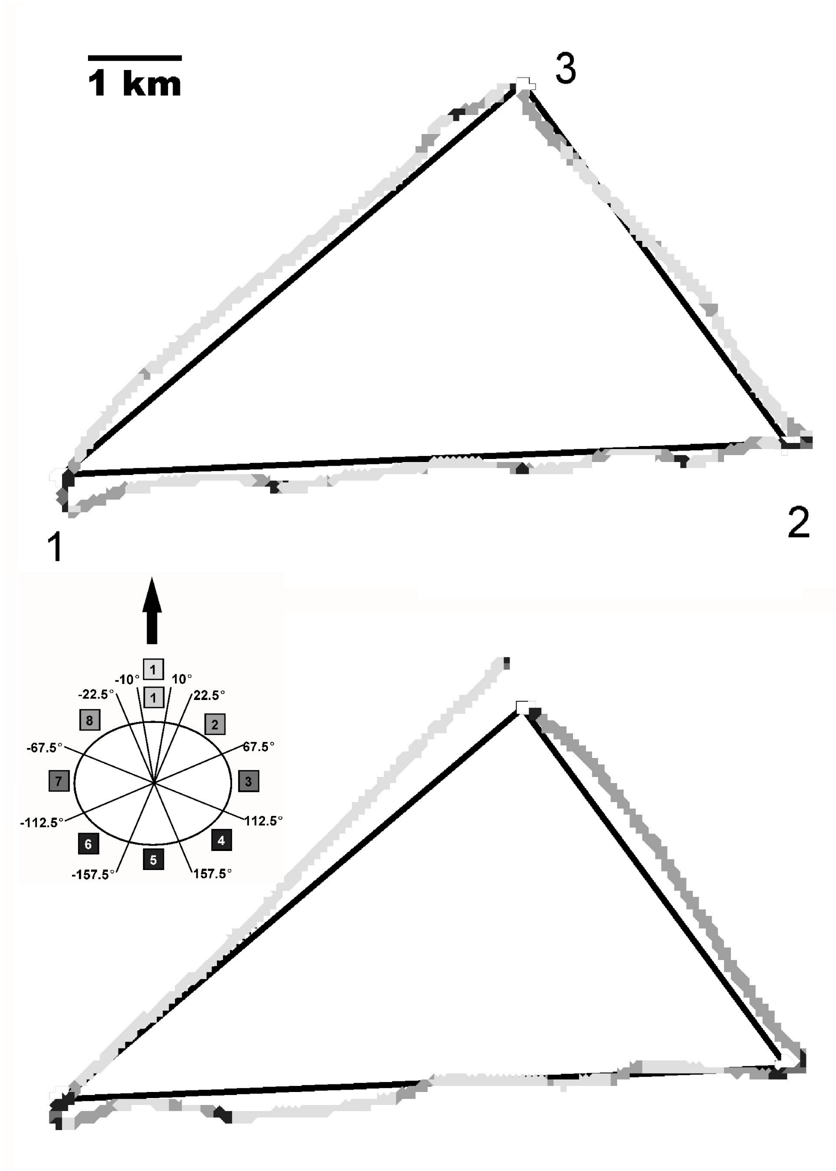

Figure 6.10. The first (upper panel) and second (lower panel) boat trial, both with support of the tactile display. The arrow indicates the direction, the grey scale the active vibrator according to Figure 6.2.

Figure 6.10 depicts the paths of the boat trials. Details of the passage of the first waypoint are depicted in Figure 6.11. The mean and standard deviation of the heading error were 0.7 (9.8)°, and -1.3 (6.3)° for the first and second trial, respectively.
The following can be seen:

- After a short familiarization (as can be seen by the sway on command of the experimenter at the start of the first leg of the first trial), the driver could well drive towards the waypoints by tactile cues only,

• Passing of the waypoints is adequate.

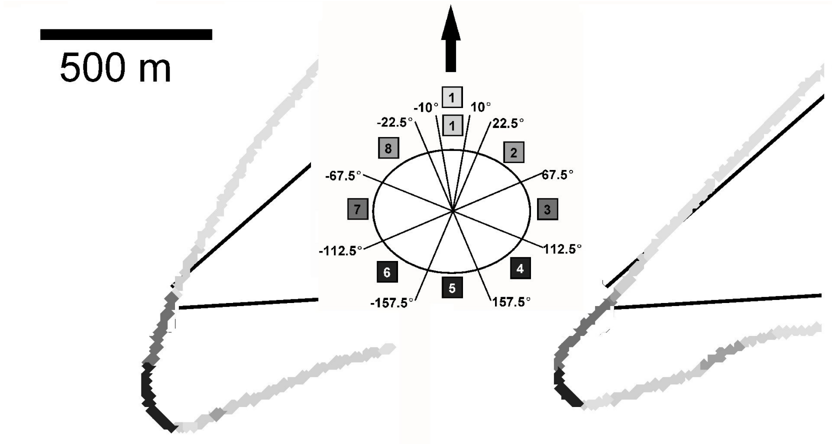

Figure 6.11. Details of the passage of waypoint one for boat trial 1 (left panel) and 2 (right panel). The arrow indicates the direction, the grey scale code the active vibrator according to Figure 6.2.

Besides the objective data, we gathered subjective remarks of the operators. We also explicitly asked them whether they had used any visual landmarks to navigate, which they both denied. For the helicopter pilot, this is confirmed by the fact that he followed the tactile navigation display in the second trial, despite the fact that the second waypoint was 'mislocated'. The boat driver added that there were no landmarks in sight, even if he had wanted to use any. Both operators were enthusiastic about the display after the trials, despite initial doubts of the boat driver. They experienced no problems in perceiving the vibrations. Both indicated that they would like to have a warning when they came close to the waypoint. This is a very simple way of coding distance. The boat driver explicitly mentioned that the display allowed him to better concentrate on the waves ahead and would make him less dependent on the (tedious) communication with a navigator.

6.4.4 Discussion of Experiment 9

The results show that the tactile navigation display is also successful in an operational environment. This is not trivial: vibrating environments could make the perception of the vibrotactile signals difficult or even impossible as reported in other research projects (Castle & Dobbins, 2004). This indicates that there is a need for general knowledge about perceiving vibrotactile signals in a vibrating environment. A second conclusion is that the results support the conclusion of Experiment 8 that the display can be used for vehicle waypoint navigation. Apparently, the display is easy to learn and can be used without extensive training. The operators' reactions were direct and adequate. The performance of the helicopter pilot showed a fast learning effect, and that of the boat driver showed no room for improvement.

6.5 General discussion and conclusion

The three experiments in this Chapter investigated waypoint navigation in 2D. The results indicate the usefulness of the tactile display: Pedestrians, chauffeurs, the helicopter pilot and the boat driver all showed adequate performance with the display after a short familiarization only. In Chapter 4, we concluded that external directions can be indicated by a localized vibration on the torso. We started with a pilot experiment to investigate how to code the second parameter: distance to the waypoint. Both the objective data and comments of the users suggested that continuous distance information is not necessary. A pre-warning in close proximity to the waypoint could be helpful however. In settings where continuous distance information is considered to be important, the confounding of distance information with the temporal resolution of the direction information should be solved. For example by displaying distance information in the tactile picture without changing the refresh rate (i.e. by manipulating frequency, amplitude, or temporal composition when the direction tactor is on), or by using an additional tactor that is controlled independently of the tactors that present the direction information.

Experiment 8 was the first operational test of the tactile display in a platform, with encouraging results. Drivers were able to follow the routes based on tactile cues only, without any formal training. We were also able to investigate specific prenav predictions. The prediction of low mental effort ratings was confirmed: the ratings were significantly lower than with the visual cues (Q7). Also, with the tactile display, performance did not suffer from an increased workload, while this was the case with the visual display. This confirms the prediction that intuitive (tactile) displays make performance independent of the workload (Q8).

In Experiment 9, we were able to investigate whether the operators would experience problems with receiving the vibrotactile display in vibrating environments as reported by Castle and Dobbins (2004). Both the performance and the results of the debriefing of the helicopter pilot and the boat driver indicate that this was not the case. Both detection and localization seem to be unaffected. There is no clear-cut explanation why the vibrating environment did not have any negative effects in the present case studies. The likely explanation is that there is no cross-channel masking between the sensory system for lower frequencies (stimulated by the vehicle vibrations) and the sensory system that is stimulated by the high-frequency tactors (see Appendix 1, Section 3.3). However, fundamental knowledge on the effect of whole body vibration on vibrotactile perception is needed. Experiment 9 also demonstrated that an 8-tactor belt on the torso has a sufficient bandwidth to present waypoint navigation in high speed vehicle control settings.

Chapter 7. Navigation in 3D[28]

Abstract

In this Chapter we make the transfer from navigation in 2D to navigation in 3D. We start by investigating the possibilities of presenting information on the third dimension via a tactile display in a simulated low-level helicopter flight (Experiment 10). In the second experiment, we test a 3D tactile display in a simulated helicopter hover task. In both experiments, the tactile instrument consisted of a 64-element tactile display covering the torso, shoulders and thighs of the pilot. The tactile display presented information on the desired direction of motion only (simple version), or included additional information on the current motion direction (complex version). In a helicopter simulator, student pilots flew under different conditions of vision (full vision and night vision), the tactile display (none, the simple version and the complex version), and the mental workload (with and without an additional mental workload task). We analysed performance and subjective mental effort ratings. The results made us conclude that the successful results of the tactile display in the 2D horizontal applications are also present in a 3D situation. Adding the tactile display greatly reduces the error under conditions of full and reduced vision and under condition of increased workload. This improvement is not accompanied by an increase in mental effort ratings. However, we cannot conclude that the tactile display was fully intuitive for these applications because it does not make the pilots completely immune to the added mental workload. However, the degradation caused by increasing the mental load is much smaller when the pilot has a tactile display at his disposal. The lack of a performance difference between the simple and the complex version of the tactile display is interpreted in terms of tactile clutter which becomes relevant when multiple tactile signals are presented simultaneously and not serially.

[28] Parts of this Chapter have been published as:

Van Erp, J.B.F., Veltman, J.A., Van Veen, H.A.H.C. & Oving, A.B. (2003). *Tactile Torso Display as Countermeasure to Reduce Night Vision Goggles Induced Drift*. In: Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures. RTO Meeting Proceedings 86, pp. 49-1 - 49-8. Neuilly-sur-Seine Cedex, France: NATO RTO.

Van Erp, J.B.F., Veltman, J.A. & Van Veen, H.A.H.C. (2003). *A tactile cockpit instrument to support altitude control*. Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting, pp. 114-118.

7.1 Introduction

In the previous Chapter, we reported experiments on navigation in 2D, with displays that indicated directions in the horizontal plane only. In this chapter we expand this to include the vertical dimension. One of the potential applications for which this third dimension is important is in aviation. In this Chapter, we discuss two experiments done in a helicopter simulator. The first experiment focuses on the third dimension in isolation in a low-level flight task (i.e. altitude in aviation). Altitude information was presented tactually by vibrating elements under the thighs and on the shoulders. In the second experiment, this display is integrated with the belt-type tactile display described in the previous chapter, resulting in a full 3D tactile display. This display is tested in a helicopter hover task in Experiment 11. We investigate questions at the cognition and action level (see Section 1.8):
Q7. Can local guidance tactile displays lower cognitive effort ratings compared to a visual display?
Q8. Is performance with a local guidance tactile display independent of cognitive workload or external stressors?
We tackle these questions by measuring mental workload and by investigating the effects of adding an additional mental workload task. To look at the effects of external stressors, we investigate the effect of flying with Night Vision Goggles.
Q9. In comparison to a visual display as baseline, can (adding) a tactile display result in better performance?
We compare the added value of the tactile display on performance under conditions of full visual view and flying with Night Vision Goggles.

Figure 7.1. View of the helicopter simulator in night vision view.

7.2 Experiment 10: Tactile altitude display

7.2.1 Introduction

In this experiment, we employ a tactile display to present altitude information to a helicopter pilot in a ground target following task. The first goal of the experiment was to investigate if a tactile cockpit instrument can support the pilot in maintaining an instructed altitude under different conditions of outside visual information: full view (day) and with night vision goggles (night). The second goal was to investigate the effect of adding an additional mental workload task in conditions with and without the tactile display.

7.2.2 Method

Experiment 10 in a nutshell.

- 12 student pilots flew in a helicopter simulator. They performed a low-level ground target following task at an instructed altitude of 15 m. They could be supported by a tactile display that indicated the instructed altitude by a vibration on the shoulders or under the thighs (simple variant), or by a tactile display that indicated the instructed altitude and wether the helicopter was climbing or descending (complex variant). They completed trials in simulated daytime and at night with simulated night vision goggles. During half of a trial, a secondary mental workload task was added. The pilots completed the rating scale mental effort (RSME) after a trial.
- The independent variables were the type of support (no support, simple display, complex display), visual conditions (day, night), and the presence of the secondary task (present, absent).
- The dependent variables were the mean and RMS altitude error, secondary task performance and the scores on the RSME.

Participants

Twelve students of the Royal Dutch Airlines Flight Academy (KLS) participated voluntarily. Their mean age was 22.4 years, their mean flying experience was 160 hour (range 110 - 200 hours). They had no experience with tactile displays and the flight simulator. They were paid €50 for their participation.

Task and simulator

The participant followed a ground target (a Leopard II tank driving at 60 km/h) while flying at low level (instructed altitude 15 m). The part task flight simulator consisted of a helicopter mock-up and a cylindrical dome measuring 140° × 40° of visual angle (see Figure 7.1). Three Evans & Sutherland® Simfusion image generators generated the visuals. Night vision was simulated by the image generators (in hardware). In the night vision conditions, the participant wore field size restricting goggles (field size 40°, 100% overlap, no optics).

During the middle 120 s of each 240 s run, the participant performed a secondary task: the auditory continuous memory task (CMT). The CMT consisted of series of spoken letters of the Dutch alphabet and was presented through headphones. Each time the participant detected a target letter a button had to be pressed, that was positioned on the stick near the thumb. There were four target letters (A, B, C and D). The letters had also to be counted in separate tallies. The button had to be pressed twice when a target letter was presented for the second time. If this response was correct, the participant heard the word "correct". When the participant pressed the button at an incorrect moment or when an omission was made, the word "wrong" was presented through the headphones. After the feedback ("correct" or "wrong") the tally for the last letter had to be set to zero. The letter's E, G, H, P, T, V and W were not used because the sound of these letters could be confused with the target letters. Target letters were never presented in succession. Thirty percent of the letters were targets. The duration of the CMT was two minutes (see Veltman & Gaillard (1996a, 1998) for further details). Mental effort ratings were given on the Rating Scale Mental Effort (RSME, Zijlstra & Van Doorn, 1985).

The simulator data were used to calculate the following flight performance measures: absolute altitude error (m) and the root mean square altitude error (m). The CMT data were used to calculate the RT (s) to the double clicks and percentage correct responses. The raw data of the subjective workload ratings were not further processed before analysis

Tactile instrument and information presentation

We developed a tactile display that consisted of 64 elements (see Figure 7.2). The tactors were custom-build and based on DC motors that were housed in a PVC block with a contact area of 1.5 × 2.0 cm (see Appendix II for details). The elements vibrated with a frequency of 160 Hz. The elements were build-in in a stretch fleece vest (worn over the participant's T-shirt), in 12 columns and five rings (equally distributed between the navel and the nipples). The remaining four elements were located on both shoulders and under both thighs. Two altitude coding versions were developed: a simple version and a complex version.

Figure 7.2. The tactile display used in both experiments consisting of 12 columns and 5 rings of tactors on the torso and tactors on both shoulders and under both thighs.

The simple version only presented information on the direction of the set point (i.e., the instructed altitude). This is implemented by activating either the leg or the shoulder tactors of the tactile display. Two analogies can be used here. The first is that the activated element indicates the desired direction (as would be done with indicating the desired route or the next waypoint, see the previous Chapter). The second analogy is that the element signals the direction of the deviation, like bumping into a virtual wall. We chose the first coding principle for two reasons.

- The first reason is the resemblance with the waypoint analogy; a consistent coding in this case would be that the vibration indicates the desired direction (follow-the-needle principle).
- Second, this coding unambiguously indicates the optimal direction of motion, while the virtual wall analogy indicates the direction to avoid, which leaves the pilot with the choice to determine the optimal steering action (this is especially relevant for the next experiment).

Thus, the desired motion in the vertical dimension was indicated by activating elements under the thighs and on the shoulders (for a set point below and above the current altitude, respectively).

In the complex version, we added information on the current direction of motion. This was implemented by presenting a climbing or descending tactile sensation over the torso indicating the actual direction of motion (up and down, respectively). The signal consisted of activating the five rings on the torso consecutively (i.e., in discrete steps but eliciting a percept of apparent motion, e.g., Sherrick, 1968;

Kirman, 1974). See Table 7.1 for details on the timing parameters. Please note that when the pilot is correctly climbing or descending, the target attitude and the motion signal both indicate the same direction.

Table 7.1. Details of the timing parameters for the direction and motion signal.

direction of the target altitude		
deviation (m)	burst duration (ms)	inter burst interval (ms)
< 1	-	-
1 - 3	100	200
> 3	50	100

current motion direction			
absolute speed (m/s)	burst duration (ms)	inter burst interval (ms)	pause between signals (ms)
< 0.1	-	-	-
0.1 - 1	5 × 100	0	200
> 1	5 × 50	0	100

Procedure

The participants came for a full day. They came in pairs and took turns after each session. After arrival they were introduced to the general procedures of the experiment, and read and signed an informed consent. During the morning they were trained on the task and the simulation environment. This training consisted of four 20-minutes sessions for each participant, with full and night vision, with and without the CMT, and with the different versions of the tactile instrument. During the afternoon, each participant flew six scenarios in a full factorial vision (full / night) × tactile instrument (none / simple / complex) design. The order of the conditions was balanced over subjects. During the middle 120 s of each scenario, the CMT was presented. After each scenario, the participant filled out the Rating Scale Mental Effort (Zijlstra & Van Doorn, 1985).

7.2.3 Results

Each run was divided in a slot with and a slot without the additional mental workload task CMT. Before analyses were performed, all measures were inspected for outliers and possible anomalities. None were found. We used individual ANOVAs for the two flight performance measures with a Vision (full vision / night vision) × Tactile display (none / simple version / complex version) × CMT (absent / present) design. For the CMT data and workload ratings, we used individual Vision (full vision / night vision) × Tactile display (none / simple version / complex version) ANOVAs. The Tukey HSD test with alpha set at .05 was applied for post-hoc analyses.

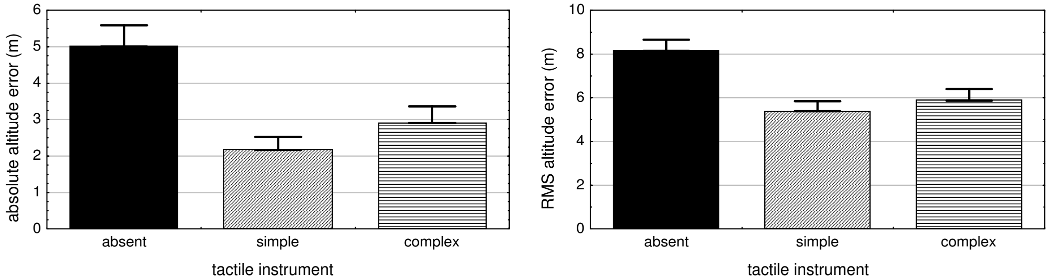

Figure 7.3. Main effect of the tactile instrument on the absolute altitude error (left) and the RMS altitude error (right). Error bars denote the SE of the mean.

The analysis of CMT performance showed no significant effects. The analysis of the absolute altitude error resulted in significant main effects of the Tactile display, $F(2, 22) = 7.21$, $p < .01$, and the presence of the CMT, $F(1, 11) = 6.92$, $p < .03$. The main effect of Tactile display showed that the tactile instrument reduced the altitude error (see Figure 7.3, left). In the no instrument runs, the mean absolute error was 5.2 m. The simple version reduced this error with 57% to 2.2 m, the complex version with 42% to 2.9 m. The CMT main effect showed that the error increased from 2.6 to 4.1 m when the CMT was present, compared to CMT absent. There were no significant interactions on the absolute altitude error. The analysis of the RMS altitude showed the same main effects: Tactile display, $F(2, 22) = 7.42$, $p < .01$, and CMT, $F(1, 11) = 9.40$, $p < .02$. Again, the tactile instrument significantly increased performance (see Figure 7.3, right). Compared to no tactile instrument, the simple version reduced the RMS error from 8.1 to 5.4 m (33 %), the complex version to 5.9 m (27 %). No interactions were significant. The subjective mental effort rating only showed a main effect of Vision. Night vision was rated higher than full vision.

7.2.4 Discussion and conclusions

The results show that the tactile instrument greatly improves performance. The mean reduction of the absolute altitude error is 50%, in other words: adding the tactile instrument halves the altitude error compared to no instrument. This result is also present for the RMS altitude error, although the reduction here is in the order of 30%. There is a weak indication that the simple version of the tactile instrument results in better performance than the complex version, although the differences are not significant. Apparently, the advantage of the complex version (i.e., adding information on the current motion direction) does not outweigh potential disadvantages. One such disadvantage may be the complexity of the coding. Two issues are important in this respect. The first is that the skin tends to integrate spatiotemporal patterns into one percept (e.g., Geldard, 1982; Van Erp, 2002a). This may result in a percept that differs from the objectively presented multiple stimuli. The second is that multiple signals (i.e., desired direction and current motion direction) may result in what we call tactile clutter. This means that cognitive processing may be needed to separate different signals that are presented simultaneously or closely in time. We will further discuss this issue in the general discussion.

Besides the main effect of the tactile instrument, we were interested in two potential interactions. The first was with the quality of the visual information. We hypothesized that the positive effect of the tactile instrument would be larger when the visual information would be degraded. However, the data cannot substantiate this hypothesis. Because of the main effect of Tactile display, this implies that the tactile instrument is not only useful in degraded visual conditions, but even under optimal visual conditions. The second interaction we hypothesized was that the tactile instrument would make the pilot's performance less

affected by additional cognitive load. However, this Tactile instrument × CMT interaction was not significant. The hypothesized effect might have been present when the comparison was made with a visual display that presented altitude information in an abstract form (e.g., numerical). However, the visual information in this experiment was direct view, which can hardly be called abstract (Gibson, 1950). We will look into this issue further in the next experiment.
The mental effort ratings did not reveal an increased rating due to adding the tactile display. This means that adding the tactile instrument improves performance without increasing the subjective mental effort. Based on these results, we can conclude the following:

- a tactile display can also present information on the third (i.e., vertical, altitude) dimension,
- adding a tactile instrument reduces the altitude error in a low level flight (in the present experiment by 50%),
- the tactile instrument is powerful enough to support the pilot under degraded and under full vision conditions,
- adding information on the current motion direction to the tactile display does not improve performance compared to a tactile display with setpoint information only,
- adding the tactile instrument does not affect the subjective mental effort of the pilot.

7.3 Experiment 11: Tactile helicopter hover display

7.3.1 Introduction

The previous experiment showed that a tactile display can also support local guidance in the third dimension. In the present experiment, the altitude display is integrated with a display that presents direction in the horizontal plane, resulting in a 3D tactile display. We test this in a helicopter hover task (see also Raj, Kass & Perry, 2000). In a hover task, the pilot has to keep a fixed position in 3D space, compensating for drift of the helicopter. This drift can be the result of external disturbance such as wind, but can also be induced by the pilot himself. The experimental setup is similar to that of the previous experiment. Trials are completed under different levels of cognitive load and with full day view or simulated night vision goggles. The reduced visual information when flying with NVGs (quantitatively as well as qualitatively) may result in degraded motion perception. As a result, a rotary wing aircraft may drift substantially without the pilot detecting motion or a changed position. We also tested a simple and a complex version of the tactile instrument, although we found no indications in Experiment 10 that the additional speed information in the complex version improved performance. The absence of an advantage may have been caused by the fact that the vertical speeds were relatively large and easily perceived visually. However, in hover situations, the speeds are expected to be much lower and possibly below the visual detection threshold (especially with degraded visual information).

Specific hypotheses for this experiment were the following:

- Our expectation was that the tactile display would improve the performance when flying with NVGs, but has no or only a small effect under full vision (with or without instruments).
- We expected that the presence of a tactile display would make performance not or less affected by cognitive load.
- We expected the complex version to be of added value because the speeds are low in hover tasks, and may even be below the visual detection threshold.

7.3.2 Method

Experiment 11 in a nutshell.

- 12 student pilots flew in a helicopter simulator. They performed a helicopter hover task at a 15 m altitude. They could be supported by a simple tactile display that indicated the instructed position by a vibration on the shoulders or under the thighs (vertical) and/or in a belt around the torso (horizontal) (simple variant), or by a complex tactile display that indicated the instructed position and the motion direction of the helicopter. They completed trials in simulated daytime and at night with simulated night vision goggles. During half of a trial, a secondary mental workload task was added. The pilots completed the rating scale mental effort (RSME) after a trial.
- The independent variables were the type of support (no support, simple display, complex display), visual conditions (day, night), and the presence of the secondary task (present, absent).
- The dependent variables were the mean and RMS hover error (vertical and horizontal), secondary task performance and the scores on the RSME.

Participants

Twelve participants flew in a rotary wing simulator. They were students of the Royal Dutch Airlines Flight Academy (KLS). Their mean age was 22.4 years, their mean flying experience was 160 hour (range 110 - 200 hours). They had no particular experience with helicopter hovering. They were paid the equivalent of €50 for their participation.

Task and simulator

The instruction was to hold a specific position in 3D space. Each trial consisted of an initial stage (30s) and a recording stage (120s without a secondary task, 120s with a secondary task, see below). At the beginning of each trial, the helicopter was at ground level. The instructed altitude was 15 m. During the initial stage, the altitude was presented as a head-up display so the pilot could easily reach the instructed altitude. Directly after the 30 s initial stage, the altitude error was switched off (other out the window cues remained available) and the recording stage started. The altitude set point for the recording phase was the instructed altitude (15 m), the horizontal set point was the horizontal position at the onset of the recording phase.

The flight simulator consisted of a helicopter mock-up with full controls and a cylindrical dome measuring 140° × 40° of visual angle. The helicopter model was a simplified, linearized helicopter model, fine-tuned by an experienced Cougar pilot. Three Evans & Sutherland® Simfusion image generators generated the visuals. NVG vision was simulated by the image generators (in hardware). In the NVG conditions, the participant wore field size restricting goggles (field size 40°, 100% overlap, no optics). During the second half of each hovering phase, the participant performed a secondary task: the auditory continuous memory task (CMT), see Experiment 10.

Based on the data stored by the helicopter simulator, we calculated the absolute altitude error (m), and the absolute error in the horizontal plane (m). Each run was divided in a slot with and a slot without the additional mental workload task CMT. The CMT data were used to calculate the RT (s) to the double clicks and percentage correct responses. The fifth dependent variable was the subjective workload rating.

Tactile display and information presentation

The tactile hardware was the same as used in Experiment 10: a 64-element tactile display in 12 columns and five rings, and with tactors on both shoulders and under both thighs. As with the altitude display in Experiment 10, we implemented two variants of the tactile hover display. The simple tactile display variant presents information on the direction of the drift (error) only. The complex variant presents error information as well as additional information on the current direction of motion (see Figure 7.4). The pulsing rhythm of the tactors was dependent on the size of the error. For errors smaller than 1 m no signal was given, for errors between 1 and 5 m the rhythm was 100 ms on - 200 ms off, for errors larger than 5 m the rhythm was 50 ms on - 100 ms off. The motion direction signal consisted of five (discrete) steps in the direction of motion. The onset of the next element coincided with the offset of the former element with a pause between the last burst and the onset of a new series. Burst duration and pause were speed dependent. Details of the timing parameters of the signals can be found in Table 7.2.

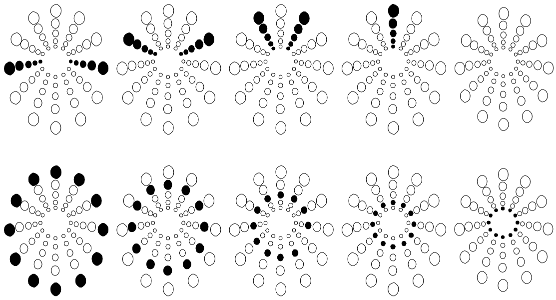

Figure 7.4. Schematic top-down perspective view of the 5 rings and 12 columns of the tactile display. The pictures in each row depict the different frames of the tactile motion patterns. The upper row presents a direction forward (to be read from left to right), the lower row downwards (to be read from left to right).

Simple version

The simple version only presents information on the direction of the set point (i.e., the origin in 3D space) by activating single points of the display. Important here is that this coding unambiguously indicates the optimal direction of motion, while the virtual wall analogy (see Experiment 10) only indicates the direction to avoid. The latter leaves the pilot with the choice to determine the optimal steering action (many motion directions will free the pilot from the wall, of which the 180° opposite (mirrored through the body midaxis?) is the optimum). The desired motion in the vertical dimension was indicated by activating elements under the thighs and on the shoulders (for a set point below and above the current altitude, respectively, see previous experiment), the desired motion in the horizontal plane was indicated by one of the tactors in the middle ring.

Complex version

In the complex version, the motion direction is added to the indication of the direction of the set point presented as in the simple version. Similar as in Experiment 10, motion was not presented by single points, but by an (apparent) motion across the torso. This was implemented in the horizontal plane by two points that move symmetrically toward the direction of motion (e.g., when moving forward, the points would start at the left and right side and move forward to meet right in front; when moving to the left, the points would start on the spine and on the navel and move simultaneously to the left. Combined with the coding of the desired direction, moving in the right direction means that the motion points end in the point that indicates the direction. As long as these points do not coincide, the pilot moves in the wrong direction.

Table 7.2. Details of the timing parameters for the direction and motion signal in Experiment 11.

direction of the target altitude		
deviation (m)	burst duration (ms)	inter burst interval (ms)
< 1	-	-
1 - 5	100	200
> 5	50	100

current motion direction			
absolute speed (m/s)	burst duration (ms)	inter burst interval (ms)	pause between signals (ms)
< 0.1	-	-	-
0.1 - 1	5 × 100	0	200
> 1	5 × 50	0	100

Procedures

The participants came for a full day. They came in pairs and took turns after each session. After arrival they were introduced to the general procedures of the experiment. During the morning they were trained on the task and the simulation environment. This training consisted of four 20-minutes sessions for each participant, with full and NVG vision and with and without CMT. During the afternoon, each participant flew three blocks of two runs. Each run took 13 minutes net flying time, after which the participant filled out the Rating Scale Mental Effort (Zijlstra & Van Doorn, 1985).

7.3.3 Results

After initial inspection of the data, all data were judged valid and the dependent measures were analysed by individual ANOVAs. The two flight performance measures with a Vision (full vision / night vision) × Tactile display (none / simple version / complex version) × CMT (absent / present) design. For the CMT data and workload ratings, we used individual Vision (full vision / night vision) × Tactile display (none / simple version / complex version) ANOVAs. When appropriate, results were further analysed with Tukey HSD tests with alpha set at .05. The statistical design and ANOVA are presented for each measure separately.

Hover performance, horizontal error

The position error in the horizontal plane showed several main effects and two-way interactions. The main effects of Vision: $F(1, 11) = 93.35$, $p < .01$ and CMT: $F(1, 11) = 57.34$, $p < .01$ showed that performance degrades with night vision and during the CMT phase, respectively (the means can be deducted from the left panels in Figures 7.5 and 7.6). The interaction between them showed that the effects strengthen each other: $F(1, 11) = 53.27$, $p < .01$. Of primary interest however, were the main effect and interactions with the tactile display. The main effect showed performance improvements with the tactile display: $F(2, 22) = 5.88$, $p < .01$. The simple variant reduces the error with 27%, the complex variant with 25%, compared to the no-display condition. The non-significant interaction between Vision and Tactile display (depicted in the left panel of Figure 7.5, $F(2, 22) = 1.05$) showed that both tactile displays reduced the position error considerably compared to the no-display condition, not only in the night vision condition (mean reduction 22%), but also in the full vision condition (mean reduction 32%).

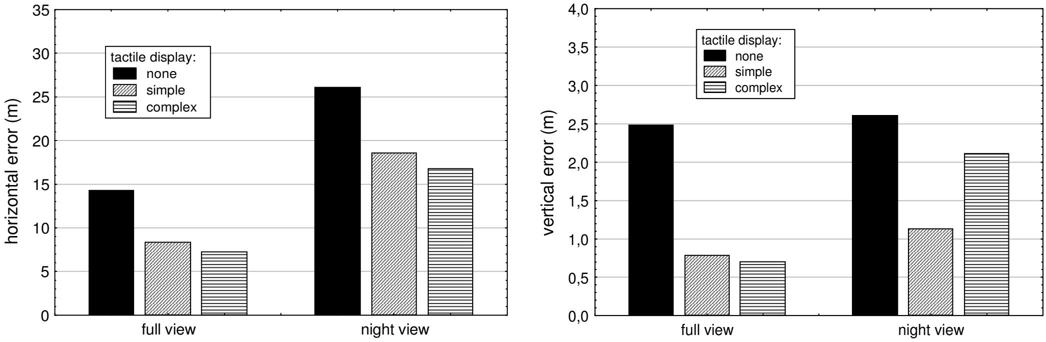

Figure 7.5. Error as function of visual and tactile display condition. Left on the horizontal error, right on the vertical error.

The interaction between CMT and Tactile: $F(2, 22) = 45.67$, $p < .01$ showed that there is no effect of the tactile displays in the phase before the CMT task, and a large error reduction (35%) during the CMT phase (see the left panel of Figure 7.6).

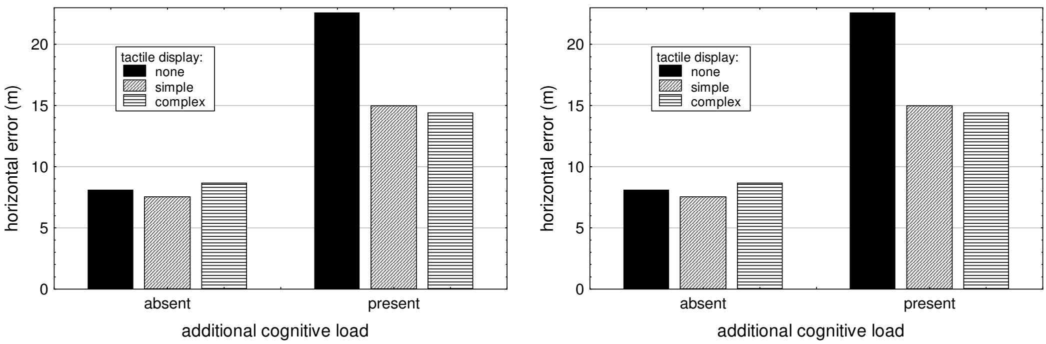

Figure 7.6. Significant interaction of the presence of the secondary task and tactile display on the horizontal (left) and vertical error (right).

Hover performance, vertical error

On the vertical error, the effects were as follows. The main effect of CMT: $F(1, 11) = 5.52$, $p < .04$ showed degraded performance during the phase with the CMT compared to without the CMT (means 1.78 and 1.17 m, respectively). The main effect of Tactile display: $F(2, 22) = 16.06$, $p < .01$ showed an error reduction of 55% for the simple variant and 47% for the complex variant, compared to performance without a tactile display. The non-significant interaction of Vision and Tactile display: $F(2, 22) = 1.58$ indicated an error reduction both with NVG vision and full vision (see Figure 7.5, right panel). The interaction of Tactile display and CMT was significant: $F(2, 22) = 3.66$, $p < .05$ and is depicted in the right panel of Figure 7.6. This interaction showed that the error reduction of the tactile displays is larger in the CMT phase than in the phase before the CMT.

Performance on the secondary (CMT) task

There were no effects on either the reaction time (mean 900 ms) or the percentage correct (mean 90%).

Mental effort rating

The mental effort rating showed a significant effect of Vision ($F(1, 11) = 7.18$, $p = .021$). The means showed a higher mental effort with night vision compared to full vision (means 57.8 and 48.4, respectively).

7.3.4 Discussion and conclusion

The first observation is that both tactile display variants improve the performance on the horizontal as well as the vertical dimension. Compared to the no-display condition, the simple variant reduces the horizontal error with 27% on average and the vertical error by 56% on average. For the complex variant, these reductions are 25% and 47%, respectively. The various interactions provide further insight into the effects of the tactile display. We will discuss them in relation to the objectives and hypotheses.

The first objective of the present study was to investigate if a tactile display can help to compensate for the degraded visual information when flying with Night Vision Goggles. We expected a positive effect under degraded visual conditions, but no effect in the full vision condition. However, the tactile display resulted in large performance improvements in both the night vision and the full vision conditions. This is actually better than hypothesized: it shows that the positive effect of the tactile display is so strong that it can even support the pilot under full vision condition.

The second manipulation was the presence of a secondary task (Continuous Memory Task, CMT). For both the horizontal and vertical error, there is a significant interaction between the tactile display and the presence of the CMT. The results confirm the hypothesis that the presence of a tactile display reduces the negative effect of adding a secondary task on performance. Without a tactile display, adding a cognitive task results in a factor 2.8 increase of the horizontal error and a factor 1.8 of the vertical error. With a tactile display, these factors are only 1.8 and 1.3, respectively. This indicates that a tactile display (or actually adding information) reduces, but not nullifies, the negative effects of an increased cognitive load. Furthermore, although the tactile display increases the amount of information to be processed, the mental effort ratings show that this is not at the cost of higher mental effort. These results partly confirm our hypotheses that a tactile display would result in low workload ratings and make performance independent of cognitive load.

The results also show that the differences between the simple and the complex variant are small. Both displays show the same effect on the horizontal error. On the vertical error, the complex variant shows the tendency to be somewhat less effective than the simple variant. This confirms the results of the previous (altitude control) experiment, where we found a weak indication that the simple version of the tactile instrument results in better performance than the complex version, although the differences were not significant.

Conclusions
This simulator study proves the potential of intuitive tactile torso displays in reducing drift. The tactile display is so effective that it not only results in performance improvement under reduced visual condition, but also under full vision conditions. Also, the presence of the tactile display reduces the performance degradation caused by a secondary (cognitive memory) task. There is no effect of the tactile display on the subjective mental effort rating.
Moreover, the results prove that tactile displays can be applied in fast man-in-the-loop tasks. Finally, advanced tactile displays that are able to present more complex stimuli open up new possibilities of information presentation. This can possibly improve performance, but may also introduce tactile clutter.

7.4 General discussion and conclusion

Q9. Main effect of the tactile display on performance

In Chapter 6 we found that tactile displays can improve performance in 2D waypoint navigation. In this Chapter we investigated whether this favourable effect would also be present for the vertical dimension. Please note that we did not investigate this dimension in the direction perception experiments in the earlier chapters. The first experiment investigated the effect of presenting vertical information on a tactile display in a low level flight. On average, the performance improvement with the tactile display was 50%, that is, the tactile display halved the vertical error. In the Experiment 11, we integrated this 3rd dimension display with the 2D display tested in the previous chapters and tested it in a 3D helicopter hover task. Again, we found that the tactile display can substantially reduce the hover error. In the vertical dimension, the error reduction is 50%, confirming the results of Experiment 10. In the horizontal dimension, the error reduction is in the order of 25%. In general, these performance improvements are present across different visual and workload conditions. Based on these results we conclude that the transition to 3D environments was successful.

Q7. Effect of the tactile display on mental effort ratings

One of the predictions of the prenav model (see Figure 1.5) is that processing information through the sensation→action loop shortcut does not consume cognitive resources. The mental effort ratings would be low, and lower than for the processing of information that requires the involvement of the cognitive ladder. Therefore, we hypothesised that if a tactile display enables the use of the sensation→action loop while a visual display does not, the mental effort ratings for the trials with a tactile display would be lower for the trials with a visual display. In the present experiments, we cannot directly test this hypothesis because we do not compare a visual and tactile display (like in Experiment 8 in Chapter 6). However, prenav would also predict that adding a tactile display would not affect the mental effort rating. We can test this prediction. The data from both experiments confirm this prediction: adding the tactile display does not affect the mental effort ratings. The fact that the out-the-window visuals (i.e., day versus night) does affect the ratings in both experiments shows that the RSME as instrument was sensitive enough to measure differences in workload ratings over conditions. These findings are supported by anecdotal evidence from tens of pilots that tried tactile display demonstrations. After a few minutes of trying, they use the tactile display information almost unconsciously while the experimenter tries to distract the pilot and sometimes even switches off the visuals.

Q8a. Effect of adding cognitive load with and without a tactile display

The prediction of the prenav model with respect to this issue in its strictest form is clear: An intuitive tactile display makes the user immune to enlarging the cognitive load. In the present experimental designs this should be reflected in the interaction of the presence of the tactile display with the presence of the additional CMT task. In Experiment 10, this interaction is not significant, indicating that the negative effects of the CMT were present regardless whether the tactile display was present or not. In Experiment 11, this interaction reaches significance for both the horizontal and the vertical error. The results show that adding the CMT results in a substantial performance degradation when the pilot has no tactile display (on average 130%). The degradation can also be seen in trials where the tactile display is available, but the degradation is much smaller (on average 56%). We have no clear explanation for the apparent contradiction between both experiments. The results of both experiments are not in accordance with the strict definition of an intuitive display. The results of the second experiment fit with the weaker variant based on the perception→action shortcut instead off the sensation→action shortcut (see Chapter 1). Three issues are relevant. The first is that pilots need instruction that explains what the instrument indicates. Albeit short (usually just one line), it means that the response is not based on reflexive behaviour. This links to the issue of information coding on a tactile instrument (see also Chapter 8). In the current instrument, we decided to code the setpoint (or origin) and not a 'virtual box' (cref. Section 7.1). However, the latter coding was successfully implemented in the TSAS hover device (Raj, Suri, Braithwaite and Rupert, 1998). Dobbins and Samway (2002a) mention this same coding issue in coding a virtual corridor on a tactile display to support course control in operating high speed powerboats. Anecdotal evidence gathered with the tactile display indicates that there is no population preference for one coding; the preference is about 50-50 (see Van Erp & Oving (2002) for control display compatibility and population preferences). This may indicate that the instrument requires involvement of the cognitive ladder to interpret the sensation into a percept for 50% of the population. The second issue is that even at the end of the experiment, the pilots have only a limited experience with the instrument, far from enough to claim that they are highly trained. Third issue is that the participants were student pilots. It may have been the case that they were not experienced enough to enable vehicle control though the sensation→action loop, making vehicle control dependent on the cognitive loop. Also relevant is that the tactile display codes the (required) vehicle movements, but not the manual control actions (especially with the complex version). An alternative that may have a different effect is to code required actions, for example by attaching vibrators to the hand.

Q8b. Effect of adding external stressors with and without a tactile display

Operating at night wearing night vision goggles is considered as an external stressor. This makes it relevant to discuss the results of this stressor in the presence and absence of the tactile display and in relation with the prenav predictions. In the present experimental setup, this effect should be reflected in the interaction of the presence of the tactile display with the visual condition. However, we should take care in interpreting the results. Wearing NVGs is not only an external stressor, it also affects the quality and quantity of the information required for the primary task. In Experiment 10, there is -rather surprisingly- no effect of the vision condition on control performance. In Experiment 11, the NVG visual condition does result in performance degradation for the horizontal dimension, but (again) there is no effect for the vertical dimension. This is probably related to the fact that the reduction in field size as consequence of wearing the simulated NVGs differs between both dimensions. The full horizontal (screen) fieldsize of 140° is reduced to 40°, while the vertical (screen) fieldsize of 40° is not further reduced by the field restricting goggles. On none of the performance measures, there is a significant interaction as hypothesised. This actually means that the tactile display improves performance in both vision conditions, that is, under conditions of restricted visual information, but also in full vision.

Simple vs. complex tactile display

In both experiments, the simple display variant performed equally good or better than the complex variant. Several aspects are relevant here: (1) the usefulness of the extra information that the complex variant presents (i.e., information on the current motion direction) (2) the interaction between tactile signals, which we call tactile clutter and (3) the extent to which the presentation or coding is intuitive. When the benefit of the additional information (1) is smaller than the costs involved (2) and (3), the complex variant may lead to worse performance than the simple variant. We hypothesise that the critical factor in the present design is tactile clutter. Although the skin is able to process large amounts of (abstract) information the complex variant may have suffered from the interaction between signals. Adding a moving stimulus may result in a cacophony of tactile stimuli that may result in unpredictable spatiotemporal interactions. Also, the moving stimuli require 5 ‘frames’ to be played, and thus lower the update rate of the information. The resulting tactile clutter may also degrade the intuitiveness of the signals; i.e., some form of processing is required to separate the different components. This latter is confirmed by the data of Experiment 11. The interaction between tactile display and CMT task shows that with the secondary task present, performance with the simple variant is better than with the complex variant. This indicates that the complex variant has a claim on some form of the higher order processing resources also required for the secondary task. In terms of control input, the additional information can only be used indirectly: when the motion is not yet in the direction of the waypoint, control input needs to be maintained or increased and v.v.

Conclusions

The most prominent result of the current experiment is that the added value of the tactile display in the horizontal dimension is also present in a 3D situation. Adding the tactile display greatly reduces the hover error under conditions of full and reduced vision and under condition of increased workload. This improvement is not accompanied by an increase in mental effort ratings. However, we cannot conclude that the tactile display was fully intuitive because it does not make the pilots completely immune to an added mental workload. However, in Experiment 11, the degradation caused by increasing the mental load is much reduced when the pilot has a tactile display at his disposal. The issue of tactile clutter becomes relevant in situations in which multiple tactile signals are presented simultaneously instead of serially.

Chapter 8. Orientation in 2D[29]

Abstract

We investigated the effectiveness of a tactile torso display as a countermeasure to Spatial Disorientation (SD). Additionally, we tested whether the display should follow an inside-out or an outside-in coding. Twenty-four subjects participated, 12 in each coding group, matched for age and gender. We used a rotating chair to build up a state of SD by rotating participants around their yaw axis followed by a sudden stop. During the following recovery phase a random disturbance signal was added to the chair's orientation. Participants actively controlled their orientation and were instructed to maintain a stable orientation which is a compensatory tracking task. Statistical analysis revealed that recovery from SD (measured as the number of turns in the recovery phase) substantially increased and that tracking performance decreased with the tactile instrument (both p's < .001), whether the instrument was available full time or during the recovery phase only had no effect. There were no differences between outside-in and inside-out coding. The present study demonstrates the potential of tactile cockpit instruments in controlling SD, even in the presence of strong, but misleading self-motion information from the vestibular sense.

[29] Parts of this Chapter have been published as:

Bos, J.E., Van Erp, J.B.F., Groen, E.L.& Van Veen, H.A.H.C. (2005). Vestibulo-tactile interactions regarding motion perception and eye movements in yaw. *Vestibular Research*, *15*, 149-160.

Van Erp, J.B.F., Groen, E.L., Bos, J.E. & Van Veen, H.A.H.C. (2006). A Tactile Cockpit Instrument Supports the Control of Self-Motion During Spatial Disorientation. *Human Factors*, *48 (2)*, 219-228.

8.1 Introduction to Experiment 12: Self-motion during spatial disorientation

The previous two Chapters described tactile display applications related to translations in 2D and 3D. This Chapter and the next are concerned with rotations in 2D and 3D. Rotations seem of minor importance in daily life: we usually stand straight and steady on our legs (this is not so trivial for people with a vestibular dysfunction[30]), and see where our nose is pointing. However, knowing how you are oriented in the world, and knowing up from down is of critical importance if you are a diver, pilot, or astronaut. Spatial Disorientation (SD) is a serious threat to military as well as to civilian pilots and aircraft. Considerable effort has been put into SD countermeasures such as training programmes and advanced cockpit displays. With regard to the latter, tactile displays have been considered a promising technology (Rupert, Guedry & Reschke, 1993; Benson, 2003).

Besides the arguments of the threat of sensory and cognitive overload, which are certainly relevant for pilots, there is an additional argument why tactile displays are considered a promising technology to counteract SD. In an SD situation, the pilot should rely on his instruments to take the necessary action irrespective of his (vestibular and other) self-motion sensations (see also Gillingham & Wolfe, 1985). Here, tactile and auditory stimulation may be superior over visual aids, because with strong rotations, the flight instruments may be difficult to read due to the Vestibulo-Ocular Response (VOR)[31]. This response aims at stabilising the direction of gaze in an Earth-fixed frame of reference, thus not necessarily in a cockpit frame of reference. This may cause the eyes to move across the flight instruments, making the flight instruments unreadable and incapacitating the pilot. Also, the advantage of a tactile over a visual display may be present under high G-load (cref Chapter 10): As far as we can tell, tactile information processing is not altered by G-loads at which visual information processing deteriorates. Although Rupert (2000a, b) reported anecdotal evidence on the potential of tactile torso displays as SD countermeasure, quantitative data gathered under controlled SD situations are not available yet.

A complicating factor when designing SD countermeasures is that SD is often caused or accompanied by confusing information from the vestibular sense. This is for example the case with motion illusions related to the semicircular canals, generally known as "somatogyral" illusions. In aviation, this illusion is responsible for the so called "graveyard spin" (Roscoe, 1997). The graveyard spin may result from inadequate recovery from an (asymmetric) stall (a situation where the wings no longer provide lift and the aeroplane starts spinning, primarily about its yaw-axis). When the pilot stops the spinning motion, the semicircular canals give a strong aftersensation, especially when recovery occurred after several spins (Bles, Kloren, Buchele & Brandt, 1983). In poor visual conditions, the pilot may then perceive spinning in the opposite direction, possibly accompanied by difficulties reading the cockpit instruments due to the VOR (Lessard, Stevens, Maidment & Oakley, 2000). By trying to cancel the vestibular sensation, the unaware pilot may re-enter the original spin. This may give the impression of straight and level flight, while in fact the aeroplane is spinning and losing height, which may lead to controlled-flight-into-terrain (CFIT). In the present experiment, we investigate the merits of a tactile torso display as SD countermeasure using a motion simulator to mimic a graveyard spin.

[30] One possible application of tactile torso displays is as balance prosthesis for people with a vestibular dysfunction (Kadkade, Benda, Schmidt & Wall, 2003; Wall, Weinberg, Schmidt & Krebs, 2001; Kentala, Vivas & Wall, 2003).

[31] (3D) Auditory displays may also be a possible solution, but fall outside the scope of this thesis (see Section 1.3).

8.2 Method

Experiment 12 in a nutshell.

- 24 participants performed an orientation task in a rotating chair. A state of Spatial Disorientation (SD) was evoked by a rotation around the yaw axis followed by a sudden stop. In the following recovery phase, participants had to retain a stable orientation while compensating for a disturbance added to the chair's orientation. A hood blocked visual cues. In half of the trials, they were supported by a tactile display consisting of a belt around the torso with 24 tactors displaying orientation information.
- The between subjects independent variable was coding of orientation on the tactile display. The within subjects independent variable was type of support (no support, support during the recovery phase only, and support during both the pre-SD and recovery phase).
- The dependent variables were recovery performance (defined as the number of turns made during the recovery phase), and control performance (calculated as the correlation between the disturbance signal and the control input).

Participants

Twenty-four employees of TNO Human Factors participated voluntarily, 9 female and 15 male, 34.1 ±12.1 years of age. They were assigned to one of two experimental groups: the inside-out or outside-in coding group (see below). The assignment was such that the two groups were matched on age and gender. All participants were naive with respect to the experimental set-up, the motion profiles, and the hypotheses. The participants were asked not to talk to their colleagues about the experiment until all participants finished the experiment.

Apparatus

The yaw rotation around an Earth vertical axis was generated by a rotating chair (see Figure 8.1). The participants were seated with their heads on the axis of rotation (i.e., with the axis of rotation through the centre of the line between both ears, resulting in minimal stimulation of the otoliths as result of the centripetal acceleration). The chair's velocity and position were measured separately by code disks and used servo control for the chair's rotational velocity (±1%) as well as for the control of the tactile display. During the pre-SD phase, chair velocity was increased during 24 s with a constant acceleration of 5°/s² up to 120°/s (either clockwise or counter clockwise). Immediately thereafter, the chair was brought to a standstill within 1.2 s (100°/s²) creating an SD situation. After 0.5 s of the standstill (part of the pre-SD phase) the recovery phase started. During the recovery phase, a quasi random angular velocity disturbance profile was presented, this was different for each of the 15 trials of a participant. Each disturbance profile consisted of a sum of 20 sinusoids with frequencies at equal intervals in the range 0.02-0.4 Hz but with random phases. Amplitudes were inversely proportional to frequency in order to ensure a constant maximum velocity contribution of each component. An interval of 40 s was chosen starting at zero velocity, and the amplitude of the disturbance signal was recalculated such that the RMS-velocity equalled 40°/s. On average, maximum velocity and acceleration over these 15 signals were 74 ±12.7°/s and 38 ±4.9°/s² (i.e., input to the chair). After 40 s, the chair was decelerated at 5°/s² to a standstill. All motion profiles were created with 50 samples per second, and filtered by means of a moving average over 0.5 s to avoid jerks around the phase transition.

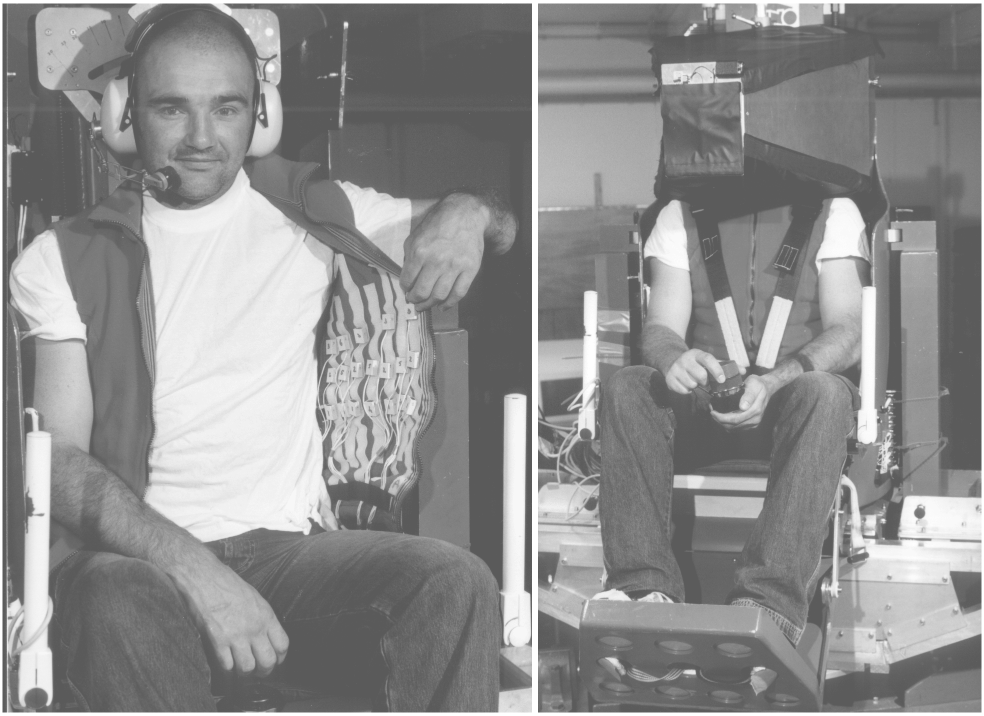

Figure 8.1. Left: the participant with unzipped tactile display showing the columns of tactile elements and the headset. Right: the situation during the experiment with the participant in the rotating chair holding the control dial. The visual cues were blocked by a hood.

During the recovery phase, participants had to nullify the chair's velocity by using a control dial. Dial position controlled chair velocity input, similar to a flight yoke. The dial consisted of two cylinders, approximately 7 cm in diameter and 4 cm high each, capable of unlimited rotation relative to each other about their longitudinal axis. Participants kept each part in one hand on their lap (see Figure 8.1, right). Clockwise rotation of the upper part corresponded to a clockwise change in chair rotation speed (180° of dial rotation resulted in a 180°/s change in chair rotation speed). The control dial's velocity signals were added to the disturbance signals and then sent to the chair. The dial output was set to zero at the beginning of the recovery phase. Combined with the unlimited rotation capability, this resulted in a control dial that provided no information with respect to zero chair velocity.

The complete experiment was controlled by a PC that generated the chair velocity signal for the pre-SD phase, as well as the disturbance signal for the recovery phase. During the recovery phase, control dial output was electronically added to the disturbance signal from the PC, the combined signal driving chair velocity. The PC also sampled (50 Hz) and stored the following signals: chair velocity control signal, chair position, chair velocity, activated tactile orientation, and dial-position.
Based on these data, two performance measures were calculated over the 40 s recovery phase: recovery performance and control performance. The recovery performance was calculated as the number of spins made in the recovery phase, indicating the inability to recover from SD (or the tendency to enter a graveyard spin). The control performance was calculated as the correlation between the chair disturbance

and the control input, which indicates the capability of counteracting the disturbance trace independent of a possible offset in angular speed when the participant is in a graveyard spin. Before being strapped into the chair, the participant donned the tactile display. During all runs the participant wore a headset that blocked auditory cues from the environment and allowed direct audio contact between participant and experimenter. A hood was placed over the head of the participant to block visual cues.

Tactile display and information coding

We implemented yaw rotation in the tactile display by a rotating signal around the observer in the horizontal plane. There are two important design parameters of the tactile instrument. The first concerns the coding of the rotation direction on the display (see also Section 7.2 on coding translations in 3D). Two different codings can be applied that resemble the inside-out and outside-in differences also recognised in the design of the artificial horizon display. Inside-out coding of yaw rotation can be realised by a tactile signal pointing to a fixed direction in the outside world. This means that the tactile signal rotates clockwise when the pilot rotates counter clockwise and vice versa. In the outside-in coding alternative, the signal rotates on the display in the same direction and with equal velocity as the pilot rotates in the outside world. The second design parameter concerns the phase during which the tactile instrument should be active. We discern two phases here: the first is the pre-SD phase in which the SD is set up, and the second is the recovery phase. Anecdotal evidence by Rupert (2000a, b) indicates that it may be advantageous to have the tactile instrument active during both phases.
The tactile display was worn over a T-shirt and consisted of 48 tactors in 24 columns of two tactors each. The columns were placed under equal angles of 15° (please note that equal distances would have resulted in different angles as the torso is not circular). Only one column (consisting of two tactors) was active at a time. A separate PC controlled the tactile display with the chair's position as input. The instrument had three modes: 'off' in which no signal was given, 'inside-out' in which the instrument presented an Earth fixed orientation (i.e., the plane through the body longitudinal axis and the active column pointed to a fixed point in the environment), or 'outside-in' in which the tactile signal rotated at the same angular velocity and in the same direction with respect to the observer as the observer with respect to Earth.

Experimental Conditions

During the experiment, each participant completed 15 trials; 6 main experimental trials and 9 control trials which included the measurement of eye movements. These control trials investigated whether a tactile instrument facilitates the generation of reflexive eye movements such as the Vestibulo-Ocular Response (VOR). However, these data are beyond the scope of this thesis and are presented elsewhere (Bos et al., 2005). Only one of the nine control conditions was relevant for the present research issues, since it provided relevant data on control performance. This was a "tactile only" condition where participants had to track the tactile signal in the absence of any chair motion (without chair motion, the disturbance is only presented on the tactile display, like the tracking tasks in Experiment 6). The order of the six experimental trials was balanced for all participants. The control condition was always run after the main experiment.
The experiment was focussed on the two design parameters discussed in the Introduction: Coding (inside-out and outside-in) being a between-subjects independent variable, and Instrument Mode (off, recovery phase only, pre-SD and recovery phase) being a within-subjects independent variable. For each level of Instrument Mode, a clockwise and a counter clockwise trial were completed. The experiment was designed to investigate the following three questions: 1) Does a tactile instrument support the operator in recovering from SD? 2) Is there a performance difference between inside-out and outside-in coding? And 3) Is it beneficial to activate the instrument during the pre-SD and the recovery phase compared to during the recovery phase only?

Procedures

The purpose of the experiment was explained to the participants beforehand, and they signed an informed consent. They first received instructions about the required tasks and the commands that would be used during the experiment. After this, electrodes for eye movement recording were positioned (see Bos et al. (2005) for the eye movement data), and the participant donned the tactile vest and was seated and strapped in the rotation chair. With the tactile instrument off and the room lights on, they were trained on using the control dial. They were initially allowed to familiarise themselves with it, driving their own velocity, followed by specific instructions for motions and positions to be realised. Then they were (repeatedly) subjected to a disturbance trace as used in the recovery phase, and they practised maintaining a constant position (i.e., compensating for the disturbance trace), until they reached an average velocity of less than 20°/s during at least 10 s. Next, they were explicitly told about the operational mode of their tactile vest (either inside-out or outside-in). The operation of the tactile display was demonstrated first by rotating the chair passively in the light with the vest active. During this phase it was also checked that the participant perceived all columns. Then, the participants were again instructed to position themselves in several orientations by means of the control dial, but now by taking the tactile instrument into account. This was first done with the eyes open, and next with the eyes closed until this could be completed. Lastly, it was explained to them that they should consider the tactile display as a cockpit instrument on which they could and should rely. During the experiment the participant and the experimenter communicated via the headset. The experimenter gave the command that indicated the start of the recovery phase. The instruction was to set and keep the chair velocity at zero, irrespective of its orientation. A rest period was included between the trials so that any possible rotation sensation could disappear. The whole testing session lasted approximately one hour per participant.

8.3 Results

None of the participants experienced sickness or was unable to complete the experiment. Before being subjected to analyses of variance, we inspected the data for irregularities such as outliers. No abnormalities were found, so we included all data in the analyses. The two performance measures were analysed with separate ANOVAs.

Main experiment

The main experiment was analysed in a Coding (inside-out, outside-in) × Instrument Mode (off, recovery phase only, pre-SD and recovery phase) × Direction (clockwise, counter clockwise) design. Both the recovery and the control performance demonstrated a main effect of Instrument Mode only: $F(2, 44) = 242.21$, $p < .001$, and $F(2, 44) = 10.29$, $p < .001$ for the recovery performance and the control performance, respectively. There were no significant effects of Coding, $F(1, 22) = 0.57$, and $F(1, 22) = 0.27$, respectively, and of Direction: $F(1, 22) = 1.46$, and $F(1, 22) = 1.57$, respectively. The main effect of Instrument Mode was further analysed by a post hoc Tukey HSD test with alpha set at .05. For both performance measures, the off mode differed significantly from both the recovery phase only and the pre-SD and recovery phase conditions. There were no differences between the latter two modes. The means are depicted in Figure 8.2 for the recovery performance and Figure 8.3 for the control performance.

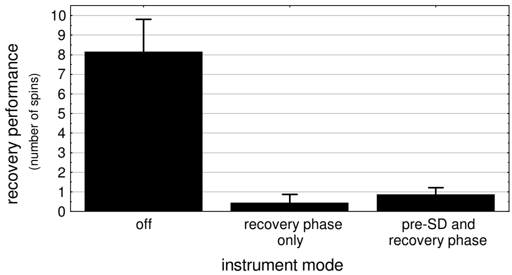

Figure 8.2. Main effect of Instrument Mode on the recovery performance (i.e. number of spins in the recovery phase). Lower values correspond to better performance.

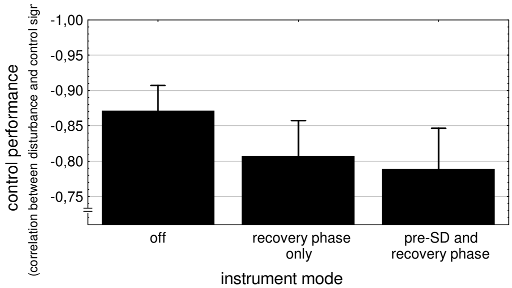

Figure 8.3. Main effect of Instrument Mode on the control performance. Values closer to -1 indicate better performance.

Control condition

Since the number of spins (i.e., the recovery performance) is meaningless in the control condition in which the signal was presented to the tactile instrument and the rotation chair was fixed, we only analysed control performance. We found a significant effect of Coding: $F(1, 22) = 5.92$, $p < .025$. The mean in the inside-out condition was -.57 (± .13) and in the outside-in -.79 (± .13).

8.4 Discussion and conclusion

Recovery from SD

The present experiment investigated the potential of a tactile cockpit instrument to counteract SD. We induced SD in observers by a sudden stop after a period of rotation around the Earth vertical yaw axis. This gave a strong aftersensation of spinning. During a 40 s recovery phase, the instruction was to minimise the yaw rotation while a disturbance motion was added. We measured recovery performance, expressed as the number of spins that were made during the recovery phase. The three main questions were the following: 1) Can a tactile instrument support recovery from SD? 2) Is there a performance difference between outside-in and inside-out coding of yaw rotation? And 3) Is it important that the tactile instrument is also active during the pre-SD phase? The results clearly indicate that a tactile instrument can support recovery from SD, or even prevent SD (in this case the simulated graveyard spin) to occur. As Figure 8.2

demonstrates, participants entered a (graveyard) spin when there was no support of the tactile instrument; during the 40 s recovery phase they made on average more than 8 full rotations (which equals a mean velocity of about 70°/s). When the tactile instrument was active, the number of spins was less than 1. This indicates that the potential magnitude of the effect of the tactile instrument may be sufficient to significantly reduce pilot error in a critical manoeuvre.

The results also demonstrated that there is no difference between inside-out and outside-in coding. This means that for the task of counteracting SD, both codings are equally strong in supporting the user. Both codings have potential advantages. An important advantage of the inside-out coding is that the position of the tactile signal on the display is Earth-fixed and thus also congruent with out-the-window visual information. This may have beneficial effects on the situation awareness of the pilot. The outside-in coding may have benefits in control tasks (see the section on control performance below). As with visual displays (Previc & Ercoline, 1999), the preferred coding on the tactile display is most likely task dependent. It should be noted that the lack of guidelines on the design of tactile cockpit displays has already resulted in the use of different coding principles in the design of a helicopter hover display (cref. Chapter 7). Although there are no data available that directly compare performance with both codings, one may expect that performance may degrade if the pilot has to switch between codings. This latter issue is also found with pilots who transfer from an outside-in to an inside-out coding of the artificial horizon (Pongratz, Vaic, Reinecke, Ercoline & Cohen, 1999).

The results also answer the third question. There was no advantage when the instrument was always on versus only during the recovery phase. This indicates that, for rotation about a vertical yaw-axis, the tactile signals are picked up fast once they start and that there is no explicit need to have the instrument running during the pre-SD phase[32]. This is not in accordance with the observations of Rupert (2000a, b). This may be due to the fact that Rupert used much more complex situations of SD (recovery from unusual attitude). This is an important observation, because a constantly active tactile instrument may have several disadvantages, including effects of adaptation of the skin to prolonged vibrotactile stimulation (e.g., Hahn, 1966), and probably reduced attention to tactile signals (called habituation). When the pilot chooses to have the instrument standard off, an important question is when it should become active. This is especially important in case of unrecognised SD (type I; Gillingham, 1992). The pilot will not switch on the instrument when being unaware of being disoriented. In this situation, it would be beneficial to activate the instrument automatically, for example based on the flight manoeuvre or profile when this is known to cause SD, based on the eye movements of the pilot (e.g., when detecting nystagmus), or based on an insufficient instrument scan pattern of the pilot. An alternative may be to include the tactile instrument in the instrument scan pattern of the pilot. This means that the pilot switches the instrument on at specific intervals.

Control Performance

Besides the ability to recover from SD, we also analysed control performance. Participants had to nullify a disturbance signal during the recovery phase. The results indicate that control performance is degraded by adding the tactile instrument (see Figure 8.3). This confirms the findings in Chapter 5, Experiment 6 that a tactile torso display is not optimally suited for tracking tasks (especially not when the resolution of the display is low, see the control experiment in Van Erp & Verschoor, 2004). The resolution in the

[32] However, the tactile instrument could play a role in preventing an SD situation to occur. But in the present experiment, the SD situation was enforced upon the participants.

present display was 15°, which is still lower than the resolution of the torso (cref. Chapters 2 and 4). The fact that the tactile instrument negatively affects control performance is an indication that the participants did rely on the instrument as they were instructed or could not ignore the signals.

We expected that the coding of the tactile instrument might have an effect on control performance, with outside-in being the preferred coding to compensate the yaw motion, the pilot can use the outside-in version of the instrument as a compensatory tracking display (the pilot has to steer against the direction of the tactile signal). In the inside-out coding, however, the pilot has to follow the signal to compensate the yaw motion. In the main experiment, there were no cues that there is an effect of coding on control performance. However, in the "tactile only" control condition (i.e., in the condition with a fixed chair), the hypothesised effect of coding was indeed present, confirming the results of the crossmodal tracking experiment described in Chapter 5. This indicates that, although coding had no effect on the recovery from SD, it may be a relevant parameter in other tasks.

Conclusions

Based on the data from this experiment, we conclude the following:

- A tactile display can support pilots in recovering from an SD situation. In the present experiment, the tactile instrument prevented the participants from entering a simulated graveyard spin. During the 40 s SD recovery phase the mean number of spins was reduced from eight without the tactile instrument to less than one with the tactile instrument.
- The tactile instrument is powerful enough to overrule the strong but erroneous information of the vestibular sense.
- With regard to recovery from a simulated graveyard spin, there are no performance differences between inside-out and outside-in coding of motion direction.
- For the situation of rotation about an Earth vertical axis, there is no advantage of the tactile instrument being active in both the pre-SD and the recovery phase (mean number of spins during the recovery phase 0.84) as compared to active in the recovery phase only (mean number of spins 0.45).
- When the tactile instrument is used in isolation (i.e., without visual and vestibular information), there is an advantage of outside-in coding over inside-out coding with regard to control performance. The correlations between the disturbance signal and the control input were -.79 and .-57, respectively.

Chapter 9. Orientation in 3D, part A[33]

abstract

In the previous chapter, we concluded that a TTTD is an effective instrument to control one's orientation in 2D. Here, we investigate orientation in 3D. Experiment 13 concerns orienting in the microgravity environment of the International Space Station (ISS). The ISS allows to study the effect of tactile information on orienting in 3D without the confounding of Earth's gravity vector. In three tasks performed by one astronaut in the International Space Station, we examined the effect of artificial tactile cues presented to the torso. The role of "natural" tactile cues on spatial orientation in microgravity, such as pressure presented to the sole of the feet, has already been shown, but it is not trivial whether the brain can also easily integrate artificial orientation information that has no real life equivalent. In a case study, we find that artificial tactile information in the form of a localized vibration on the torso that indicates "down" can make orienting in microgravity faster, better and easier. The importance of the artificial tactile information seems to increase over the initial seven days of staying in microgravity while the weight of visual information decreases over the same period. The results underline the capacity of the brain to adapt to unusual environments and to use and integrate artificial cues.

[33] Parts of this Chapter have been published as:

Van Erp, J.B.F., Van Veen, H.A.H.C. (2006). Touch down: the effect of artificial touch cues on orientation in microgravity. *NeuroScience Letters*, *404*, 78-82.

Van Erp, J.B.F. & Van Veen, H.A.H.C. (2004). SUIT – Experimenteren met een trilvest in de ruimte. *Ruimtevaart*, *53 (2)*, 22-24.

9.1 Introduction to Experiment 13: Orientation awareness in microgravity[34]

After the successful application of a tactile torso display in controlling rotation in 2D, we make the transition to the 3D situation in this chapter. We investigate the potential of a tactile display in a case study in microgravity onboard the International Space Station (ISS). In everyday life, we determine up and down based on input from our visual, vestibular and proprioceptive senses, and our body reference frame, the so-called idiotropic vector (Graybiel & Kellogg, 1967). Adequate orientation depends on weighting and integrating the different cues (Bisdorff, Wolsley, Anastasopoulos, Bronstein & Gresty, 1996; Dichgans & Diener, 1989; Friederici & Levelt, 1987; Zupan, Merfeld & Darlot, 2002). Models that describe cue weighting can be summarized with the concept that the most reliable cue has the largest influence in minimizing the variance in the final estimate (Ernst & Banks, 2002; Rosas, Wagemans, Ernst & Wichmann, 2005). In a microgravity environment such as the ISS, the otoliths that sense (gravitational) acceleration and the skin senses no longer provide useful information about up and down (Mittelstaedt & Glasauer, 1993). This requires astronauts to adjust the integration of orientation cues. Data show that spatial orientation in microgravity differs from that on Earth, possibly facilitating space motion sickness (Glasauer & Mittelsteadt, 1998). For instance, in a survey among 104 cosmonauts, 98% reported orientation illusions (Kornilova, 1997). In the process of adjusting the weightings of the different cues, those of the visual information (Friederici & Levelt, 1987) and of the idiotropic vector increase (Jenkin et al., 2005; Young, Mendoza, Groleau & Wojcik, 1996). The increased weight of visual information may result in susceptibility to illusions such as inversion (Lackner, 1992) and visually-induced self-motion (Young & Shelhamer, 1990), with the effects remaining present in the first few days after return to Earth (Bles & Van Raaij, 1988). The increased weighting of the idiotropic vector is reported to occasionally result in the experience of pushing and pulling the space station back and forth when making knee bends while strapped to the station and the experience of a rotating station when performing a somersault.

Supporting orientation awareness may be beneficial for astronauts' performance, safety and well-being. Previous experiments have shown that touch cues that mimic the cues we have in a 1 G environment influence orientation in microgravity (Carriot et al., 2004; Lackner, 1992; Lackner & DiZio, 1993; Young & Shelhamer, 1990) and in people with a loss of vestibular functions (Bles, De Jong, & De Wit, 1984). For example, bungee cords that pull an astronaut's feet to the floor of the station or during parabolic aircraft flight give a strong indication of up and down and can attenuate the visually induced sense of self-motion (The National Academy of Sciences, 1988). However, this technology prohibits free movement and is thus of limited practical relevance. By using vibrotactile elements, tactile information can be presented without needing physical contact with the space station. However, herewith the cues may also lose their daily life equivalence. It is not trivial whether the brain can also easily integrate artificial orientation information that has no real life equivalent. It has been shown that a localized vibration on the torso is easily interpreted as indicating a direction (see Chapter 4) and may be used to counteract spatial disorientation, overruling strong but erroneous information from the vestibular sense (see Chapter 8). Also, tactile information on the torso has been applied in sensory substitutions in which visual or vestibular information is replaced by touch (Bach-y-Rita & Kercel, 2003; Kadkade, Benda, Schmidt & Wall 3rd, 2003; Rupert, 2000a). With respect to reduced gravity, several studies have shown that the effect on tactile perception is small, if present at all (Tan, Lim & Traylor, 2000; Traylor & Tan, 2002; see also Van Erp, Van Veen & Ruijsendaal, in prep.). These observations led us to propose that an astronaut's orientation

[34] This research was supported by the ESA life sciences team, and the Dutch Experimental support Centre for mission DELTA.

awareness could benefit from providing artificial tactile cues. More specifically, a localized vibration on the torso of the astronaut could indicate the direction of down, that is the floor of the station. Important questions are whether the information can be used to determine one's orientation in microgravity and how it is integrated with other orientation cues.

Figure 9.1. The test astronaut and the assisting crew member in the task in which the test astronaut is rotated like the hour hand of a clock. The vest worn by the astronaut included 56 small vibrators. The location of vibration indicated the direction of down. Here, the vibrator on his right shoulder is active. (Photo NASA/ESA).

9.2 Method

Experiment 13 in a nutshell.

- One participant performed several orientation tasks in the microgravity environment of the International Space Station. The tasks were repeated on four days during adaptation to gravity. The astronaut could be supported by a tactile vest covering his whole torso. The location of the vibration on the vest indicated the direction of down.
- The independent variables were the day in microgravity (4) and sensory modality with task-dependent levels (e.g. eyes only, vest only and bimodal).
- The dependent variables were subjective difficulty score, and task dependent performance measures.

The experiment was undertaken onboard the ISS. The design of living and working quarters, instrument racks, and light sources in the ISS are such that there is a visual distinction of up and down. Figure 9.1 provides an indication of the visual richness of the environment used for the experiments. A male ESA astronaut wore a vest containing 56 vibrators in a matrix covering his torso, three gyroscopes to determine the direction of down, a control unit with data storage device, and a voice recorder. The hardware was manufactured on our specifications by Dutch Space (Leiden, The Netherlands). The vibrator nearest to the intersection of the astronaut's torso with a vector perpendicular to the station floor was activated,

indicating "down". Due to practical constraints (Van Erp, Ruijsendaal & Van Veen, 2005), the vibrators were not distributed completely symmetrically over the torso. The vibrators were divided over 6 rings (i.e., 12 tactors for 360°, each tactor covering a vertical section of 30°). Four rings consisted of 8, one of 12, and one of 16 vibrators (i.e., sections of 45, 30, and 22.5°, respectively). This resulted in mean sector size of 30° × 39° averaged over the display.
The astronaut was familiarised with the tactile information during two sessions in Earth's 1G environment (each less than 1 hour). During these sessions he experienced the signals of the tactile display and the effect of moving his body with respect to the gravity vector, for instance by lying on a table and rolling along his body midaxis or being turned around in a rotating device (see Figure 9.2). On his 2nd, 3rd, 6th, and 7th day onboard the ISS, the astronaut performed orientation tasks with the assistance of a second crew member. This crew member was strapped to the space station in an upright position as defined by the (visual) layout of the station (see Figure 9.1) and wore a second voice recorder. The assistant could move and rotate the participant and was trained to do so without adjusting the grip on the participant but by moving his own arms and upper body only. The participant wore the standard ESA ear mufflers and a blindfold when appropriate. Compact flash memory cards stored the data of the equipment, including the data of the gyroscopes, the condition, the calculated sector of the vest that indicated down, and whether the tactile cues were active or not. The data cards and both voice recorders were synchronised before each session. The voice recorders and data cards were returned to Earth after the experiment. Details of the orientation tasks and instructions are given in the results section. For each task, the test astronaut rated the task difficulty on a scale ranging from 1 (no problem) via 3 (moderately difficult) to 5 (almost undoable). After return to Earth, objective performance measures were calculated based on the recorded data.

Figure 9.2. The astronaut during the familiarisation in the rotating chair at TNO Human Factors.

9.3 Results

The first task was performed blindfolded, and was designed to assess if the tactile information could be used to determine orientation in the absence of gravitational and visual cues. The astronaut started upright and was rotated by the assisting crew member like the hour hand of a clock with a randomly chosen rotation direction and angle between 180 and 360° in the roll (coronal) plane (see Figure 9.1). The rate of rotation was between 30 and 60°/s so that the duration of the rotation provided no cues to the total amount of rotation. Consecutively, the astronaut reported the hour of the clock his head was pointing at. Next, directly starting from the last orientation, he was rotated to a new orientation. This was repeated ten times. This task was performed in two conditions: the first ten repetitions with no tactile information, followed by ten repetitions with the tactile information activated. After return to Earth, we calculated the absolute difference between the verbalised clock hour and the actual position in the roll plane. The astronaut performed significantly better with tactile information on (mean absolute error of 38°, close to the 30° vertical sector size of the display) than off (mean absolute error of 85°), $t(39) = -5.36$, $p < .001$. Since the absolute error ranges between 0 and 180°, the error without the tactile cues is close to the expected error of 90° when guessing. There were no differences over the ten repetitions. Figure 9.3 gives the results over the four sessions. As can be seen from Figure 9.3, there is no learning effect for the tactile cues over the sessions. The tactile information reduced the difficulty ratings from a 5 (almost undoable) to a 3 (moderately difficult), $t(3) = -4.90$, $p < .02$. These results indicate that the astronaut could use the tactile information to determine his orientation in the absence of visual and otolith information. Without the tactile cues, the second and following repetitions already had an absolute error at the guessing level. Since the semicircular canals that measure angular velocity do work correctly in microgravity, the results confirm that people are poor at integrating angular velocity over time (Guedry, 1974).

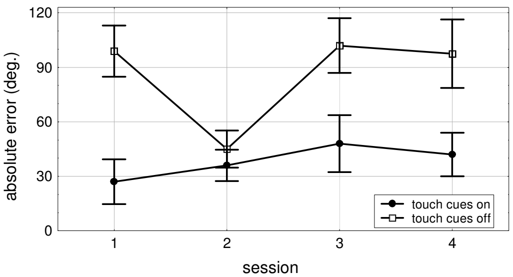

Figure 9.3. Objective performance (absolute error) in the first task as function of the sensory cue and the test session (averaged over ten repetitions). Without the tactile cues, performance is at the guessing level of 90°. Error bars present the standard error of the mean.

The second task was performed in three sensory conditions: visual cues, tactile cues, and both. The astronaut started upright with the tactile information off and his eyes closed. He was then brought into a random orientation (in roll and/or pitch and/or heading) by the assisting crew member and commanded to open his eyes and/or switch on the tactile information. His task was to call out as fast and accurate as possible the direction of down (using eight sectors defined by front-back, left-right, head-feet). This was repeated three times per condition, always starting from upright. The task was not done on the 7th day in the ISS. After return to Earth, we calculated the Reaction Times (RT) as the interval between the command of the assistant and the start of the answer of the test astronaut, and whether the called sector was correct or not. The latter resulted in a proportion correct over the three repetitions in each sensory condition on each test day. The upper panel of Figure 9.4 gives the mean RT. The analysis of variance showed that the RT is about 30% faster in the tactile only and visual and tactile condition compared to the visual only condition, $F(2, 24) = 7.01$, $p < .01$. The proportion correct is depicted in the lower panel of Figure 9.4 and was analysed with the nonparametric test Cochran's Q, $Q(2) = 7$, $p < .05$. The score in the condition without tactile information is above chance level but still incorrect in two out of three cases. This indicates that it is either very difficult to orient oneself based on the available (visual) information, or that it takes more time than the average of 7 s to answer. The score in the condition with both visual and tactile cues might indicate that the visual (but apparently unreliable) cues are weighted heavier than the tactile cues. Due to the fact that there is only one value for each combination of condition and session, we cannot statistically analyse this. The verbal comments, however, give a hint on the shifting sensory importance. The astronaut's responses to the question: "What strategy did you use to perform this task?" were the following: on day 2 in the ISS: "the tactors [the tactile cues] help very much to verify what you see"; day 3: "[the tactile cues are] easy to get a global idea, verified with my eyes"; and day 6: "I didn't look, only used the vest [the tactile cues]". This indicates a shift from visual dominance on day 2 to tactile dominance on day 6. The subjective difficulty scores were 3.7, 2.3 and 1.7 for visual cues, tactile cues, and both cues, respectively. The subjective data show that the tactile cues are easily used and integrated with other orientation cues.

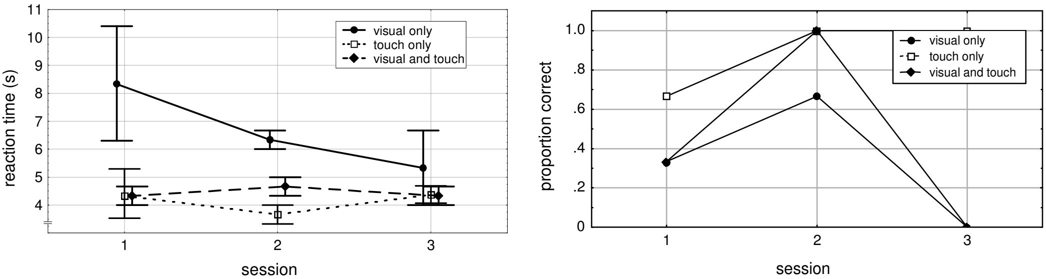

Figure 9.4. Objective performance in the second task as function of the sensory cue and session. Left the reaction time to report the section of down (averaged over three repetitions, bars present the standard error of the mean). Right the proportion correct responses.

Finally, we wanted to obtain an insight into the relative importance of the idiotropic vector. Because this cue cannot be switched off, we undertook the following assessment. The astronaut was brought into a slow somersault by the assisting crew member. After two full rounds, the astronaut was stopped and asked: "Were you rotating or was the ISS rotating?". In this situation, the idiotropic vector would indicate that the astronaut was stable and the ISS was rotating. However, the cognitive model would indicate that the astronaut was rotating himself. The semicircular canals predominantly provide cues at the onset and offset of the rotation. Both the tactile cues and the visual cues indicate that the ISS and the astronaut are rotating with respect to each other, but not whether one of them is steady.

The responses (Table 9.1) are an indication that the relative weight of the idiotropic vector may increase compared to other cues during exposure to microgravity, confirming the anecdotal observations (Lackner, 1992; Lackner & DiZio, 1993). There were also indications that the onset and offset cues provided by the semicircular canals are reflected in the responses, more specifically on day 2 and 7.

Table 9.1. The astronaut's answers to the question: "Are you rotating or is the ISS rotating?" after making a somersault.

Day in microgravity	Answer
2	I was, but when I stopped the ISS was turning.
3	I was rotating.
6	The station was rotating, but I could switch in my head.
7	Station was rotating, hmm, ahh, well I was rotating, then the station*.

* In the debriefings, it was confirmed that the astronaut referred to the start and somersault with the latter part.

9.4 Discussion and conclusion

We may conclude that tactile cues can be used to orient oneself in the presence of other non-informative or biassed orientation cues, confirming the results of the spatial disorientation experiment in the previous chapter (Experiment 12). The advantage of this technology over formerly investigated touch cues is that it doesn't require physical contact with the station. This allows the astronaut to move around freely inside and possibly outside the station. For astronauts, this technology might be of particular interest for extra vehicular activity or emergency situations when darkness or smoke reduce the availability of visual cues. We will discuss the results in the light of the research questions of this thesis below. The experiment also provides more insight in two of our questions. Working under conditions of microgravity is a typical example of an external stressor. The condition is blamed for difficulties with concentrating and all kind of other cognitive tasks. Although we were not able to gather data in a controlled fashion, we have some anecdotal evidence that the astronaut became less aware of the presence of the tactile display. During his stay onboard the ISS the astronaut also used the display during daily life activities (these slots are not reported here because they fall outside the scope of this thesis). During the debriefings, he mentions that after a while, he is no longer aware that the display is still there and providing him with information. This may be due to the fact that the signals are completely ignored by his sensory system or that the signals are sheer automatically integrated in his sensation→action loop, like we use the pressure on the sole of our feet to keep our balance without being aware of the signals. Indications that the tactile display makes the tasks less effortful comes from the difficulty scores, although these scores not only reflect mental workload ratings. Adding the display systematically lowers the difficulty scores. This data confirms our expectation that tactile displays are useful in the presence of external stressors.

We were also interested in investigating Q9 in this experiment: in comparison to (a visual display as) baseline, can (adding) a tactile display result in better performance? We have shown that artificial tactile cues can be used to determine orientation in the absence of visual and gravitational cues. Although the role of touch cues have been demonstrated before, these cues were always simulating the cues we are used to in our normal lives, such as pressure on the sole of our feet. The tactile cues we provided, localized vibrations on the torso, have no link to orientation cues encountered in normal life. The results therefore underline the capacity of the brain to adapt to unusual environments and to use and integrate artificial cues. We demonstrated that orientation performance with the artificial tactile cues can be better than with the visual cues available in the ISS. This advantage is already present in the first test session. Because the astronaut was not trained in using the tactile cues, this indicates that there is no learning required to use the artificial cues.

When both visual and tactile cues are available, they will be weighted and integrated. We found indications that over the seven days in microgravity, the relative importance of the visual cues decreases while those of the tactile cues and the idiotropic vector both increase. The latter resulting in the experience of a rotating space station when making a somersault. In terms of current sensory weighting models, this indicates that visual cues are being considered as less important and/or the tactile cues as more important during the process of adaptation to microgravity.

Chapter 10. Orientation in 3D, part B[35]

abstract

This Chapter is the last Chapter describing applications of tactile torso displays in the local guidance task space. In the previous chapter, we described a case study in which a tactile display was used to support orientation awareness in 3D. Experiment 14 is a controlled experiment in a human centrifuge / flight simulator in which 9 pilots intercepted and chased targets that popped-up. The fighter pilots pulled G loads up to 8-9 Gz when chasing the threats to get them in the centre of the head up display. The tactile display information was perceived and used without problems under these high G loads. Therewith, we are the first to show that tactile display information can be perceived and used in a super agile aircraft environment. The results of the interception task performance showed an advantage of adding the tactile display to the visual display on the initial RTs (200 ms or 15% reduction) and on the total chase time for targets behind the aircraft (1 s faster chase or 8% reduction). The tactile display can thus capture attention at a threat pop-up, and improve threat awareness for threats behind the own aircraft. There were no effects of adding a secondary workload task, possibly due to a floor effect in the task load.

[35] Parts of this Chapter have been published as:
Eriksson, L., Van Erp, J.B.F., Carlander, O., Levin, B. Van Veen, H.A.H.C. & Veltman, J.E. (2006). *Vibrotactile and visual threat cueing with high g threat intercept in dynamic flight simulation*. Proceedings of the 50th annual meeting of the Human Factors and Ergonomics society meeting. Santa Monica: Human Factors and Ergonomics Society.

10.1 Introduction to Experiment 14: Targeting under high G load[36]

After the successful proof-of-concept of a tactile display to support orientation awareness in 3D in Experiment 13, Experiment 14 is a more formal study after the use of a tactile display for orientation in 3D. The experimental design was chosen such that we are able to investigate Questions 7-9 (see Section 1.8).

Fast jet pilots operate in one of the hardest working environments imaginable. Besides the physical load of flying a highly agile aircraft, tasks such as controlling the aircraft, building situational awareness, and split second decision making put a high demand on perception and information processing. This makes it an ultimate challenge to improve the pilot cockpit interface to enhance performance and to lower (mental) workload.

In the previous chapters, we have gone through a series of laboratory and field experiments, looking at the (added) value of a tactile display on pilot performance and mental workload. Favourable results were found for the pilot cockpit interface for waypoint navigation (Experiment 9), low level flight (Experiment 10), helicopter hover (Experiment 11), and counteracting Spatial Disorientation (Experiment 12). However, these situations are relatively pilot-friendly environments. To make a tactile display potentially useful in a super agile environment, a step further must be made. Although we found promising results in a first small pilot study focussed on the perception of vibration signals under high G loads (not reported in this thesis, see Van Veen & Van Erp, 2001), there are no systematic data of the effects of high G load, pressure suits and straining on the sensing and processing of tactile display information.

Therefore, the present experiment was run in a high-end flight simulator able to enforce up to 9 G on a pilot in an interactive flight simulation (the Dynamic Flight Simulator (DFS) in Linköping, Sweden). To further explore the local guidance task space and to challenge the pilots to pull high Gs, we introduced a targeting task in which the pilot had to detect, chase and intercept a threat that popped-up. Nine Swedish Airforce pilots flew scenarios in four conditions: with and without the tactile display and with and without an additional mental workload task. We measured performance (on the primary flight task as well as on the added mental workload task) and workload ratings. We tackle Questions Q7 through Q9 (see Section 1.8). The previous experiments have not provided a clear answer to two questions. Q8: is performance independent of the workload? In the in-vehicle navigation experiment (Experiment 8), we concluded ‘yes’; in the low-level flight experiment (Experiment 10), we found no effects, and in the helicopter hover experiment (Experiment 11), we concluded that it was ‘partial’. And Q9: can a tactile display improve performance when added to a visual display? So far, we only compared tactile with a visual display (i.e., not out-the-window visuals) in Experiment 8 and found favourable effects. Therefore, we test the tactile display when added as additional display to the current (state-of-the-art) visual threat warning head-up and head down displays of the Gripen aircraft. Compared to these displays, the tactile display is expected to have a strong alerting function and it is independent of gaze direction. Therefore, we expected potential benefits of the tactile display in the initial reaction times. Furthermore, the pilot's skin and the tactile display cover a complete 3D sphere around the aircraft (i.e., the tactile display is omnidirectional) while the pilot's eyes have a limited field of view, and the HUD threat indicator compresses the threat directions that are outside the forward visual cone. This may result in a general benefit of the tactile display with respect to threat awareness. Due to the limited resolution of the tactile display we expected no benefit of

[36] This study was performed in co-operation with FOI, Linköping, Sweden. We acknowledge the co-operative, straightforward, and patient fighter pilots from the Gripen OT&E Unit, Aeromedical Centre, Defence Material Administration, and of other air force units that participated in the experiment, and the DFS crew of the Defence Material Administration.

the tactile display in the last phase of the interception, where the target is in the high resolution visual display. Finally, we were also interested in the question whether the tactile display information is perceivable and useful under high G forces. High G forces may affect the mechanical motion of the vibrators (e.g., because of the increased pressure exerted on the vibrators), the contact between the vibrator and the pilot's skin (the vibrators will be pushed further into the skin), as well as the movement of the skin and the human sensory system that detects vibration. Research has shown that (whole body) vibration may degrade the perception of vibratory information (Holmes & Furnell, 2002). However, we know of only one case study into the perception of vibratory information under higher G loads (Van Veen & Van Erp, 2001). In a case study with a single pilot, we showed that vibrotactile detection performance was not substantially impaired up to +6 Gz (the highest level tested), even though wearing a pressure suit for the legs and performing straining manoeuvres were part of the experimental conditions. In addition, Rupert and McGrath (2005) tested tactile display hardware at various +Gz levels up to and including +6.5 Gz in an effort to quantify the force and frequency changes (if any) of the tactors in the high-G environment. They concluded that the force level and frequency generated by the tactors were not significantly affected by G level.

10.2 Method

Experiment 14 in a nutshell.

- Nine pilots performed a target interception and chase task in a high G flight simulator. After a target pop-up the instruction was to get the target in a small forward cone as fast as possible. Standard visual displays were always present. In half of the trials, additional support was provided by a tactile vest. The location of vibration indicated the direction of the target. In half of the trial, an additional mental workload task was presented. After a run, the pilots completed the modified Cooper-Harper scale and a questionnaire.
- The independent variables were the cueing modality (visual only or visual and tactile), workload (additional task absent or present), and position of the threat at pop-up (8).
- The dependent variables were the G forces pulled during interception, the initial reaction time to target pop-up, task completion time, rating on the questionnaires, workload rating, and performance on the secondary task.

Participants

Nine Swedish Airforce pilots participated voluntarily. They were all in active duty and qualified to fly the Gripen aircraft. They had a fighter aircraft flight experience between 250 and 4400 hrs (mean 1605) and were aged between 29 and 53 years (mean 37). No further selection criteria were used. The experiment and experimental equipment were approved by the relevant FOI and DFS institutions. After being given verbal and written information on the experiment, the pilots read and signed an informed consent. The physical condition of the participant during the experiment was constantly monitored by a flight surgeon.

DFS

The Dynamic Flight Simulator (DFS, see Figure 10.1) is a two-axis three degrees of freedom human centrifuge capable of a high onset/offset rate with direct control of gimbal positioning, and with a flight simulator system including a flight performance model of the JAS 39 Gripen fighter aircraft. A change in speed is followed by a precise coordination of the roll and pitch gimbals utilising perceptual control algorithms to generate realistic vestibular, proprioceptive, and visual sensations in flight simulation of high

performance aircraft. Thus, the DFS combines the functions of a human centrifuge and a flight performance model making flight simulation realistic by the inclusion of gravitational-inertial forces acting upon the pilot.
In this experiment, the maximum onset rate was restricted to 6 Gz/s with a maximum G load upper limit set to 9 Gz. The 3 m in diameter DFS gondola was equipped with a Gripen cockpit mock-up containing real aircraft hardware, such as a Martin Baker seat, stick, throttle, and oxygen regulator. See the overview of the DFS system including the gondola attached at the end of the rotating arm in Figure 10.1. The gondola also included interfaces for visual head-up displays (HUD) and head-down displays (HDD), visual out-the-window displays conveying the simulated outside world, and equipment for the tactile display and the additional mental workload task.

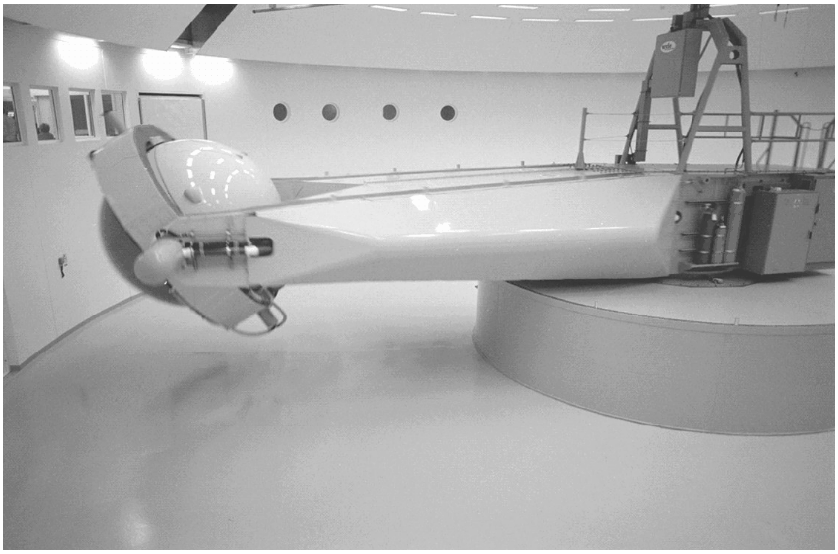

Figure 10.1. The Swedish Dynamic Flight Simulator, a combination of a flight simulator and human centrifuge. The gimbal (3 m in diameter) contains a high fidelity Gripen cockpit mockup.

Visual display: Gripen HUD

The about 30° of visual angle wide simulated Gripen HUD utilised an interface symbology based on a sphere concept (see Figure 10.2, left). The own aircraft was positioned in a virtual sphere fixed to the gravitational vertical while the aircraft HUD scanned parts of the sphere. The HUD depicted segments of latitude circles increasing in curvature with increased deviation from the horizontal. Thus, the HUD actually depicted parts of 'climb-circles' and 'dive-circles' to indicate aircraft attitude and support spatial orientation and attitude awareness.
The used threat symbology was a round symbol connected to a straight line indicating the direction to the threat as illustrated in the right panel of Figure 10.2. The direction to the threat was continuously and rapidly updated with regard to threat and own-ship positions during dynamic flights. This symbology resembles, but is not completely similar, to the presently implemented symbology in the real aircraft.

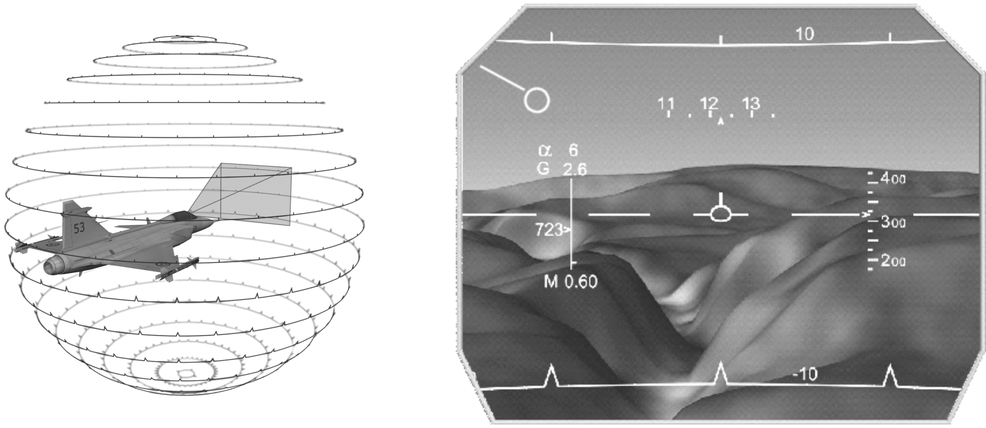

Figure 10.2. Left: representation of the sphere concept used in the DFS Gripen simulator. The HUD scans a part of the sphere depicting the curved latitude circles. Right: simulated Gripen Head Up Display with threat indication in the top left corner.

Tactile display: TNO Tactile Torso Display

The tactile display was a tactile display version JHJ-3 with the tactors driven in a 100 ms on - 200 ms off rhythm. To help the pilot in identifying the middle ring, we used a different rhythm (double speed) for the tactors in the middle ring working as an artificial anchorpoint (see Cholewiak & Collins (2003) for the importance of anchorpoints in vibrotactile localization).

Scenarios

Four different scenarios were created that were flown in the different conditions (balanced over the participants). The general layout of a scenario was as follows: at the start, the pilot would fly straight and level at a speed of around 0.9 M between 7000 and 8000 m altitude, not diverging from horizontal attitude more than 5º. Threat pop-up would occur after being in this position for 5, 8, or 11 s. This actually gave the pilot a high degree of control over the timing of the threat pop-up. The primary task was to detect a threat pop-up and manoeuvre towards the threat as fast as possible. As soon as the target was within a 15° (H) × 10° (V) forward cone for at least 5 s, the target disappeared and the pilot returned to the original flight plan. When the aircraft was within the altitude range and straight and level, the next target popped-up after 5, 8, or 11 s. Each scenario consisted of a total of 8 target pop-ups, which were systematically positioned on a 3D sphere around the aircraft: at the positions of 60º heading/20º elevation, 60º/-20º, 80º/51º, 80º/-51º, 120º/51º, 120º/-51º, 140º/20º, and 140º/- 20º. That is, there were actually 16 possible threat positions but the presentation of the threats to the right or left was randomised for each of the eight specified positions above for the first pilot and counterbalanced for the second.

Secondary mental workload task

Half of the scenarios were flown with the added secondary mental workload task. We chose to use the auditory Continuous Memory Task (CMT) in which the pilot had to respond to each odd and even occurrence of four target letters in a continuous stream by clicking the odd or even button on the control stick. If this response was correct, he heard the word "correct". When he pressed the wrong button, pressed a button at an incorrect moment or when an omission was made, the word "wrong" was presented. After the feedback ("correct" or "wrong") the tally for the last letter had to be set to zero. Target letters were never presented in succession. Thirty percent of the letters were targets.

Figure 10.3. One of the participants just before the start of the experiment showing the tactile display and the electrodes for the physiological workload measures and health monitoring function.

Design

The experiment had a threat Cueing modality (2) × Workload level (2) × Threat positions (8) full factorial within-subjects design. The threat cueing modalities were *visual only* or *visual and tactile* in combination. The two workload levels were *CMT absent* or *CMT present*. In each of the four cueing modality / workload combinations, eight threats were presented. The first two and last two blocks were performed in the same cueing modality. The CMT was performed every other block of trials. The presentation order of the cueing modality and of the presence of the CMT was counterbalanced over pilots. Five of the pilots started with the *visual only* cueing and four started with the *visual and tactile* condition. The presentation order of the threats was randomised.

Figure 10.4. Participant inside the gondola.

Procedure

After being equipped with the sensors and cables for the physiological registering (see Figure 10.2), the pilot read the written instructions and was verbally briefed about experimental procedures and tasks. The tactile display and the anti-G pants were fitted before the pilot seated himself in the DFS gondola. In the gondola, the tactile display and sensors cables were connected to the DFS system. Figures 10.3 and 10.4 show one of the fighter pilots prior to the experiment. The equipment was tested and security checked, including the pressurising of the anti-G pants, the tactile display functions, and the rest of the relevant DFS equipment. The pilot then performed a training session of the flight and target chasing task and the CMT with a stationary gondola, consisting of three visual threat pop-ups and chases without the CMT, followed by three visual threats with the CMT, three visual/tactile threats without the CMT, and finally three visual/tactile threats with the CMT.
The DFS was then brought to idle level at around 1.4 Gz and the pilot then flew freely with higher G loads as a warm-up. Muscle and respiratory straining manoeuvres were performed according to regular flight procedures assisting the anti-G pants. After each threat chase, when deviating from the starting position of 7000 to 8000 m altitude, the pilot made the decision when to get back into the starting position to enable threat activation. He could thus decide to take short breaks from pulling higher G loads in threat chases. After each condition, the pilot rated his mental workload using the modified Cooper-Harper scale with levels from 1 (low) to 10 (high mental workload). After each condition, there was an 8-10 min break at idle level, during which further comments were encouraged. After the pilot's completion of all 32 threats, the gondola was brought to its starting position and rating and comments were made before his equipment was disconnected from the gondola/DFS. After leaving the gondola, the pilot answered a questionnaire and participated in an unstructured interview. The 32 threat chases were completed in about 1 h, and the total time of an experimental session from initial preparation to the pilot being ready to leave was about 3.5 h.

10.3 Results

G load

The highest Gz-peak was 9.0 Gz (the limit set during the experiment) with all pilots having a maximum peak above 8 Gz. The means of each pilot's 32 G peaks ranged from 5.9 to 8.0 Gz.

Interception performance

We calculated two performance measures: the initial reaction time (iRT) defined as the time between target pop-up and an aircraft roll of 10º from straight and level flight, and the total reaction time (tRT) defined as the time between target pop-up and successful interception (i.e., the threat within the $15 \times 10°$ cone). Please note that the iRT is in ms and the tRT is in s. Repeated measures ANOVAs were applied to the iRTs and tRTs with p-values corrected with the Greenhouse-Geisser correction values.

The ANOVA of the iRT showed a significant main effect of Cueing modality $F(1, 8) = 8.00$, $p < .025$, with no other significant effects. The *visual only* cueing generated a mean iRT of 1458 ms with standard error (SE) of 54 ms, and the *visual and tactile* cueing had a mean iRT of 1245 ms (SE = 88).
Inspecting the tRT data showed a mean of 11.3 s with a SD of 6.2 s. It also revealed that there were 3 scores of the 288 cases (1.1%) that deviated more than 5 SD values from the mean. These scores were not systematically related to one of the independent variables and thus replaced by the overall mean before statistical analyses were performed. The ANOVA of the tRT showed a significant main effect of threat position, $F(7, 56) = 4.79$, $p < .05$, with no other significant effects. This main effect shows that some threats positioned farther away (angle wise) from own-ship generated greater total times. Since the surplus value of the tactile display was expected for targets behind the own aircraft, we further analysed the data dividing the data in threats in front of and behind the own aircraft. The ANOVA revealed a significant interaction between display condition and threat position: $F(1, 8) = 5.59$, $p < .05$. Figure 10.5 presents the results and reveals that there is no additional value of the tactile display for the tRT when the threats are in front of the own aircraft, but there is a favourable effect for the targets behind the own aircraft. This advantage of the tactile display is in the order of 1 s.

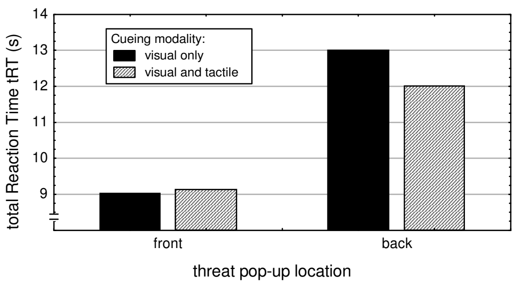

Figure 10.5. The chase time from target pop-up till interception for target pop-up in the front of or behind the own aircraft as function of cueing modality. Adding the tactile display to the visual Head Up Display results in a second gain in chase time for targets popping-up behind the own aircraft.

Questionnaire

The questionnaire data were analysed with a non-parametric Wilcoxon signed ranks test. Because of the limited number of participants, we decided to use an alpha level of .10. Significant different scores for the visual and the tactile display were present on the following three questions (all in the advantage of the tactile display over the visual display, see also Figure 10.6):

- Did the visual / tactile information capture your attention? The mean rating for the visual display was 4.9 and for the tactile display 6.0 ($p < .10$).

- Did you experience an initial clear threat position from the visual / tactile indication? The mean for the visual display was 3.4 and for the tactile display 5.7 ($p < .02$).
- How hard was it to spot the threat with visual / tactile indication? The mean for the visual display was 3.1 and for the tactile 2.0 ($p < .02$).

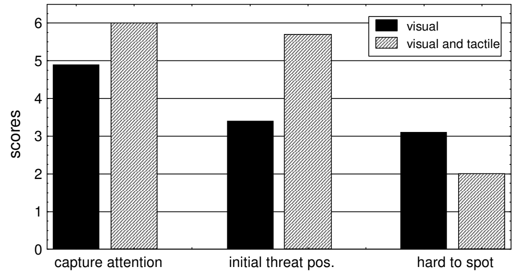

Figure 10.6. The three questions with a significant different score for the two cueing modalities, all in the advantage of the visual + tactile cueing modality (see text for further explanation).

The ratings were all in favour of the tactile display, confirming the objective data. There were no significant different ratings on the following questions (overall mean in between brackets):

- How was the reception of the visual / tactile indication during G load (5.2)?
- How much support did you receive from the visual / tactile information (5.5)?
- Did the visual / tactile indication bother you (1.7)?
- Did you experience a clear threat position from the visual / tactile indication during middle phase (4.2)?
- Did you experience a clear threat position from the visual / tactile indication during final phase (5.4)?
- Did you experience the visual / tactile information as easy to interpret (5.5)?

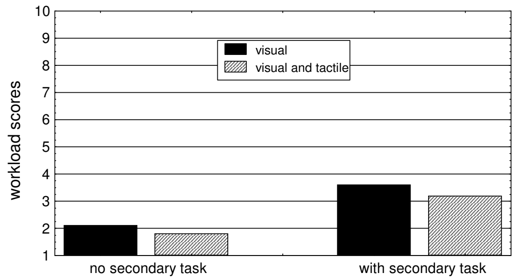

Figure 10.7. Mean workload ratings on the modified Cooper-Harper scale (1 - 10) as function of cueing modality and the presence of the secondary mental workload task.

Workload ratings

The workload ratings were made from the modified Cooper-Harper scale (1 - 10 from low to high). Three values out of 288 were missing and were replaced by condition means in the values. In general, the score were very low (see Figure 10.7) and there were no significant differences between the conditions. Even in the presence of the secondary CMT task, the scores are low.

Secondary task performance

We calculated three performance measures on the CMT task: the proportion missed hits (i.e., the proportion of the target letters the pilot did not respond to), the proportion false alarms (i.e., the proportion of the non-target letters that the pilot -incorrectly- responded to), and the reaction time of the correct responses. The proportion missed hits and false alarms were both very low: .086 and .0071, respectively. The mean reaction time was 934 ms in the *visual only* condition and 894 ms in the *visual and tactile* condition. These reaction times are in the lower part of the range found with four target letters (Veltman & Gaillard, 1996b). None of the measures reached statistical significance: missed hits: $(F1, 8) = 0.60$, $p = .46$; false alarms: $F(1, 8) = 0.01$, $p = .86$; Reaction Time: $F(1, 8) = 2.39$, $p = .16$. This is probably due to a floor effect: performance was close to perfect in both cueing modalities.

10.4 Discussion and conclusion

One of the things that we were interested in was whether the tactile display could a) be perceivable and b) of any use during high G load. Both the objective and subjective data show that this was the case. There are no indications that the high G forces affected the mechanical properties of the vibrators or the pilot's sensory system. There were no complaints on the perceivability of the tactile cues, the pilots rated the accuracy of the tactile cues higher than the visual cues during the initial phases of the chase, the initial RT became faster when the tactile display was added to the visual display, and the threat awareness for targets behind the own ship improved with the tactile display added. This study is the first to show the usefulness of tactile information under G loads above 6G. These results underline the potential of the tactile display for use in high performance aircraft. We also investigated Questions 7-9. With respect to Q7 (Can local guidance tactile displays lower cognitive effort ratings compared to a visual display?), we cannot confirm our expectations. There is no significant effect on the workload rating in the present experiment. The task load turned out to be very low. The ratings were low, also in the scenarios with the added mental workload task, possibly reflecting a floor effect. Apparently these highly trained pilots were not stressed hard enough by the targeting task and had ample spare capacity to be not affected at all by the secondary mental task. Their scores on this secondary task are also extremely high. Therefore, Q8 (Is performance with a local guidance tactile displays independent of cognitive workload or external stressors?) becomes irrelevant. With respect to Q9 (In comparison to a visual display as baseline, can (adding) a tactile display result in better performance?), we can state that the tactile display can improve performance, even in the presence of a high quality visual display. This effect is actually above the hypothesised favourable effect of the tactile display. The 200 ms gain in initial reaction time may mean the difference between life and death in critical situations (e.g., when under threat of hostile aircraft or missiles). The advantage of the tactile display is also present for targets that pop-up behind the own ship. The gain in chase time here is a full second. It is relevant to note that the advantages of the tactile display were apparent in a situation that was not extremely favourable for the tactile display to show a positive effect. On the contrary, the effects were found despite the fact that:

- the pilots had no formal training with the tactile display (while they were accustomed to the visual display),
- the pilots worked under very low levels of workload as indicated by the workload ratings and the secondary task performance,
- the pilots had a high-end visual display available in all conditions,
- the pilots had a high degree of control over the timing of threat pop-up.

Based on the higher score on attention capture and cue clarity of the tactile over the visual display in the present experiment, one can argue that the advantage of the tactile display may be larger in a situation of an unexpected threat pop-up or in situations with a higher visual or mental load.

Chapter 11. Discussion and conclusions

11.1 Summary and discussion of the findings

In Chapter 1, we introduced the prenav model for human behaviour in platform navigation and control. The prenav model served as framework for this thesis and revealed two factors that can affect performance negatively in local guidance tasks: sensory overload and cognitive overload. The innovative concept of tactile torso displays can possibly deal with these factors. By using the skin as an information channel, a tactile display can reduce the overload of other sensory modalities such as ears and eyes. For example, a localized vibration on the torso can serve as a 'tap-on-the-shoulder' to provide local guidance information. Such information may be processed intuitively, which reduces the risk of cognitive overload. In Section 1.8, we formulated nine questions at the sensation, perception, cognition and action level. These questions were addressed in 14 experiments described in the previous chapters.
Before we discuss the findings of these experiments, the following methodological issues are relevant. Although common in experimental research, these issues should be kept in mind when interpreting the results of our experiments. Firstly, the fundamental studies (Experiments 1-6) were done under optimal laboratory circumstances. One has to be careful with interpreting these lab results in the context of real-world operational applications. For instance, the spatial resolution of an operational vibrotactile display worn over clothing and with the tactors embedded in a belt that causes spreading of the vibration may differ from the results found in our lab experiments where the tactors were individually attached directly to the skin. Secondly, the simulator studies (Experiments 8, 10, 11, 12, and 14) may approximate real world situations to a large extent, but not completely. For example, it is likely that out-the-window visuals and stress levels differ between simulations and operational environments[37]. We also learned that participants in our experiments appreciated tactile displays as new and often as an 'exotic' display, possibly leading to an above average focus of attention for the tactile display. Finally, in none of the experiments, the participants were formally trained[38], neither for the specific task, nor in how to interpret the tactile display. In most experiments, they were at best only shortly familiarised. This may have caused learning effects during an experiment. By accurate balancing the order of the experimental conditions of participants, possible learning effects have not systematically affected the experimental effects we were interested in.

Questions at the sensation level

We stated the following three questions and hypotheses at the sensation level.

[37] However, since we were mainly interested in relative effects between different conditions and not so much in absolute performance, this issue becomes less important.

[38] With formally trained, we mean: trained to a specific criterium, till performance reached an asymptote, or till performance mimicked performance with for instance a visual display. The only exception was the control of the rotating chair in Experiment 12.

Q1. What is the spatial resolution of the torso for vibratory stimuli, as a function of the location on the torso? This question is relevant for designing tactile displays that are adjusted to the sensory characteristics of the torso. We hypothesised that the spatial resolution is in the order of centimetres and evenly distributed across the torso, vertically as well as horizontally. Experiment 1 largely confirmed our hypothesis. We found an evenly distributed resolution of 3-4 cm, except for the horizontal direction near the body midline where the resolution was 1-2 cm. A possible explanation for this phenomenon (which we called the midline effect) is that the way vibrotactile stimuli on the torso midline are processed makes the midline a so-called anchorpoint. Previous studies have shown that anatomical anchorpoints improve performance in vibrotactile localization tasks.
Q2. What are the effects of timing parameters on the spatial resolution? This question is important for two reasons. Firstly, timing is the preferred stimulus parameter to code secondary parameters such as the distance to a waypoint. Secondly, dynamic local guidance applications may require rapid changes of the stimulus pattern. We hypothesised that both the Burst Duration (BD) and the Stimulus Onset Asynchrony (SOA) of the pulses in a vibrotactile pattern would affect localization performance. This was confirmed in Experiment 2, although the influence of the SOA on performance seemed markedly larger than that of BD. Localization performance for smaller SOAs is related to temporal order judgment, and the occurrence of apparent motion can enhance localization performance. The results show that those tactile display applications that require high localization accuracy can benefit from longer BDs and SOAs. On the other hand, applications that require a fast presentation, can benefit from a larger distance between the tactors.
Q3. How well can observers determine the absolute location of vibratory stimuli? Questions 1 and 2 were concerned with the relative localization of two stimuli. However, for a tactile display that maps an external event on a specific location on the torso, absolute localization is also relevant. Since we are able to hit a mosquito on our torso without looking, we hypothesised that observers are able to determine the absolute location of a stimulus with a resolution of several centimetres. In Experiment 3, we found that observers are able to localize a vibratory stimulus close to its veridical location. The pattern of responses made us believe that stimulus locations on the torso are coded in polar co-ordinates with the body midaxis as origin. When the veridical and observed stimulus location do not coalesce, the difference is in distance but not in angle (shifts up to several centimetres occur, which actually means that observers could have localized the stimulus below or above the skin surface). A shift along the radius has neglectable effects on the perceived direction of the stimulus. The results indicate that angles are the perceptual invariant for torso stimuli.

Questions at the perception level

At the perception level, the following questions were investigated.
Q4. Are observers able to perceive an external direction in the horizontal plane based on a localized vibration on the torso, and what is the accuracy (and bias) in this direction perception? We hypothesised that since the sense of touch is used to externalise stimuli, people can easily externalise a localized vibration to a direction in the outside world. We expected the accuracy to be the equivalent of the spatial resolution (i.e., for a spatial resolution of 4 centimetres and a torso circumference of 80-100 cm in the order of 15-20°) with no bias. We investigated direction perception in Experiment 4. The results show that the accuracy is on average better than the hypothesised 15-20° and dependent on the location on the torso: variability is lower on and near the midsagittal plane (4° for the direction straight ahead) than on the sides of the torso (10-14°), probably due to the fact that these locations act as anchorpoints. We also found a bias in the perceived direction. This bias is toward the midsagittal plane, that is, perceived directions are toward straightforward for tactors on the frontal side, and toward straight backward for tactors on the dorsal side when compared to their veridical directions. The bias is close to 0° for the four cardinal directions and increasing up to 10° for the directions in between. For applications requiring a higher

directional resolution than the 12 hours of the clock, the mapping of direction on torso locations (i.e., the placement of the tactors) should compensate for this bias.

Q5. How do people extract a direction from a (‘dimensionless’) point stimulus? We hypothesised that people use an internal egocentre to extract the direction of a point stimulus on the skin comparable to the cyclopean eye for visually perceived directions, and the cyclopean ear for auditory stimuli. For the torso, this egocentre (or cyclopean skin) was thought to be located on the body midaxis. The data of Experiment 4 did not seem to fit with the existence of a single internal reference point located at the body midaxis. However, they did fit with the existence of an internal reference point for each body half. This observation is consistent over observers, and results in a mean lateral distance between both reference points of 6.0 cm across participants. The existence of two internal reference points may again be related to the way vibrotactile stimuli are processed in the central nervous system. Stimuli presented to a specific location on the torso are processed by the contra lateral hemisphere, except for stimuli on or close to the body midline. In that sense, the two torso halves can be seen as different body parts, each having its own internal reference point. The role of the midline is hypothesised to be the integration of the phenomenal space of both body sides into one coherent percept.

Q6. Which model can describe the crossmodal tactile-visual perception of time and space? We hypothesised that a model based on common, modality independent representations can accurately describe crossmodal visual-tactile perception. This means that crossmodal comparisons were expected to be as good as intramodal comparisons. This was confirmed by Experiments 5 and 6 in which we studied the accuracy and bias of human time-interval perception and spatial tracking, respectively. The data of Experiment 5 on open interval comparisons showed that vision and touch are not always ‘calibrated': the length of a visual interval is systematically underestimated compared to that of a tactile interval for interval durations below 200 ms. Experiment 6 showed that tracking errors increase when there is an external disturbance signal present in the tactile signal. However, in both experiments, the crossmodal comparisons can be predicted on the basis of the unimodal sensitivities, which indicates that there is no additional noise involved in crossmodal compared to unimodal comparisons, confirming our hypothesis.

Questions at the cognition level

At the cognition level, two questions regarding mental workload are relevant.

Q7. Can local guidance tactile displays lower cognitive effort ratings compared to a visual display? We hypothesised that mental effort ratings for navigation tasks supported by a tactile display are lower than when supported by visual information, because with the specific display design processing tactile local guidance information requires no or less cognitive resources. We investigated this issue in Experiments 8 (in-vehicle navigation task) and 13 (orientation in microgravity). In both experiments we find higher mental effort ratings in the visual conditions than in the tactile and bimodal conditions. Also relevant here is the effect of adding a tactile display to a baseline condition that includes visual information. According to the predictions of the prenav model, adding an intuitive tactile display will have no or little effect on the mental effort rating because there are no or little cognitive resources required to come from the sensation to the required action. We investigated this issue in Experiments 10 (low level flight), 11 (helicopter hover), and 14 (target interception). In none of these experiments, the ratings were raised after adding the tactile display, thus confirming our hypotheses. These results show that the tactile information is processed at a low level on the cognitive ladder and lower than visually presented information. This makes Q8 relevant: can we show that the tactile display information can be processed without involving the cognitive ladder at all?

Q8. Is performance with a local guidance tactile display independent of cognitive workload or external stressors? The prenav model would predict that a display that closes the sensation→action loop makes the user immune to high mental workload situations. In other words, adding additional mental tasks will not negatively affect performance (we called this the strict definition of an intuitive display). When the information needs to be processed through the perception→action loop, conditions with a higher mental workload will result in performance degradation, but not as much as displays that require even higher levels of cognitive processing (we called this the less strict definition of an intuitive display). Designing an intuitive display is a big challenge. We explicitly strived for little training time and steep learning curves, and tried to keep the displayed information simple by using low bitrates and single function displays. However, in all experiments, users needed instruction to explain what the display indicates. Albeit short (usually just one sentence), it means that the response is not based on reflexive behaviour, but requires an "if - then rule". This also links to the issue of information coding on a tactile instrument (see the section below on coding and standardisation). We investigated Q8 in Experiments 8 (in-vehicle navigation), 10 (low level flight), and 11 (helicopter hover)[39]. The data showed a mixed picture. The results of Experiment 8 are in accordance with the strictest definition: there is no detrimental effect of the high workload condition in the presence of a tactile display, while performance degrades when only a visual display is available. Based on these results, the tactile display may be called intuitive. However, the results of Experiment 11 are in accordance with the less strict definition: with a tactile display, performance is degraded by high mental workload, but not as much as in the condition without a tactile display. The results of Experiment 10 do not fit with either prediction. Performance degradation in the high workload conditions is the same for trials with and without the tactile display. These results show that it is possible to make the user less vulnerable for high mental workload situations, but that it is not exactly clear yet how to realise this. The different results may be related to the task characteristic and the information coding on the tactile display. In Experiment 8 (in-vehicle navigation), the task clearly has the character of a pursuit tracking task in which the user steers towards an indicated direction. The same, although less clear, applies to Experiment 11 (helicopter hover) in which pilots were instructed to 'follow the needle' to reach the desired position. On the other hand, Experiment 10 (low level flight) had a different task because the user had to stay clear of no-go zones (please note that the pilots were given the same 'follow the needle' instruction as in Experiment 11). Despite the different task characteristics, the direction of vibration coded the desired direction in all three experiments. This coding fits with the pursuit tracking task character of Experiments 8 and 11, but is less suited for the character of Experiment 10, thus requiring more cognitive resources to translate the tactile display information into the required action. Further research is needed to investigate the relation between task characteristics and information coding.

Questions at the action level

At the action level, we investigated whether a tactile display is effective across the range of local guidance tasks.

Q9. Can (adding) a tactile display result in better performance compared to a visual baseline? We expected that a tactile display improves performance when there is either: a) high visual load, or b) high cognitive load. We investigated performance across the local guidance task range in Experiments 7-14. In all experiments, performance with a tactile display is good. This seems trivial in conditions where visual information is degraded, for instance when flying with night vision goggles or under conditions of Spatial Disorientation. However, even in the presence of direct view as in Experiments 10 (low level flight), 11 (helicopter hover), and 13 (orientation in microgravity) or with a (state-of-the-art) visual display like in Experiment 8 (in-car navigation) and 14 (target interception), performance improves with a tactile display. This shows that a tactile display has surplus value not only in conditions of degraded visual information. Part of this advantage may be ascribed to the commonly found performance gain with integrated redundant

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[39] We also planned to investigated this in Experiment 14, but the workload manipulation in this experiment failed to result in a difference between low and high workload conditions.

information sources in, amongst others, speeded force choice tasks. However, we think that the tap-on-the-shoulder principle of the tactile display is such a strong concept to present local guidance information that it can compete directly with visually presented local guidance information.

The effect of external stressors

In the prenav model, external stressors such as noise, vibration, and altered G environments affect cognition. We did not explicitly test this aspect of prenav through the manipulation of such environmental aspects. However, many of the experiments were run in environments that would be considered to act as external stressor: whole body vibration (Experiment 9), wearing night vision goggles (Experiments 10 and 11), spatial disorientation evoking motion profiles (Experiment 12), in microgravity (Experiment 13), and under high G-loads (Experiment 14). In all these experiments under conditions of external stressors, we concluded that a tactile display improves performance compared with visual information.

Prenav

Prenav was introduced as a framework to sketch the problems (and possible solutions) with human behaviour in platform navigation and control, to operationalise the concept of intuitive displays, and to help interpreting observations and experimental results. We did not intend to validate the model, but we tested some of its qualitative predictions. In retrospect, we conclude that the model is a useful framework. We propose to replace the strict boundary of the cognitive ladder. Rather, the amount of cognition involved in the task of platform navigation and control is a continuum, and not a matter of all or none (see Figure 11.1). Factors such as the display coding principle, user expectations and preferences, instruction and amount of training can all cause a shift on this continuum.

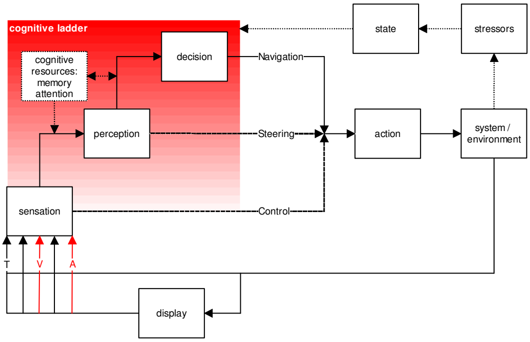

Figure 11.1. The prenav model in which the cognitive ladder is no longer a rigid all or none factor with a strict boundary. The amount of cognitive resources involved is rather a continuum depicted by the gradient. See Section 1.2 on further details of the prenav model.

Longitudinal effects

The experiments we described reflect first shot performance. Experiment 13 (orienting in microgravity) is the only experiment in which we measure performance over a longer period (8 days). Studying longitudinal effects requires different experimental methods and are in general more expensive and more cumbersome for the participants. Even for an intuitive display, training and/or prolonged use may improve performance. For example, eye-hand coordination is a process that is trained for years, and participants used this experience in many of the (visual) baseline conditions. However, users had not more than a couple of hours to train the specific skin-hand coordination required in using the tactile display. Even at the end of an experiment, participants had only a limited experience, far from enough to claim that they were highly trained. One might expect performance to improve when skin-hand coordination is further fine-tuned. A second relevant aspect is trust in the display. Since participants were not used to tactile displays, some may have needed more time to learn to trust the tactile messages. We expect that over longer periods of use, performance will improve further, especially in situations in which the display is one of the alternative information sources. Longer periods of use will decrease initial hesitance in trusting the information. Finally, effects of prolonged stimulation deserve attention: adaptation (referring to increased perceptual thresholds) and habituation (referring to loss of attention to constant stimuli). The effects of adaptation may be counteracted by measures such as using duty cycles below 100%, using on-off stimuli instead of continuous stimuli, and by using alternative locations when the duration of stimulation crosses certain limits. Habituation is an effect that occurs in all sensory modalities. For instance, the ticking of a clock seems to be absent after a while, but instantly returns when somebody points it out or after leaving and re-entering the room. It is difficult to predict to what extend the tactile modality shows habituation. On the one hand, we stop feeling the pressure of our clothing or wrist watch on our skin after a very short time. On the other hand, this doesn't mean that tactile information isn't processed subconsciously, for example to keep our balance.

Coding and standardisation

Intertwined with intuitive design is the algorithm used to code information on the tactile display. This issue was relevant in Experiments 10 and 11 (helicopter low level flight and helicopter hover), and Experiment 12 (orienting in 2D). For example, in the helicopter hover display we choose to code for the desired direction (as we did in the waypoint navigation display), while for example Raj et al.(1998) modelled a virtual sphere around the hover location, and coded bumping into the inner walls of this sphere. Similar coding differences exist for displaying virtual corridors. In coding self motion as we did in Experiment 12, the same inside-out vs. outside-in (or status vs. command) discussion occurs that has been going on for visual artificial horizon displays for many years. Although we did not systematically investigate this issue, anecdotal evidence indicates that there is no population preference for one algorithm or the other in the helicopter hover task. The preference is about 50-50, which also means that the coding is less intuitive for half of the population. Also, switching between different coding algorithms may result in problems (like experienced by pilots that transferred from an outside-in to an inside-out coding of the artificial horizon; Pongratz et al., 1999). This pleas for a coding that can either be adjusted to user profiles or preferences, or that is standardised across applications, countries and manufacturers. Appendix III gives a handful of guidelines that were based on this thesis and related activities.

Limitations of intuitive displays and tactile clutter

Although the skin is able to process large amounts of information (people who are trained in Braille can actually read with their fingertips), there will be a tradeoff with the intuitiveness of the tactile signals (Braille reading consumes a large amount of cognitive resources, as does reading with the eyes). That is, a high tactile information transfer rate usually yields codings that are not intuitive and require a lot of training. In Chapter 7, we introduced the term tactile clutter to describe a situation where displaying multiple signals in parallel on a tactile display results in difficulties interpreting them. Apart from the possible spatiotemporal interaction of individual signals, some form of processing or (spatial) attention may be required to separate the different chunks of information, or, for example, to track one signal and ignore a second. Also, as Van Veen and Van Erp (2003) showed: a lack of vocabulary may hamper to separate tactile signals comparable to listening to an orchestra without knowledge on the different instruments. The limitations to present more complex navigation messages with tactile displays become a relevant issue in presenting global awareness information instead of only local guidance cues (the visual analogy would for example be an arrow versus a map). According to the prenav model, global information requires processing of information at a higher level (namely the navigation level) than that involved in local guidance (steering and control level). Presenting information at the navigation level will require substantial cognitive resources (regardless of display modality). In Chapter 6, we gave an example for an in-vehicle navigation display: “take the left lane immediately after a right turn 100m ahead”. In these situations, it may be beneficial to limit the function of the tactile display to drawing the user’s attention to a message or map displayed on a visual display.

Multimodal integration

We believe that a tactile display will rarely be used in isolation but often in a combination with visual and/or auditory displays in a multimodal setting. This raises many issues, including how to calibrate touch with other modalities in space and time, and how to allocate information to the sensory modalities (e.g., Van Erp, Kooi, Bronkhorst, Van Leeuwen, Van Esch & Van Wijngaarden, 2006). In a simple multimodal interaction approach, information would be displayed redundantly via two or even three modalities. In general, this approach may result in faster reaction times and a lower workload (see for example Experiments 8 and 14; Stein & Meredith, 1993). A more complex approach than presenting information redundantly is to make the information from the different modalities complementary. This resembles the way our senses work together in everyday life: in finding a ripe orange, we use our eyes, hands, and nose to each sense the attributes they are specialising in. A similar approach to a multimodal display could guide the distribution of information attributes across different displays. For example, the target indication used in Experiment 14 consisted of a direction only. However, normally, it would include a distance or threat level indication or an identification label as attribute. The tactile modality worked well in displaying the direction, but may not be optimally suited to display an identification label. Following the complementary approach could result in a target presentation in which the direction attribute is presented via touch, and the identification label via audition. However, besides the potential synergy between the senses in such an approach, there may also be costs involved. For example, the different attributes that are spread over modalities may not be perceived as belonging to the same entity. Also, there are costs involved in switching attention between the different senses (in terms such as time, Spence, 2001; Spence & Driver, 1997). Additional research is needed to get more insight in the balance between the potential advantages and the costs involved with the complementary approach (Weder, Van Erp, Toet & Werkhoven, 2006).

Open research issues

In the previous sections we discussed several issues that were touched upon in this thesis but not resolved yet, including longitudinal effects, coding and standardisation, and tactile clutter. We can add the following important issues:

- Age-related effects. The present experiments were all run with participants from a relatively young population. Important aspects in the design for older users include: thresholds and spatial resolution (in general, the processing of tactile stimuli will degrade with age), learning skin-hand coordination, and trust in the system.
- Algorithms to aid the user in switching on the tactile information. Continuous stimulation may result in adaptation and habituation effects, and may even be experienced as annoying. The decision when the display should be switched-on then becomes relevant.
- Perceiving vibrotactile signals in a vibrating and other stressful environments. There is no systematical knowledge available on tactile perception as function of real world aspects such as vibrating environments, clothing, etc. Although we encountered no problems in the experiments

described here, other groups report degraded tactile perception under conditions of for instance whole body vibration (e.g., Castle & Dobbins, 2004; Holmes & Furnell, 2002).

- Multifunction tactile displays. In this thesis, tactile displays are designed and tested for one application in isolation. The same need for multifunction visual displays also applies for tactile displays: introducing a single function display will not be attractive in many cases. In a multifunction tactile display, the user should have information on the function that is displayed, similar to for example the icon and text in the upper bar of a window on a visual display. Methods for separating functions in tactile displays (such as sequential separation, spatial separation, sensational separation, and the use of icons and multimodal cues) must be further developed.

Spin-off to other applications and domains

This thesis focussed on tactile displays for local guidance tasks. Besides pilots, astronauts, car and boat drivers, people working in challenging environments such as divers and firefighters can benefit from the technology. However, the spin-off is not restricted to challenging environments only. We foresee that tactile display technology might be useful in other application and task domains, such as:

- Sports: A localized vibration can provide navigation information (i.e., where to move to), but also evoke limb initiation (i.e., how to move), and possibly improve movement coordination (when to move), see Van Erp, Van Veen, Saturday, Jansen & Werkhoven (2006).
- Remote control: tactile displays can help in reproducing critical perceptual cues of the remote world (Van Erp, 2006a). For example, in controlling an uninhabited ground vehicle, many road conditions can better be felt than seen, and the same holds for turbulence in an aerial vehicle (Ruff, Narayanan & Draper, 2002).
- Detecting unexpected events: the higher score on attention capture and cue clarity of the tactile over the visual display that we found in the target interception task, and the faster reaction times in the car navigation task indicates that a tactile display can be advantageous in the detection of and reaction to unexpected events (e.g., Sklar & Sarter, 1999).
- Time critical tasks: several experiments show that tactile displays result in faster reactions than visual displays (including work described here and the body of evidence is growing rapidly (e.g. Martens & Van Winsum, 2001). This makes them well suited for time critical tasks.
- Directional warning and attention allocation system. Localized vibrations may not only draw attention, but may also direct attention to a specific direction or location (Calhoun, Draper, Ruff & Fontejon, 2002). This can be an event in the outside world (such as a target or threat), but may also be a visual that displays further information.
- Simulation and virtual environments. Adding the sense of touch may enrich simulated environments. This can be in the form of mimicking real world touch sensations when bumping into or grabbing objects, supporting the user's situational awareness, or as substitute for experiences that are difficult to simulate like weight or friction.
- Gaming. Touch cues can also add an extra dimension to games. One could even think of touch-only games. What about using a tactile display as playing field for soccer, tennis or games such as snake and pacman? In multi-player settings, the possibilities are sheer endless.
- Communication. By translating for example military hand signals into a tactile pattern, a tactile display can enable covert communication between team members (Merlo et al., 2006). The same principle can be applied to communicate (a part of) the much more elaborate vocabulary of the sign language for the deaf and hard of hearing.
- Team coordination. Tactile displays can also be used to coordinate actions within a team, whether a team of dismounted soldiers on a secret mission, or a boyband that has to learn how to dance (Van Erp, Saturday & Jansen, 2006).

- People with special needs. Last but certainly not least is the possible spin-off to people with special needs, including people with a visual (Bach-y-Rita et al, 1969), auditory (Borg, Rönnberg & Neovius, 2001) or a vestibular dysfunction (Kadkade et al., 2003; Wall et al., 2001; Kentala, Vivas & Wall, 2003), and the elderly (Priplata et al., 2006).

11.2 Conclusions

We conclude with answering the three main questions given in the introduction:
1) Do they work?
Yes. In all experiments, we found improved performance when users were supported with a tactile display, even in the presence of state-of-the-art visual displays.
2) Can they lessen sensory overload?
Yes. The tactile display proved to be a powerful support tool in situations where other sensory modalities were heavily loaded or provided erroneous cues.
3) Are they intuitive to the degree that they lessen the effects of a high cognitive load?
Potentially, but not automatically. Although we found instances were conditions of a high workload do not degrade performance at all as long as the user has the support of a tactile display, this effect was not present in all experiments.

All in all, we conclude that data gathered in the present experiments are important evidence that using the tactile modality in local guidance tasks can improve performance and lessen the workload, therewith improving the quality and safety of the man-machine-interface for local guidance tasks.

Abstract

Perceiving and understanding information of, for example, a visual navigation display may be difficult for people with a visual challenge or in situations where the user's visual sense and cognitive resources are heavily loaded. Developing information presentation schemes that reduce the threat of overloading eyes and mind becomes increasingly important. Employing the sense of touch can reduce the reliance on the visual system. By developing an intuitive information presentation concept, we may also lessen the cognitive load. In this concept, the display evokes the correct user response automatically. In the tactile sense, an intuitive presentation concept may be based on the proverbial tap-on-the-shoulder. For instance, a localized vibration on the torso can present navigation information like the direction of a waypoint. This made us believe that a tactile display covering the torso may be a three-dimensional display that can reduce the risk of overloading the user's sensory and/or cognitive system.

This thesis addresses nine questions concerned with how we process tactile stimuli on the torso and the behavioural aspects of tactile orientation and navigation displays. The first two questions are concerned with the spatial resolution of the torso for (vibro-) tactile stimuli, and the role of the timing parameters of the presentation. We found a uniform acuity of 3 - 4 cm at the largest part of the torso with only a higher acuity in the area around the midline (1 - 2 cm). We hypothesised that this effect was caused by the fact that the body midline acts as an anchorpoint. The burst duration of the presentation has only a small effect on the acuity, but the Stimulus Onset Asynchrony (SOA) is an important determinant of performance. A smaller SOA (i.e., a more rapid sequential presentation) requires a larger distance between stimuli to make their locations distinguishable. The third question was about the ability to determine the absolute location of stimuli on the torso as opposed to relative localization addressed by the first questions. Observers could localize stimuli within 5 cm from their veridical location. Mislocalizations were mainly along a line originating from the body midaxis. This may indicate that stimulus locations on the torso are coded in polar co-ordinates of which the distance is less important. Displaying directions is the heart of local guidance displays. Therefore, the fourth and fifth question addressed how accurate users can perceive directions with localized vibrations on the torso, and how they determine a direction based on a single point stimulus. There is a bias in perceived directions toward the midsagittal plane, but observers are consistent in their direction determination. The data suggest that observers used one of two internal reference points (one for each torso half) to determine the direction of the point stimulus. The sixth question concerned the crossmodal visual-tactile perception of direction and time and is important because tactile information must often be integrated with other sensory information, especially in a multimodal interface. The experimental results indicate that the same internal representation is used in unimodal and multimodal comparisons. The last three questions addressed the behavioural aspects of local guidance tactile displays and the effect on performance and workload. Question 7 looked at the effect on mental effort ratings when a tactile display is present together with, or instead of, visual information. We investigated this aspect in several task environments including driving and flying. The results show that users rate the required mental effort as lower when they have a tactile display at their disposal. The next relevant question then becomes whether a tactile display can make users immune for (high levels of) mental workload. We found mixed results. We hypothesised that this issue may depend on the design of the tactile information and whether or not it is in accordance with the task characteristics. Finally, we were interested in navigation and orientation performance with a tactile display. Favourable effects were found across the full range of local guidance tasks tested, including vehicle waypoint navigation, target

interception in a jet fighter, maintaining a stable hover in a helicopter, and counteracting spatial disorientation. We conclude that in comparison to a baseline with visual information, tactile displays for orientation and navigation can improve performance and lower the risk of sensory and cognitive overload. All in all, we conclude that data gathered in the present experiments are important evidence that using the tactile modality in local guidance tasks can improve performance and lessen the workload, therewith improving the quality and safety of the man-machine-interface for local guidance tasks.

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Appendix I. Information processing in the cutaneous system: neurophysiology and psychophysics

AI.1 Introduction

This Appendix contains a comprehensive overview of the most relevant neurophysiological and psychophysical data. It serves both as a more detailed introduction to the skin and its information processing system, and as reference for and legitimisation of some of claims and assumptions made in the body of the thesis at places where a detailed explanation would disturb the flow too much.

AI.2 Neurophysiology

This section introduces the physiology involved in cutaneous processing first at a general level, next more specific for vibrotactile stimuli. Many researchers have investigated the physiology of the sense of touch. A comprehensive overview can be found in "Principles of Neural Science, Chapters 24 to 26" (Kandel et al., 1991; see also Greenspan & Bolanowski, 1996; Johansson et al., 1982; Johansson & Vallbo, 1983).

AI.2.1 General physiology

The skin

For the skin to sense a stimulus, the stimulus must evoke a response in at least one receptor. There are several types of receptors in the skin which have a different structure and react differently to different characteristics of the stimulus. In general, four physiological channels are discerned which are assumed to have a 1-to-1 link with mechanoreceptor types in glabrous skin[40]. The superficial skin contains rapidly adapting Meissner corpuscles (also abbreviated to RA or FA I and are presumably linked to the physiological channel NP I) and slowly adapting Merkel receptors (SA I, NP III channel). Deeper tissue contains rapidly adapting Pacinian corpuscles (PC or FA II, P channel) and slowly adapting Ruffini endings or corpuscles (SA II, NP II channel)[41]. Table AI.1 presents an overview of the major

[40] Glabrous skin is non-hairy skin and mainly found in the palms of the hands and on the sole of the feet. Most other skin areas are hairy skin.

[41] Important to stress here is that the terms fast or rapidly adapting and slowly adapting have a relative meaning. Slowly adapting means that the mechanoreceptor response does not change for stimulus durations longer than 1 sec, while rapidly adapting means that it does. However, the timescale of rapidly adapting is not strictly defined (e.g., in the order of hundreds of milliseconds). The signal durations used in this thesis are always smaller than 1 s and usually smaller than 250 ms, and thus in the order that they can evoke a continuous response in both fast and slowly adapting receptors.

characteristics of these four physiological channels. It must be noted that these characteristics are mostly based on measurements of the physiological channels and not directly of the mechanoreceptors.
In hairy skin, the existence of at least three physiological channels has been demonstrated that operate over approximately the same frequency range as the SA II fibres, the RA fibres and the PC nerve fibres in glabrous skin (Bolanowski, Gescheider & Verillo, 1994). In glabrous skin, the two principal types of mechanoreceptors are the Meisner's corpuscle and the Merkel's receptor, in hairy skin it is the hair follicle receptor (Martin & Jessell, 1991) and presumably the PC for higher frequencies (Mahns et al., 2005). Subcutaneous tissue beneath both glabrous and hairy skin contains Pacinian Corpuscles and Ruffini's corpuscles.

The perceptual qualities of touch are likely determined by the combined inputs from the four channels. For instance, both SA Is and RAs are responsible for fine spatial discrimination on the skin, as in the perception of pattern, form and texture (Johansson, 1978). Also, complex events will be coded by ensembles of afferents (Johansson & Birznieks, 2004). Since at certain frequencies the four channels partially overlap in their absolute sensitivities, stimuli may activate two or more channels at the same time. However, with regard to vibrotactile stimuli, one often speaks about two frequency bands or channels: one below 80-100 Hz and one above. Psychophysical results may differ between the two channels, and some effects (like adaptation) only occur within a channel, but not across channels.

Important difference between both types of fast adapting receptors is that the Meisner corpuscles give a more sustained response to vibrotactile stimuli (Gardner & Palmer, 1990) and that the Pacinians show a more on/off response (i.e., one spike only when a stimulus enters or leaves the receptive field). This means that Pacinians are not able to give high quality position information (the size is up to 1 by 4 mm, Sinclair, 1967), although this is argued by Gardner and Palmer (1989). The responses of Pacinians are much more irregular and some have an extra response when the stimulus crosses the centre of the receptive field (Palmer & Gardner, 1990; Loewenstein, 1971), or when the stimulus moves in one of two opposing directions (i.e., orientation specific). The function of the latter may be lateral facilitation (Essick, 1998).

Table AI.1. Characteristics of the four types of mechanoreceptive fibres (physiological channels) of the cutaneous system in glabrous skin.

	rapidly adapting	slowly adapting
superficial skin	**Meissner corpuscle (RA)** ● presumably NP I channel ● small receptive field ● not sensitive to temperature ● 10-100 Hz ● constant threshold over frequency range ● temporal summation: no ● spatial summation: no ● local vibration and perception of localized movement ● extremely sensitive to minute skin indentation, range 4-400 μm	**Merkel cell (SA I)** ● NP III channel ● small receptive field ● sensitive to temperature ● 0.4-100 Hz ● temporal summation: no ● spatial summation: no ● tactile form and roughness ● surround suppression ● sensitive over indentation range 15-1500^{+} μm.
deeper tissue	**Pacinian corpuscle (PC)** ● P-channel ● large receptive field ● sensitive to temperature ● extremely sensitive to vibration (threshold 10 nm) ● 40-800 Hz ● U-shaped threshold-frequency characteristic with a maximum sensitivity near 300 Hz ● sensitive to stimulus size ● sensitive to stimulus duration ● temporal summation: yes ● spatial summation: yes ● perception of external events	**Ruffini ending (SA II)** ● NP II channel ● sensitive to temperature ● large receptive field ● 15-400 Hz ● temporal summation: yes ● spatial summation: ? ● sensitive to skin stretch

The nervous system

The information from the different skin receptors is conveyed to the cortex by afferent nerve fibres that enter the dorsal root (spinal cord) through the dorsal root ganglions. Each dorsal root ganglion serves a specific area of the skin also known as a dermatome. Dorsal roots are organised topologically. The afferent fibres ascend to the contra lateral side of the thalamus via the dorsal column-medial system. Neurons in the thalamus send axons to the primary somatosensory cortex (S1) and the secondary somatosensory cortex (S2). S1 is subdivided into four functional areas: Brodmann's areas 1, 2, 3a and 3b (Kaas, Nelson, Sur, Lin & Merzenich, 1979). All these areas project to S2. Some thalamic neurons project to the posterior parietal cortex, which also receives input from S1. Area 2 sends inputs from the entire body to the primary motor cortex. Finally, the somatosensory cortex projects back to the thalamus and subcortical regions.
In each of the Brodmann's areas of S1, one submodality of proprioception dominates. In area 3a the dominant input is from muscle stretch receptors, in area 3b from cutaneous receptors, in area 2 from deep pressure receptors and in area 1 from rapidly adapting cutaneous receptors. Neurons in area 3a and 3b respond to relatively punctuate stimuli and have quite small receptive fields. Neurons in areas 1 and 2 are involved in the later stages of somatosensory processing, respond to more complex features and have larger receptive fields. The receptive fields are often oval-shaped, both in the afferent fibres (Johnson & Lamb, 1981; Loe, Whitsel, Dreyer, & Metz, 1977), in the thalamus (Kaas, Nelson, Sur, Dykes & Merzenich, 1984) and in S1 (Sur, Nelson & Kaas, 1978, 1982). In the posterior parietal cortex, the

information from the cutaneous and kinesthetic senses is integrated with other modalities. For the processing of vibration, the relevant areas are 3b and 1 of S1 and S2.

AI.2.2 The processing of vibrotactile point stimuli

Melzack and Wall (1962) introduced six general propositions for the sensory processing of stimuli:
1) receptor activity is specialised with respect to the stimulus characteristics
2) the neuronal patterns from the receptors may be filtered
3) central nerve cells may also be specialised (i.e., they can act as a filter or select specific features)
4) central cells may filter or select on the basis of input from multiple fibres
5) central cells have specific connections (including inhibitory and excitatory connections)
6) central cells need more than a single pulse for detection (either from the same fibre or from different fibres).

For the processing of vibrotactile stimuli, we can simplify this by discerning the following stages / structures:
1. the periphery, in which there are two types of mechanoreceptors in the skin that respond to vibrotactile stimuli (and the neuronal paths to the thalamus and on to higher cortical areas which are merely involved in transporting the mechanoreceptor signals),
2. the primary somatosensory cortex, principally area 3b and area 1,
3. the secondary somatosensory cortex.

The periphery: mechanoreceptors and primary afferents

An important observation is that vibrotactile stimuli with a fixed location (including those eliciting apparent motion) predominantly elicit a response in fast adapting mechanoreceptors and not in the slowly adapting (Gardner & Palmer, 1989). This means that only Meisner (Me) and Pacinian corpuscles (PC) are involved in the processing of this kind of stimuli. Please note that this also implies that the peripheral processing of *apparent* motion (i.e. discontinuous, nonmoving stimuli) fundamentally differs from the processing of real motion (either with or without friction, and continuous or discontinuous, e.g. see Edin, Essick, Trulsson & Olsson, 1995; Olausson, 1994; Norrsell & Olausson, 1994; but see also Gardner, Hamalainen, Palmer & Warren, 1989; Lerner & Craig, 2002).

Studies of peripheral responses to spatio-temporal patterns have revealed that there may be some processing happening at the peripheral level. Although an individual mechanoreceptor may have a preferred direction of motion, it is not clear whether there is a preference across a population of mechanoreceptors or not. For example, Essick and Edin (1995) found no indication, while Valbo, Olausson, Wessberg and Kakuda (1995), who studied spikes in afferents, found more activity in the distal to proximal direction than vv. This indicates that some form of feature extraction may already be performed at the peripheral level. Primary afferents have a systematic coding. For example, opposing directions show mirror patterns of activation (Ray, Mallach & Kruger, 1985). However, whether this is also the fact for frictionless discontinuous motion is not clear.

Central: primary and secondary somatosensory cortex

Unfortunately, not all authors use the same level of specificity when presenting data related to the somatosensory cortices. In general, going from less to more specific areas, authors speak of the somatosensory cortex; the somatosensory cortex divided in the primary (S1) and secondary (S2) somatosensory cortex; and S1 subdivided in areas 1, 2, 3a and 3b. The processing of vibratory stimuli in S1 is predominantly done in areas 1 en 3b. Also, much of the research is based on studying animals. In this Section, I indicate this with the addition ‘nonhuman data’ with the reference.

The global architecture after the primary afferent fibres is as follows (see also Figure 3.1). Signals follow the lemniscal pathway up to the contralateral thalamus. The thalamus has only one somatotopic map, but keeps the strict separation between the physiological channels. The thalamus knows no motion (Kandel & Jessell, 1991). The thalamus projects to different cortical areas, amongst others: to the secondary somatosensory cortex and to area 3b and area 1 in the primary somatosensory cortex (e.g., Mountcastle, 1984). The debate about whether the processing in S1 and S2 is parallel or serial has not resulted in a definite answer yet (Turman, Morley & Rowe, 1998 (nonhuman data); Iwamura, 1998). However, there are dense connections between the different areas, including from S1 to S2 and vv. (Mountcastle, 1984). Also relevant are the connections within S1 from area 3b to 1 (Turman, Morley & Rowe, 1998 (nonhuman data); Mountcastle, 1984), and possibly vv. (as found by Turman, Morley & Rowe, 1998 (nonhuman data), but not by Mountcastle, 1984). In some areas, there are also ipsilateral projections through callosal connections and/or bilateral terminations. Ipsilateral projections are absent in 3b, partly in 1 (midline and proximal areas only), and complete in S2. The clustering of callosal neurons and bilateral terminations leads to a body midline that is congruently represented in both hemispheres (midline fusion) probably to ensure a unitary perception of the somatosensory space (Conti, Fabri & Manzoni, 1986 (nonhuman data); Manzoni, Barbaresi, Conti & Fabri, 1989; Iwamura, 1998; Fabri et al., 2005). Ipsilateral projections and the level at which callosal connections are established may play an important role in certain psychophysical phenomena and perceptual illusions (see Section AI.3.5).

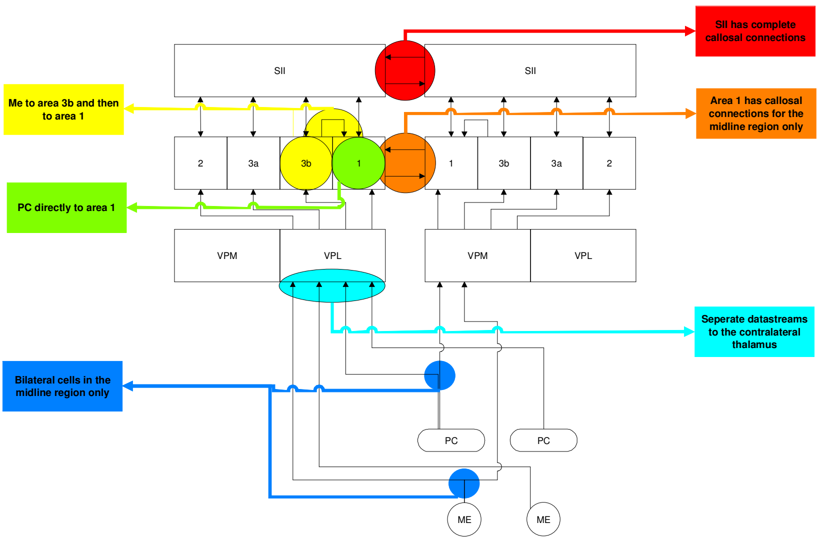

Figure AI.1. Overview of the most important structures involved in the processing of vibrotactile stimuli. PC means Pacinian Corpuscles, Me Meisner receptors. S2 is the secondary somatosensory cortex, 2, 3a, 3b, and 1 are the areas of the primary somatosensory cortex, VPM and VPL are the areas of the Thalamus. Please read the figure from bottom to top.

Area 3b

Area 3b receives its input mainly from the Meisner corpuscles (Turman, Morley & Rowe, 1998 (nonhuman data)). The lower level neurons in 3b are hypothesized to have a three-factor model (DiCarlo & Johnson, 2000 (nonhuman data)). In theory this model is direction sensitive through the lagged inhibitory component. Although area 3b shows a response to moving stimuli (Bodegard, Geyer, Naito, Zilles & Roland, 2000; brushing stimuli, PET scan), it is a matter of debate if area 3b contains motion sensitive neurons. Kandel and Jessell (1991) and Gardner (1984) do not find any motion sensitive neurons, but Romo, Zainos, Merchant, Hernández and García (1998, nonhuman data) do. However, area 3b is not sensitive to *direction* of motion[42] (Romo et al.,1998, nonhuman data).

Area 1

Area 1 receives its major input from the Pacinian corpuscles (Turman, Morley & Rowe, 1998 (nonhuman data); Kaas, 1984 (nonhuman data); although debated by Romo et al., 1998 (nonhuman data)). The receptive fields are relatively large (e.g., Kandel & Jessell, 1991). In area 1, motion, orientation, and direction specific neurons are identified (e.g., Gardner, 1984). Area 1 is therefore probably the first level at which direction sensitive neurons are found (Bodegard et al., 2000). The population seems to have a bias for transversal over longitudinal and for distal over proximal directions (Gardner, 1984; Kandel & Jessell, 1991). Confirmed by psychophysical data (Fuchs & Brown, 1984, with two point discrimination, and Gould, Vierck & Luck (1979) with a continuous probe stimulus).

S1

Data in this section are on S1 and are not further specified to the subarea where they were recorded. The existence of motion and direction sensitive neurons in S1 is confirmed by for example Warren, Hamalainen and Gardner (1986, nonhuman data), and Whitsel, Roppolo and Werner (1972, nonhuman data). Essick and Whitsel (1993) found interesting effects for the presentation of two motion stimuli at specific locations in the RF and either simultaneously or consecutively. For example, for some cells the activation for sequential presentation of two motion (brushing) stimuli is larger than for simultaneous presentation, while other cells show an enlarged activation with simultaneous presentation. This also seems to depend on the spatial configuration. Some cells have increased amplitude in their centre when motion is initiated outside the RF (Moore, Blake, Coq, Strata, Garabedian, Dale & Merzenich, 2002 (human and nonhuman data)). Other facts described in the more specific sections above are also confirmed: the size of the RF is much larger than that of the peripheral RFs (Gardner et al., 1992). Sometimes responses are uniform across the receptive field, sometimes strong at initial point of entry. Because a point of entry alone cannot contain motion information, it may also indicate the existence of a feed forward mechanism (e.g., from area 3b to area 1). Also the existence of lateral inhibition (Calford, Clarey & Tweedale, 1998) and the restricted ipsilateral map (Manzoni et al., 1989) are confirmed.

S2

The secondary somatosensory cortex receives its main input from the Meisner corpuscles (Turman, Morley & Rowe, 1998 (nonhuman data)). S2 has a complete ipsilateral map (Manzoni et al., 1989).

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[42] In general, a distinction is made between motion sensitive (i.e., independent of direction), orientation sensitive (i.e., sensitive to motion along a specific axis only) and direction sensitive (i.e., sensitive to motion in a specific direction only).

Somatosensory cortex

Some authors use the very general term somatosensory cortex. Cortical RFs are larger than peripheral (Gardner, Palmer, Hamalainen & Warren, 1992). Sometimes, the responses are equal across the RF (i.e., the responses contain no specific location or direction information within the RF), sometimes they are strongest at the initial point of entry. Gardner et al. (1992) found that low frequency repetitive stimuli are more effective in activating cortical neurons while higher pulse rates are not.

AI.3 Psychophysics

The following four sections are concerned with an overview of psychophysical data related to the amplitude, location, timing, and frequency of stimuli. These four parameters define the touch stimuli the skin is sensitive to (i.e., excluding temperature and nociceptive stimuli, see Section 1.5). The perception of spatiotemporal patterns which is of particular interest to the present research is presented in Section 2.3.5.

AI.3.1 Psychophysics of amplitude

The first aspect of a stimulus is of course that it should be detected. In other words: the stimulus should have a minimal amount of energy, often expressed in the amount of force, indentation or amplitude. Linked to amplitude are the difference threshold, or the minimal required change in amplitude to be detected, and subjective magnitude: how does the objective intensity or amount of energy of a specific stimulus relate to the intensity the observer perceives?

Absolute detection threshold

Sherrick and Cholewiak (1986) indicate that the absolute threshold for vibrotactile stimuli for the trunk is 4 microns at 200 Hz. A more extensive study was done by Wilska (1954) who measured thresholds for 200 Hz vibration over the body, including the frontal side of the torso (lower part: threshold 4 micron, upper part 2 micron) and the dorsal side of the torso (4 micron). In a recent study, Cholewiak, Brill and Schwab (2004) measured detection threshold on six sites around the torso as function of frequency. Their results show that thresholds vary little as a function of body site over the six stimulus frequencies. Since the pattern of results resembled that found on the forearm by Bolanowski et al. (1994), the authors suggested that a similar range of receptor types underlies vibrotactile sensitivity on the torso.
Verrillo (1962, 1963) measured thresholds for vibrotactile stimuli on the glabrous skin of the palm as a function of frequency, location and several contactor properties. The threshold as a function of frequency was U-shaped with a maximum sensitivity in the region of 250 Hz. However, this value is only valid for relatively large contactor areas. Different locations differed in sensitivity. Verrillo (1966) also determined absolute thresholds as function of frequency on the hairy skin of the volar forearm. There were two marked differences with the results found with glabrous skin. First, thresholds on hairy skin were higher than those on glabrous skin. Second, the maximum sensitivity shifted from 250 Hz for glabrous skin to 220 Hz for hairy skin. The thresholds for force as measured by Weinstein (1968) are in the order of 60-80 milligrams for the torso.
Other factors that have an effect on the absolute threshold but are not relevant for the experiments in this thesis are the contactor layout (Van Doren, 1990), the presence of a rigid surround and how deep the contactor is pressed into the skin (Verrillo, 1962, 1963), waveform, and temperature (Green, 1977).

Difference threshold

Craig (1972) measured difference thresholds for the intensity of vibrotactile stimuli. For taps, the Weber fraction depends on the stimulus intensity with higher fractions for low intensities (0.35 at 15 dB) and lower fractions for higher intensities (0.25 for 25 dB and higher). For bursts, the Weber fractions were 0.20 and constant over the range of stimulus intensities (15-35 dB). Other factors that have an effect on the difference threshold are background vibration (Craig, 1972), and adaptation (Goble & Hollins, 1993).

Subjective magnitude

The intensity of a supra threshold stimulus is often indicated with reference to the absolute threshold of the stimulus (dB SL). Stimuli with the same objective intensity level are not necessarily perceived to be equal in subjective intensity, and for example doubling the objective intensity or amount or energy does not necessarily result in a doubled subjective intensity. Verrillo, Fraioli and Smith (1969) found that the subjective magnitude as a function of objective magnitude is a power function with an exponent around 1. In a second experiment, contours of equal subjective intensity were measured as function of vibration frequency. At low intensities the equal-subjective-intensity contours were parallel to the (U-shaped) absolute threshold curves. At higher intensities the contours assumed a smoother, more uniform slope over the entire frequency range. Other factors that have an effect are the stimulus duration (Verrillo & Smith, 1976), the number of successive bursts (Verrillo & Gescheider, 1975), the presence of static surround (Verrillo & Chamberlain, 1972), the frequency and intensity of a preceding stimulus (Verrillo & Gescheider, 1975), and the number of simultaneous vibrators Cholewiak (1979). As a coding parameter, (subjective) intensity seems less appropriate. Not more than 4 different levels should be used between the detection threshold and the comfort / pain threshold (Craig, 1972).

Spatial summation

The change in threshold as function of the area of stimulation is known as spatial summation. Makoes et al. (1996) investigated spatial summation under different conditions. Their results showed that spatial summation exists for high frequencies for all types of skin. However, for low frequencies summation was present on the hairy skin of the forearm but not on the glabrous skin of the hand. Sherrick and Cholewiak (1986) already concluded that the sense of touch exhibits spatial summation, but that it is small and probably a central and not a peripheral process. Other factors that have an effect are skin indentation, pressure and force (Craig & Sherrick, 1969), intensity level (Green & Craig, 1974), and the number of loci (Craig, 1968).

AI.3.2 Psychophysics of location

The foregoing section dealt with perceiving (the intensity of) a stimulus at a single location. This section deals with the perception of stimulus location. Relevant issues are how well we can determine the location of a stimulus (absolute localization), how well we can discern different locations from each other (relative localization or the spatial resolution of the skin), and how can spatially separated stimuli influence each other (spatial masking). The latter is discussed in Section AI.3.5 on spatiotemporal patterns.

Absolute localization

With absolute localization, we refer to the ability to locate a stimulus on the body or in 3D space. The methods to measure spatial resolution are based on relative localization of two stimuli, or the difference between two stimuli, but do not measure where on the body the stimuli are precisely located. For a display that links external events with a specific location on the body, absolute localization is at least as important as relative localization. Principally, both measures can be independent, like a darter that throws his dart close together (i.e. a high spatial resolution), but in the wrong number (bad absolute localization). Only recently, absolute localization became a topic of psychophysical studies. Besides the work at TNO that started in 2002 (Van Erp & Van Veen, 2002), Cholewiak and colleagues started their first attempts somewhat later in 2003 with studies in which observers had to translate the perceived location of a single stimulus on the forearm (Cholewiak & Collins, 2003) or the abdomen (Cholewiak, Brill & Schwab, 2004) to predefined categories such as markers on a cylinder. In both studies, it was found that localization[43] was affected (or biassed) by body landmarks or anatomically defined anchor points (including elbow, spine and navel) that acted as reference points and enhanced performance.

Spatial acuity

Spatial acuity of the skin has been investigated by several methods, e.g. two-point discrimination, gap detection, grating resolution, and letter recognition (Johnson & Phillips, 1981). However, many studies use pressure stimuli to measure spatial acuity, and not vibrotactile stimuli as was the case for the detection threshold. This lack in the literature was recently confirmed by Cholewiak and Collins (2003). Also, most studies investigated the finger (tips) as body locus. Because vibratory stimuli act upon different sensory receptors (see Section AI.2) and result in both longitudinal and shear waves that may degrade spatial resolution (depending on the tactor - skin contact; see Vos, Isarin & Berkhoff (2005) for wave propagation models for the skin), it is doubtful whether pressure data may be generalised to vibration stimuli.
A classic study is that of Weinstein (1968) who measured thresholds of two-point discrimination and tactile point localization on several body loci using pressure stimuli. Although he did not use vibratory stimuli and there are several methodological problems with the two point-point threshold as measure for spatial resolution (Craig & Johnson, 2000), the results give a good idea of the enormous differences between different body loci (see also Stevens & Choo, 1996). Lowest thresholds were found for the fingertips, about 2 mm. Thresholds for the trunk were much larger, up to 4 cm. Other interesting observations were that sensitivity decreased from distal to proximal regions (see also Vierodt's law of mobility; Vierodt, 1870), which Weinstein did not find for the detection threshold), and that the acuity correlated with the relative size of cortical areas subserving a body part (Merzenich & Kaas, 1980[44]).

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[43] Actually, Cholewiak et al.'s task is more a location classification task than an (absolute) localization task. See Chapter 4 for a further discussion.

[44] Because somatotopic maps are found throughout the somatosensory cortex, it is hard to pinpoint the location were acuity related tasks are performed. Besides the receptive field sizes of single afferent nerve fibres, one has also determined the receptive field sizes of the different cortical regions involved in cutaneous processing. Between the different cortical regions, body parts are differently represented. The smallest receptive fields are found in area 3b, but the high spatial sensitivity in area 3b is still less than that of most peripheral receptors (Burton & Sinclair, 1996). Combined with the fact that the spatial resolution (in mm) of peripheral fibre innervation patterns can be less than some spatial thresholds (in mm) (Lamb, 1983a, b; LaMotte & Whitehouse, 1986), this suggests the involvement of some central enhancement mechanism, for instance via excitatory and inhibitory connections (Mountcastle, 1984). In general, the spatial acuity in the Meisner corpuscles afferents and in area 3b are higher than elsewhere in the central processing chain, so this may be a logical location for spatial acuity tasks to be located. However, the Meisner corpuscles afferents also projects directly from the thalamus

Other factors that have an effect on spatial resolution are the temperature of the objects that are touched (Stevens, 1982) and of the skin itself (Provins & Morton, 1960). Sherrick, Cholewiak and Collins (1990) investigated spatial localization with vibrotactile stimulation. The frequency range of the vibration had little effects. They also studied apparent location. The apparent points were more difficult to localize than physical points.
Interestingly, hyper acuity in tactile sensation has hardly been investigated. However, the results of Loomis and Collins (1978) show that the thresholds for frictionless shifts in the position of a point stimulus were 10-30 times smaller than the resolution reported by Weinstein (1968), also when measured on the torso. Later, Essick and colleagues showed that judgment of the direction of apparent motion induced by dense arrays of tactors is much better than predicted on the basis of local spatial resolution (Essick et al, 1991; Essick, 1998).

AI.3.3 Psychophysics of timing

This section concentrates on the role of time in cutaneous perception: the temporal resolution of the skin and temporal masking and summation effects, but also adaptation after prolonged stimulation.

Temporal acuity

Several methods have been used to measure temporal acuity. A general definition of temporal acuity would be: the minimal difference in the time domain required to distinguish two stimuli, including temporal order (which came first), duration, and gap detection. Unimodal threshold studies have shown that the temporal resolution of the skin lies between those of hearing and vision (Kirman, 1973). This relation goes for numerous time related measures and tasks, including discrimination of duration (Goodfellow, 1934), synchronization of finger taps (Kolers & Brewster, 1985), and adjusting empty intervals to equal pulse duration (Craig, 1973).
Like spatial resolution, temporal acuity has also been measured by several methods, including for example temporal numerosity (Lechelt, 1974). Important work was done by Gescheider (1974) who measured the perception of successiveness as the ability of observers to distinguish between successive and simultaneous events. He showed that two stimuli of 1 ms must be separated by 5.5 ms to be perceived as two stimuli at a single locus on the fingertip. Petrosino and Fucci (1989) measured thresholds of successiveness as the ability to accurately count a series of events presented within a temporal epoch. Thresholds were found to increase with age and locus and ranged from 13 to 30 ms. These values are larger than that obtained by Gescheider (1974).
Hirsh and Sherrick (1961) investigated the perception of temporal order, i.e. the ability to judge which of two successive tactile events came first in time, and found that the percentage correct increased with temporal separation between the stimuli, with 20 ms as 75% correct threshold. This value is larger than that for successiveness, but the task involves both what and when: observers had to judge the temporal order and which pattern was presented first.
Craig and Baihua (1990) measured temporal order judgements for stimuli presented to a single finger pad (same site), to two fingers on the same hand (ipsilateral), or to two fingers on opposite hands (bilateral). Thresholds were 12 ms for the same-site condition, 65 ms for the bilateral condition and 125 ms for the

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to S2 (not via S1) and a task such as point localization can easily (and with high acuity) be performed when the points straddle the body midline (Adams & Helson, 1966; Fuchs & Brown, 1984). This indicates that these tasks can very well be performed by S2, were both the contralateral and the ipsilateral body half are represented. The function of the high spatial resolution of area 3b may be related to other tasks than spatial acuity tasks, such as perceiving structures and surfaces.

ipsilateral condition. In a control experiment, subjects judged which of two locations received a pattern first when the same pattern was delivered to both locations. Thresholds for the bilateral and ipsilateral condition were similar to those obtained by Hirsh and Sherrick (1961), although they used a 1 ms-pulse instead of a vibration stimulus of 26 ms.

Short burst duration

In general, stimuli with a short burst duration (BDs smaller than 30 ms) are supposed to be processed differently by the nervous system (Sherrick, 1968a, b; Kirman, 1974a). Although there are no psychophysical data available that investigates this directly, several authors come to the same statement. For example, Hill and Bliss (1968b) suggest that for small BDs, the sequence of the presentation is lost, not the content (in their case which of 24 regions of the fingers was stimulated). In the data of Kirman (1974a), there is a small hint that there is a larger SOA required for stimuli with smaller BD to be felt as successive instead of simultaneous. Important data also comes from studies on apparent motion. To feel smooth apparent motion requires a steeply rising SOA for BD values below 30 ms (see section 2.3.5).

Temporal difference thresholds

Only a few studies investigated difference thresholds in the timing domain, or more specifically, the Weber fractions for temporal intervals. Important theoretical work was done by Grondin and colleagues. The Weber fractions reported range from 0.10 (Grondin, 1998; McKee and Taylor, 1984; Goodfellow, 1934 or p. 219 in Fraisse, 1978) up to 0.25 (Grondin, 1993) all for stimulus durations shorter than 1 s.

Temporal summation

The relationship that exists between duration of a stimulus and the threshold required for detection is known as temporal summation. Verrillo (1965) found effects of summation to require a minimal area of stimulation. Summation effects were found up till durations of 1000 ms. For taps, temporal summation is exponentially for the range 1-10 ms and constant for 10-100 ms.

Adaptation

Another effect of stimulus duration is adaptation. Adaptation corresponds to a change in the percept of a stimulus after prolonged stimulation[45]. The absolute threshold increases and the sensation magnitude decreases with increasing adaptation. The time constant of the adaptation process is approximately 2 min (Hollins et al., 1990) and the effects can be found up to 25 min of constant stimulation after which the change in the threshold is about 17 dB and the change in sensation about 6.5 dB. Recovery time is approximately half the duration of the adaptation time (Hahn, 1966, 1968). Adaptation does not occur across frequency bands (Verrillo & Gescheider, 1975; Gescheider & Verrillo, 1979; Capraro et al., 1979; Hollins et al., 1990; Hollins et al., 1991). Interesting to note is that O'Mara et al. (1988) investigated vibrotactile adaptation by means of physiological experiments. They found that extended exposure to a vibratory stimulus produced substantial changes in the responsiveness of subcortical cells but not in the peripheral afferents. This indicates that vibrotactile adaptation is largely a central process.

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[45] Adaptation refers to a change in the sensitivity of the sensory system while habituation refers to attentional effects or loss of awareness for a repetitive stimulus. Habituation effects disappear as soon as attention is given to the stimulus.

AI.3.4 Aspects related to frequency

As with the other parameters, one can also manipulate the frequency of stimulation and measure for example difference thresholds of frequency as Goff (1967) did. However, when varying frequency, care must be taken not to vary subjective intensity as well. Similar to the detection threshold, subjective magnitude of vibrotactile stimuli is frequency dependent. This requires measuring frequency contours of equal intensity first. Goff found that the Weber fraction of frequency increased with increasing frequency and for stimuli with a lower intensity, and ranged between 0.18 and 0.55. Cohen and Kirman (1986) showed that thresholds increased for stimuli with a very short duration (30 ms). Rothenberg, Verrillo, Zahorian, Brachman and Bolanowski (1977) found Weber fractions in the order of 0.20-0.25 for pulse repetition rates between 20 and 300 Hz. Goff advised not to use frequency as an information parameter in tactile communication systems at high frequencies.

AI.3.5 Aspects related to spatiotemporal perception

Vibrotactile phenomena such as apparent motion and position, and determining the relative location of two or more consecutively presented stimuli (point localization) are based on the processing of spatiotemporal patterns. This implies that there is a mechanism that is able to integrate place and time. This mechanism might actually be very powerful (for example, judgments of the direction of apparent motion can be more accurate than spatial resolution performance (Essick et al, 1991; Essick, 1998)), but may also result in masking effects.

Spatiotemporal processing in the primate and human brain is assumed to be based on location as primary parameter and additional time-modulated processes such as lateral inhibition and facilitation. Through these processes, neurons are created that are sensitive to specific spatiotemporal patterns. This assumption is logical because representations in the somatosensory cortex and other areas involved in the processing of somatosensory stimuli are location based (also called somatotopic). Spatial relations are carefully preserved in the neuronal pathways and in the representations in the cortex.

Sensory saltation

The saltatory area (Cholewiak, 1976; Geldard, 1975, 1982, 1985; Geldard & Sherrick, 1983, 1986; Kilgard & Merzenich, 1995) refers to the area where mislocalization occurs for two successive and spatially separated stimuli. Saltatory areas are found over the whole body, but they never cross the body midline. Their size and form are related to those of the cortical RFs, i.e. small at body loci with a large cortical representation (fingers, arm), and vv. (thigh, torso), and with an oval form along the long axis of the limb). The process exists for strict timing parameters, of which the ISI has the major influence. BD must be in the order of 5 ms. The vividness and strength of the saltatory effect are supported by psychophysical data from a study done by Cholewiak and Collins (2000). They investigated the perception of different line qualities (e.g. length, smoothness) under veridical and saltatory presentation modes as function of the timing parameters. They concluded that there were no differences between the two modes.

The cutaneous rabbit

The cutaneous rabbit is the name given to a spatiotemporal perceptual illusion that made the researchers think of a tiny rabbit hopping over their body (Geldard & Sherrick, 1972). The rabbit also occurs under strict temporal parameters. Again the BD must be very short, i.e. a tap in the order of 2 ms. The illusion is based on a series of these taps, delivered to two separate locations, with multiple taps at the first location. When the timing between the taps is right, the observer feels the taps spaced between the two locations where the taps were actually delivered (please note that this both resembles saltation and apparent motion, except for the fact that individual taps are felt instead of continuous motion). For ISIs larger than 200 ms, the effect is absent. For ISIs between 200 and 100 ms, the displacement starts, with the taps more or less evenly spaced at 100 ms ISI. The illusion is optimal for ISIs between 40 and 60 ms for a five-tap rabbit. The number of taps becomes illusory for ISIs below 40 ms. The importance of the timing parameter is confirmed by the fact that gaps in the stream seriously degrade the illusion. Besides the ISI, the number of taps is important: 2 is enough, 4-6 is optimal, 18 is too much. Distance is not important. The rabbit can cross the body midline only if one of the locations is on the body midline. The illusion is very strong when both locations are within the same dermatome, but very weak or absent between dermatomes (Geldard & Sherrick, 1972).

Apparent motion

Apparent motion is a perceptual illusion in which two or more nonmoving stimuli activated in a specific spatiotemporal pattern evoke a percept of continuous motion. The percept is not always stable. Although mentioned in the early psychophysical literature (e.g., Hulin, 1927), it was not until the 1960s that researchers were able to evoke a reproducible effect (Sherrick, 1968a, b; Bice, 1969). Sherrick reported that apparent movement can be induced by successive bursts of vibration but not by pressure stimuli, which yield unreliable judgements of movement. It has been shown that the significant variable for the appearance of ‘good’ movement is the interval between onsets of stimuli (SOA). Sherrick investigated which variables determined the optimal SOA for good movement. The following variables had no effect on the quality of movement or the optimal SOA: vibration frequency (60-250 Hz), body locus (forearm, back, stomach, hand), subjective magnitude (6-30 dB SL, see also Gardner & Sklar, 1994), direction of motion (proximal-distal or vice versa) and magnitude imbalance (when one stimulus had twice the intensity of the other). Stimulus duration was crucial for good apparent movement: the optimal SOA varied linearly with stimulus duration for 25 to 400 ms (with SOA about 0.70 of the stimulus duration, and an offset of 60 ms). Kirman (1974a) used a rating method to measure the quality of apparent movement. The degree of apparent movement varied as function of SOA: the function first increased and then decreased. Both the optimal SOA and the impressiveness of apparent movement increased with stimulus duration above 20 ms.

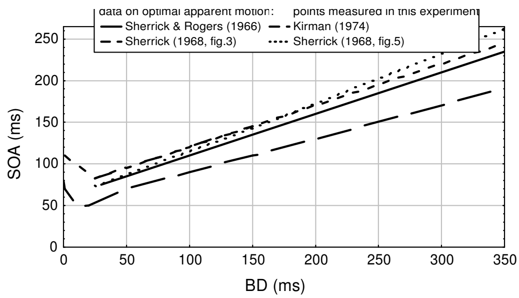

Figure AI.2. Typical relation between the burst duration (BD) and the stimulus onset asynchrony (SOA) for good vibrotactile apparent motion.

Apparent motion is thus an illusion that is mainly related to timing parameters (and the number of stimulus sites, Kirman, 1974b, Sparks, 1979). When apparent motion is plotted as function of BD and SOA, the typical pattern (depicted in Figure 3.5) shows a decreasing SOA for smaller BD till a bottom value around 30 ms (which is equivalent to a decreasing ISI for larger BDs as found by Grossberg and Rudd, 1992). For BDs smaller than 30 ms, the required SOA increases (Sherrick & Rogers, 1968; Sparks, 1979;

Kirman, 1983; Kirman, 1974a; Grossberg & Rudd, 1992). This dip or kink is of course absent in studies that haven't used BDs near or below the critical value.
What is remarkable about the dip in Figure 3.5 is that it is located near the threshold for temporal order and the critical BD value below which stimuli may be processed differently (see Section 2.3.3). Interesting is that the data for vibrotactile stimuli are similar to that for the visual system (including the dip)[46]. The dip is also present for movement between both arms (Sherrick, 1968a, b). This indicates that apparent motion can be extracted at a post callosal level.
The existence of a specific motion detection mechanism was concluded from the facts that motion is not related to the processing of place and time as separate entities (for details on the prove of this, see Gardner & Sklar, 1994; Essick, McGuire, Joseph & Franzen, 1992), that there is no link between motion and point localization (Norrsell & Olausson, 1994), and that place, time and motion can exist independently (Essick & Whitsel, 1988).

Pattern recognition

Pattern recognition (i.e., identification and discrimination, see also Cholewiak & Collins, 1995) as function of timing parameters has not extensively been studied. Cholewiak and Craig (1984) report that their data is more accurately described by SOA than ISI. An interesting fact in their data is that there is a dip in the BD / SOA relation, quite similar to that found in the apparent motion graphs.

Masking

Masking is a change in the percept of a stimulus (target) when a second stimulus (masker) is close in time and/or space. The masker may (negatively) effect several aspects of the target. Including the absolute threshold, the difference threshold (e.g., Craig, 1974), and the perceived location. Furthermore, observers may respond with the masking stimulus as though it was the target (also called response competition, which assumes that both target and non target interfere at a later state of processing; Craig, 1995; Evans & Craig, 1992). When two patterns occupy the same location at different times, one speaks of temporal masking. In general, the interference between the patterns decreases when the temporal separation between the onsets of the two patterns increases. The masking pattern can be presented prior to the pattern to be identified (forward masking) or subsequently to the target pattern (backward masking). Both types do not always result in the same amount of masking (Craig & Evans, 1987). At brief SOAs (< 100 ms) they found more backward than forward masking. However, when the SOA was relatively long (> 200 ms) backward masking became negligible whereas forward masking remained visible for SOAs up to 1200 ms. The same pattern was already found by Bliss et al. (1966). However, Gescheider, Bolanowski and Verrillo (1989) did not find differences and Weisenberger (1994) found more forward masking than backward masking for relatively short ISIs. The difference between the mentioned studies might be due to the difference between signal detection (Gescheider, Bolanowski and Verrillo, 1989; Weisenberger, 1994) and pattern

[46] Parallels between the visual and the tactile system in general and with regard to motion processing in specific were pointed out by Campos, Lopez and Perez (1998), Feinsod, Bach-y-Rita, Madey and Somoes (1973), Hsiao (1998), and Kirman (1974a). However, Hsiao's choice to assign the Meisner corpuscles the same function as the magnocellular pathway in vision is rather arbitrary. The main argument is that the spatial resolution of the Pacinian corpuscles is too low. However, it may be argued that spatial resolution is far less critical in apparent motion perception (i.e. with discontinuous stimuli) than in tasks such as structure and surface perception. This is not in contradiction with the extremely high sensitive found with continuous stimuli, which is often higher than spatial resolution tasks, see Barlow (1987) for an overview.

recognition (Craig and Evans, 1987; Bliss et al., 1966). Probably very different processes are involved in detecting simple vibrotactile signals and in recognising complex patterns of stimulation. Other factors that affect the amount of temporal masking are the type of masking stimulus (Craig, 1982a) and the frequency of the stimuli (no cross-channel masking, Verrillo & Gescheider, 1983). When two stimuli occupy two locations but at different (possibly overlapping) times, one speaks of spatial masking[47]. Sherrick (1964) measured the detection threshold of a pulse masked by a second pulse as function of the inter stimulus interval and the spatial distance. He found that the amount of masking decreased when the spatial separation between the two stimuli increased. He also found that contralaterally placed maskers showed masking effects which indicates that the interaction between the pulses is not solely a peripheral process but requires some degree of central involvement. Verrillo and Gescheider (1983) found masking (increased detection thresholds) predominantly for high frequency stimuli. A very specific situation occurs when a target is masked by another stimulus that is presented at the same location and at the same time. Gescheider, Bolanowski, Verrillo, Arpajian and Ryan (1990) measured this by presenting a specific target (an amplitude change) in a continuous white noise vibration. The thresholds increased with increasing masking intensity. Finally, masking can also occur when target and masker overlap neither in time nor in space (although they are in close proximity both spatially and temporally). Weisenberger and Craig (1982) let subjects identify vibrotactile patterns presented to their left index fingertip in the presence of spatially adjacent masking stimuli. Forward and backward masking decreased with increasing SOA (although actually ISI is a better term to indicate the amount of overlap). Maximum interference in pattern recognition was found to occur at an SOA of about 50 ms.

Theories for spatiotemporal processing

In general, the psychophysical theories do not agree on the specific mechanisms underlying spatiotemporal integration or masking phenomena[48]. Below, some theories on masking will be discussed briefly.
Bliss et al. (1966), studying the effect of temporal masking on pattern identification, described masking with a model consisting of three intervals: 1) a read-in interval of 50 to 100 ms in which stimuli occurring in the interval are superimposed, 2) a period of 75 to 200 ms in which a second stimulus may cancel or replace the first stimulus because both stimuli occur in the same temporal epoch, and 3) an interval in which the mutual interference between the two stimuli is reduced. Craig (1982a, 1982b) and Evans (1987) suggested that temporal masking obtained with vibrotactile patterns occurs because of two processes: interruption and integration. Interruption arises when the features of a target are distorted or confused with features of a masker. It is responsible for producing greater amounts of backward masking than forward masking. Temporal integration operates in both backward and forward masking paradigms. Two patterns that are presented in close temporal and spatial proximity are integrated into a composite form in which the target pattern is obscured.

[47] Please note that many of the phenomena presented in the beginning of Section 3.5 of this Appendix can also be considered as masking effects since the percept differs from the original stimuli because of overlap in time and/or space.

[48] The existing neurophysiological models of spatiotemporal mechanisms focus on a specific neuronal structure or the interaction of two or small groups of neurons. Although these models describe or explain specific effects, they do not make a link to behaviour of the organism as reflected in the psychophysical data and which is also the main focus of this thesis. The same holds for the general models or theories of cutaneous sensitivity, such as the specificity theory of von Frey (see Melzack & Wall, 1962) and the pattern theory of Nafe (Nafe, 1934; Nafe & Kenshalo, 1962; Weddell & Miller, 1962).

Craig and Evans (1987), who found that forward masking occurred for SOAs up to 1200 ms, argued that the presentation of a vibrotactile pattern yields an internal representation that persists following the cessation of a stimulus for a certain amount of time. The information contained within the tactile sensory store decays rapidly at first (till SOA = 100 ms) and then at a slower rate (till SOA = 1200 ms). Backward masking is strong at SOAs < 100 ms since information presented to the same place of the skin is integrated over a temporal window of approximately 100 ms. The reason that at relatively long SOAs there is more forward masking than backward masking is that the representation of a pattern persists for about 1200 ms. Gescheider, Bolanowski and Verrillo (1989) mentioned that according to Kirman (1984) forward masking may be primarily a peripheral interaction maximally evident when peripheral interaction between target and masker occurs, while backward masking has a strong central component. However, Craig and Evans (1987) discussed that the persistence of features of vibrotactile patterns after stimulation, which explains forward masking at long SOAs, is probably not a peripheral process.
Gescheider et al. (1990), who found that the effect of a masking stimulus on the vibrotactile threshold was independent of frequency, concluded that either the neural processes responsible for vibrotactile masking must be the same for each vibrotactile channel or the whole process operates at a level in the central nervous system that integrates information across the psychophysical channels. However, the first conclusion seems to be more likely, since Verrillo and Gescheider (1983) found that masking did not occur between these channels.

A specific issue that has not been discussed yet is that tactile sensitivity (both in detection threshold and spatial and temporal resolution) may be lower in the older observer than in the younger (e.g., Cholewiak & Collins, 2003; Stevens & Choo, 1996; Stevens, Cruz, Marks & Lakatos, 1998; Van Doren, Gescheider & Verillo, 1990; Verrillo, 1993). However, we have shown that in an operational setting resembling the proposed applications, older observers performed as well as younger (De Vries, Hogema, Van Erp & Kiefer, 2004). Therefore, this issue is not specifically investigated further.

Appendix II. Hardware details

We used four different types of tactors in the experiments described in this thesis:

- the MiniVib-4 tactor (Special Instruments Development AB, PO Box 3050, S-181 03 Lidingö, Sweden)
- TNO tactors (TNO Human Factors, PO Box 23, 3769 ZG, Soesterberg, The Netherlands)
- DS tactors (Dutch Space, Newtonweg 1, 2333 CP Leiden, The Neherlands)
- TTTD JHJ-3 tactor (TNO Science and Industry, PO Box 6235, 5600 HE Eindhoven, The Netherlands).

Table AII.1 indicates which tactor was used in which experiment.

Table AII.1. Overview of the tactors used in the 14 experiments.

Experiment:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
MiniVib-4	■	■	■	■	■	■		■						
TNO							■		■	■	■	■		
DS													■	
JHJ-3														■

The MiniVib-4 was used for all psychophysical studies and for part of the lab studies. The TNO tactors were used for part of the lab studies and for the field studies, except for the 3D orientation experiment in which the DS tactor was used. The JHJ-3 tactor is an improved version of the TNO tactor with rounded edges and improved wiring and was approved for use under high G-load by the Swedish Defence Material Administration. Details of the tactors are presented in Table AII.2. All tactors and stimuli in all experiments were always amply above threshold (in the range of 15-20 dB above threshold, which is judged comfortable; Boff & Lincoln, 1988).

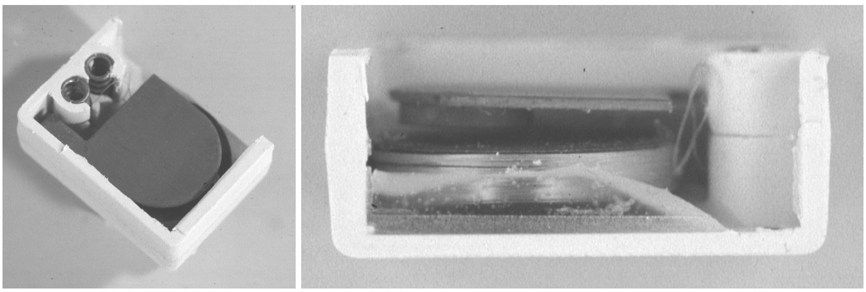

Figure AII.1 Top and side view of a MiniVib-4 vibrator with the housing partially removed.

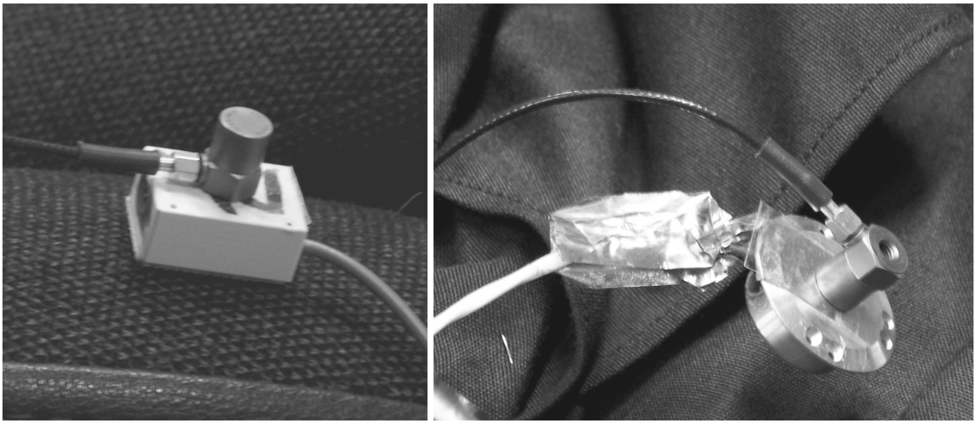

Figure AII.2. The TNO tactor (left) and the DS tactor (right) during the measurements with the B&K accelerometer attached with double sided sticky tape.

Table AII.2. Main characteristics of the MiniVib-4, the TNO tactor and the DS tactor.

	MiniVib-4	TNO tactor / JHJ-3	DS tactor
manufacturer	Custom made and calibrated by Special Instruments Inc., Sweden	TNO Human Factors / TNO Science and Industry, The Netherlands	Dutch Space, The Netherlands
principle	resonator	DC motor	DC motor
contact area	rectangular, 16×22 mm	rectangular, 15×20 mm	circular, diameter 18 mm
frequency	fixed at 250 Hz, independent of amplitude	variable around 155 Hz, confounded with amplitude	variable around 165 Hz, confounded with amplitude
waveform	pure sine	undefined, see Figure AII.3	undefined, see Figure AII.4
input	sine wave	DC	DC
outer material	PVC	PVC	coated aluminium
Figure	AII.1	AII.2, left	AII.2, right

The MiniVib-4 was always driven by a 250 Hz sine wave. Tables AII.3 and AII.4 and Figure AII.5 give a summary on the linearity and the frequency modulation of the MiniVib-4. The high frequency minivib-4 reaches half its amplitude within 10 ms, and a super threshold amplitude within its first sine wave (i.e., within 4 ms).

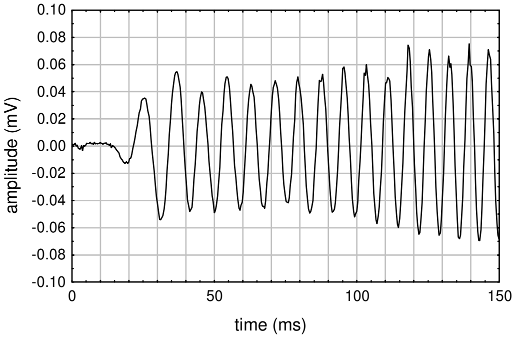

Figure AII.3. Response characteristics of the TNO tactor when driven by the hardware used in the experiments.

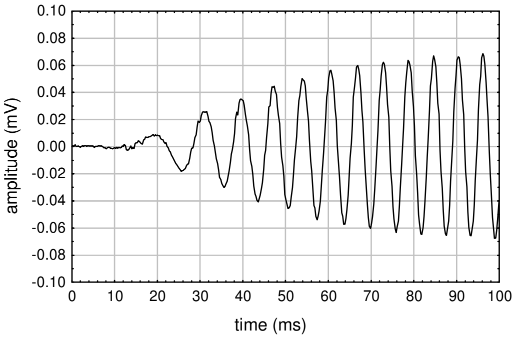

Figure AII.4. Response characteristics of the DS tactor when driven by the hardware used in Experiment 13.

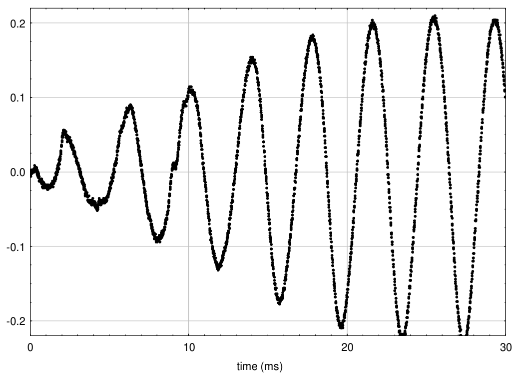

Figure AII.5. Response characteristics of the Minivib-4 tactor when driven by a 250 Hz sine wave. 50% of the amplitude is reached after 10 ms.

Table AII.3. Linearity of the MiniVib-4.

Peak level input (dB)	Max. rms output	Average rms output
0	-10,51	-13,25
-5	-15,49	-18,25
-10	-20,54	-23,25
-15	-25,59	-28,15
-20	-30,65	-33,24
-25	-35,7	-38,33
-30	-40,79	-43,31
-35	-45,8	-48,39
-40	-50,88	-5342

Table AII.4. Frequency modulation depth of the MiniVib-4.

mod. freq. (Hz)	Modulation depth in	Modulation depth out
0,5	1	0,99
0,63	1	0,99
0,8	1	0,99
1	1	0,99
1,25	1	0,99
1,6	1	0,99
2	1	0,99
2,5	1	0,99
3,15	1	0,99
4	1	0,99
5	1	0,99
6,3	1	0,98
8	1	0,98
10	1	0,97
12,5	1	0,95
16	1	92

Appendix III. Guidelines

Tactile interaction is becoming increasingly important, not only in navigation and orientation tasks, but also in communication, in assistive technologies and in special purpose computing environments. While considerable research exists, lack of ergonomic standards in this area may result in systems being developed without sufficient concerns for either ergonomics or interoperability (Van Erp, Carter & Andrew, 2006). This can lead to difficulties for users of multiple, incompatible or conflicting tactile displays or applications (see the section on coding and standardisation in Chapter 11). Guidelines are important to bring the field of tactile interactions a step further. Based on this thesis and the work done for the European Telecommunications Standards Institute (ETSI) on multimodal icons, symbols and pictograms (ETSI, 2002) and for the International Organization for Standardization (ISO) on guidance on tactile and haptic interactions (ISO, 2006), we come to the following.

Guidelines on tactile interactions.

- The system should provide context to help the user to understand the meaning of the tactile sensation.
- The system should provide information on which task or function is active.
- The system should ensure comfort over short and extended periods of use. Reducing the risk of tactile fatigue can be achieved by careful choice of body location for stimulation, method of contact with the body, and lowest effective magnitude of the stimulus.
- The system should maintain coherence between sensory modalities, including the descriptions of actions.
- When using multiple modalities, the system should avoid causing sensorial contradictions or sensorial overload.
- The system should prevent the spreading of vibration from an active tactor to non-active tactors.
- Options to adjust tactile parameters should be provided to prevent discomfort, pain or injury.
- Acoustic energy emissions created by tactors should not annoy nearby persons or interfere with the user perceiving presented auditory information.
- The system should minimise the occurrence of sensory adaptation, and when adaptation occurs, the system should enable the user to recover from sensory adaptation to stimuli.
- The system should minimise the occurrence of unintended perceptual illusions for example caused by stimuli that are presented closely in time and space.
- Where available, well known tactile patterns, which are familiar in daily life or that are easy to learn, should be used for presenting information.
- System behaviour should conform to user expectations.
- The system's spatial resolution should be appropriate for the task and in accordance with the user's perceptual capabilities.
- Apparent location may be used to increase the spatial resolution of a vibrotactile display.
- Where high spatial acuity is needed, the system should interact only with the distal body parts.
- Displays designed for trained or expert users may use a higher density of stimuli.
- Apparent motion may be used to simulate actual motion.

- When encoding information in a temporal pattern, the time between signals should be perceivable and customizable.

Guiding information for the design and application of tactile torso displays for local guidance:

- The resolution of a tactile torso display may be in the order of 3 - 4 cm, both vertically and horizontally.
- Applications that require a high spatial resolution can benefit from longer stimulus presentation times, those that need a fast presentation require a larger distance between the tactors.
- In the horizontal plane, the system may use a direction resolution up to 15° for static stimuli.
- The system may use the body midaxis as origin of perceived directions for resolutions as small as 30°. Applications that use a higher resolution should use an individual mapping of external directions on skin locations.
- Most accurate direction perception is achieved for directions straight ahead or straight behind.
- Tactile direction perception can be complementary to 3D sound, in the sense that 3D sound is optimal to present lateral directions but has a relatively high occurrence of front - back reversals.
- The system should ensure coherence between sensory modalities and compensate for biases in tactile and visual phenomenal space and time.
- The system can apply crossmodal comparisons as well as unimodal comparisons.
- Tracking errors with a tactile display increase when there is an external disturbance signal present in the tactile signal.
- 2D navigation with an 8-tactor waist belt indicating waypoint direction by a localized vibration is adequate and quickly learned. The system may indicate approaching the waypoint by a simple alerting signal.
- Navigation system should not have pauses longer than 2 s between consecutive signals.
- In waypoint navigation settings where continuous distance information is considered to be important, the presentation of distance information should not be confounded with the temporal resolution of the direction information.
- The system may employ a bimodal presentation to decrease reaction times.
- Tactile displays can release the load on the visual modality in local navigation tasks.
- Tactile cues can be used in time critical tasks.
- In environments with external stressors such as vibration and high G-load, or under conditions of spatial disorientation, tactile displays may be employed when the use of visual displays is hindered.
- The preferred coding on the tactile display is task dependent. The system should use the best coding for the task.
- The system should avoid tactile clutter resulting from the parallel presentations of tactile signals or functions.
- A tactile display can lessen performance degradation that is a consequence of increasing workload.
- Tactile displays can lower experienced mental effort.
- Tactile displays can improve 360° threat awareness.

Appendix IV: Overview of experimental methods in a nutshell

Experiment 1 in a nutshell: spatial resolution as function of location.
- Four observers performed a spatial discrimination task. After the presentation of two vibrations they responded whether the second was left or right from the first. The stimuli were located all over the torso.
- The independent variable was the location on the torso.
- The dependent variable was the spatial acuity, defined as the 84% threshold of the fitted curve.

Experiment 2 in a nutshell: spatial resolution as function of timing parameters.
- Four observers performed a spatial discrimination task. After the presentation of two vibrations they responded whether the second was left or right from the first. The stimuli were located on the dorsal side of the torso.
- The independent variables were the burst duration (BD)and the stimulus onset asynchrony (SOA).
- The dependent variable was the percentage correct responses.

Experiment 3 in a nutshell: absolute localization.
- 15 observers performed a triangulation task in which they had to line up a cursor with two stimuli of which one was attached to the frontal side of the torso.
- The independent variables were the location and the modality of the torso stimuli. There were 15 stimulus locations and two modalities: visual and tactile.
- The dependent variable were the subjective location of the stimulus (either in x, y co-ordinates or in polar co-ordinates).

Experiment 4 in a nutshell: direction perception.
- Ten observers performed a direction perception task, in which they positioned a cursor on a table surrounding them such that it indicated the direction of a vibration on the torso.
- The independent variable was the angle of the tactor (there were 15 tactors in a belt around the torso), calculated from the body midaxis.
- The dependent variables were the bias (calculated as the difference between the angle of the tactor and the indicated direction), and the consistency (calculated as the standard deviation over multiple responses given to the same tactor).

Experiment 5 in a nutshell: temporal interval discrimination.

- Eight observers performed an interval discrimination task, in which they responded wether the second of two intervals was shorter or longer than the first. The two open intervals had different lengths. An interval was marked with either two visual flashes or two tactile bursts. The two intervals could be of the same modality or of two different modalities.
- The independent variables were the combination of interval modality and the interval length.
- The dependent variables were the bias and the sensitivity.

Experiment 6 in a nutshell: tracking task.

- 12 participants performed several tracking tasks in which the error between a target and a cursor had to be minimised. The cursor and target were either displayed on a visual display (dots presented on a table surrounding the participant) or on a tactile display (a belt with tactors around the torso).
- The independent variables were the modality of the cursor and target (visual and/or tactile) and the tracking task (compensatory or pursuit).
- The dependent variable was the RMS tracking error.

Experiment 7 in a nutshell: waypoint navigation on foot.

- 12 participants walked several routes on an open terrain (each consisting of six waypoints), while waypoint information was presented on a belt with 8 tactors around the torso. The location of the vibration indicated the direction of the next waypoint. The rhythm of the vibration displayed information on the remaining distance.
- The independent variable was the scheme to code for the remaining distance.
- The dependent variable was the effective walking speed (calculated as the distance between two waypoints divided by the walking time.

Experiment 8 in a nutshell: waypoint navigation in car.

- 16 drivers completed 12 routes through a town in a driving simulator. Route navigation information was displayed on a visual display (an arrow for direction, and a number for distance information) and/or on a tactile display (vibration on the left or right leg for direction, and different rhythms for distance). The drivers were instructed to use their turn indicator as soon as they received the navigation message. During navigation a peripheral detection task PDT) was presented. The rating scale mental effort (RSME) was completed after a block of four routes.
- The between subjects independent variable was workload (normal, high), the within subjects independent variable was display modality (visual, tactile, bimodal).
- The dependent variables were reaction time to the navigation message, RSME score, reaction time and errors in the PDT.

Experiment 9 in a nutshell: waypoint navigation in helicopter and fast boat.
- One boat driver and one helicopter pilot navigated their vehicle along a triangular course marked by three waypoints. The direction of the waypoints was indicated on a tactile display consisting of 8 tactors in a belt around the torso.
- We gathered descriptive (vehicle location) data during the runs and gathered subjective comments from the participants.

Experiment 10 in a nutshell: helicopter low level flight.
- 12 student pilots flew a in helicopter simulator. They performed a low-level ground target following task at an instructed altitude of 15 m. They could be supported by a tactile display that indicated the instructed altitude by a vibration on the shoulders or under the thighs (simple variant), or by a tactile display that indicated the instructed altitude and wether the helicopter was climbing or descending (complex variant). They completed trials in simulated daytime and at night with simulated night vision goggles. During half of a trial, a secondary mental workload task was added. The pilots completed the rating scale mental effort (RSME) after a trial.
- The independent variables were the type of support (no support, simple display, complex display), visual conditions (day, night), and the presence of the secondary task (present, absent).
- The dependent variables were the mean and RMS altitude error, secondary task performance and the scores on the RSME.

Experiment 11 in a nutshell: helicopter hover task.
- 12 student pilots flew in a helicopter simulator. They performed a helicopter hover task at an 15 m altitude. They could be supported by a simple tactile display that indicated the instructed position by a vibration on the shoulders or under the thighs (vertical) and/or in a belt around the torso (horizontal) (simple variant), or by a complex tactile display that indicated the instructed position and the motion direction of the helicopter. They completed trials in simulated daytime and at night with simulated night vision goggles. During half of a trial, a secondary mental workload task was added. The pilots completed the rating scale mental effort (RSME) after a trial.
- The independent variables were the type of support (no support, simple display, complex display), visual conditions (day, night), and the presence of the secondary task (present, absent).
- The dependent variables were the mean and RMS hover error (vertical and horizontal), secondary task performance and the scores on the RSME.

Experiment 12 in a nutshell: counteracting SD in rotating chair.

- 24 participants performed an orientation task in a rotating chair. A state of Spatial Disorientation (SD) was evoked by a rotation around the yaw axis followed by a sudden stop. In the following recovery phase, participants had to retain a stable orientation while compensating for a disturbance added to the chair's orientation. A hood blocked visual cues. In half of the trials, they were supported by a tactile display consisting of a belt around the torso with 24 tactors displaying orientation information.
- The between subjects independent variable was coding of orientation on the tactile display, the within subjects independent variable was type of support (no support, support during the recovery phase only, and support during both the pre-SD and recovery phase).
- The dependent variables were recovery performance (defined as the number of turns made during the recovery phase), and control performance (calculated as the correlation between the disturbance signal and the control input).

Experiment 13 in a nutshell: orientation awareness in microgravity.

- One participant performed several orientation tasks in the microgravity environment of the International Space Station. The tasks were repeated on four days during adaptation to gravity. The astronaut could be supported by a tactile vest covering his whole torso. The location of the vibration on the vest indicated the direction of down.
- The independent variables were the day in microgravity (4) and sensory modality with task-dependent levels (e.g. eyes only, vest only and bimodal).
- The dependent variables were subjective difficulty score, and task dependent performance measures.

Experiment 14 in a nutshell: target interception task.

- Nine pilots performed a target interception and chase task in a high G flight simulator. After target pop-up the instruction was to get the target in a small forward cone as fast as possible. Standard visual displays were always present. In half of the trials, additional support was provided by a tactile vest. The location of vibration indicated the direction of the target. In half of the trial, an additional mental workload task was presented. After a run, the pilots completed the modified Cooper-Harper scale and a questionnaire.
- The independent variables were the cueing modality (visual only or visual and tactile), workload (additional task absent or present, and position of the threat at pop-up (8).
- The dependent variables were the G forces pulled during interception, the initial reaction time to target pop-up, task completion time, rating on the questionnaires, workload rating, and performance on the secondary task.

Appendix V: Selected tactile publications

Tactile journal papers

Bos, J.E., Van Erp, J.B.F., Groen, E.L., Van Veen, H.A.H.C. (2005). Vestibulo-tactile interactions regarding motion perception and eye movements in yaw. *Journal of Vestibular Research, 15*, 149-160.

De Vries, S.C., Van Erp, J.B.F. & Kiefer, R.J. (Submitted). Direction Coding Using a Tactile Chair.

Van Erp, J.B.F. (2005). Presenting directions with a vibrotactile torso display. *Ergonomics, 48(3)*, 302-313.

Van Erp, J.B.F. (submitted). Absolute localisation of vibrotactile stimuli on the torso. Submitted to *Perception & Psychophysics*.

Van Erp, J.B.F., Eriksson , L., Carlander, O. Veltman, J.E., Levin, B. & Vos, W. (submitted). A tactile display supports target interception under high G-load. Submitted to *Aviation, Space, and Environmental Medicine*.

Van Erp, J.B.F. & Van Veen, H.A.H.C. (2004). SUIT : Experimenteren met een trilvest in de ruimte. *Ruimtevaart, 53 (2)*, 22-24,.

Van Erp, J.B.F. & Van Veen, H.A.H.C. (2004). Vibrotactile in-vehicle navigation system. *Transportation Research Part F, Human Factors, 7*, 247-256.

Van Erp, J.B.F. & Van Veen, H.A.H.C. (2006). Touch down: The effect of artificial touch cues on orientation in microgravity. *Neuroscience letters, 404*, 78-82.

Van Erp, J.B.F., Van Veen, H.A.H.C. & Ruijsendaal, M. (submitted). More than a feeling: bringing touch into astronauts's spatial orientation. *Submitted to Microgravity Science and Technology*.

Van Erp, J.B.F. & Verschoor, M.H. (2004). Cross-modal visual and vibrotactile tracking. *Applied ergonomics, 35*, 105-112.

Van Erp, J.B.F. & Werkhoven, P.J. (2004). Vibro-tactile and visual asynchronies : sensitivity and consistency. *Perception, 33*, 103-111.

Van Erp, J.B.F., Groen, E.L., Bos, J.E., & Van Veen, H.A.H.C. (2006). A tactile cockpit instrument supports the control of self-motion during spatial disorientation. *Human Factors, 48(2)*, 219-228.

Van Erp, J.B.F., Van Veen, H.A.H.C., Jansen, C. & Dobbins, T. (2005). Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception, 2(2)*, 106-117.

Tactile conference proceedings (first author only)

Van Erp, J.B.F. (2001). *Tactile displays in Virtual Environments*. In: What is essential for virtual reality systems to meet military performance goals? RTO proceedings. AC/323 (HFM-058) Tp/30, Neuilly-sur-Seine, France: RTO NATO, 2001. pp. 109-114.,

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Van Erp, J.B.F. (2002). Guidelines for the use of vibro-tactile displays in human computer interaction. In: *Eurohaptics 2002*. Ed. by S.A. Wall (et. al) Edinburgh 2002 p 18-22.

Van Erp, J.B.F. (2005). Vibrotactile spatial acuity on the torso: effects of location and timing parameters. In: *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* 2005, pp. 80-85,

Van Erp, J.B.F. (2006). The multi-dimensional nature of encoding tactile and haptic interactions: from psychophysics to design guidelines. In: *Proceedings of the Human factors and ergonomics society 50th annual meeting* 2006. Santa Monica: Human Factors and Ergonomics Society. p 685-688.

Van Erp, J.B.F. (2006). The multi-dimensional nature of encoding tactile and haptic interactions: from psychophysics to design guidelines. In: *Proceedings of the Human factors and ergonomics society 50th annual meeting* 2006. Santa Monica: Human Factors and Ergonomics Society. p 685-688,

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Van Erp, J.B.F. & Spapé, M.M.A. (2003). Distilling the underlying dimensions of tactile melodies. *Eurohaptics 2003 proceedings* July 6th - 9th 2003, Dublin 2 Ireland. p 111-120.

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Van Erp, J.B.F., Jansen, C., Dobbins, T. & H.A.H.C. van Veen. (2004). Vibrotactile waypoint navigation at sea and in the air: two case studies. In: *Eurohaptics 2004*, pp. 166 - 173,

Van Erp, J.B.F., Saturday, I. & Jansen, C. (2006.) Application of tactile displays in sports: where to, how and to move. *IEA 2006.*

Van Erp, J.B.F., Carter, J. & Andrew, I. (2006). ISO's work on tactile and haptic interaction guidelines. In: *Eurohaptics 2006* July Paris, pp. 467-470. (CD),

Van Erp, J.B.F., eltman, J.A. & Van Veen, H.A.H.C. (2003). A tactile cockpit instrument to support altitude control. *Proceedings of the human factors and ergonomics society 47th annual meeting* 2003. p 114-118,

Van Erp, J.B.F., Veltman, J.A., Van Veen, H.A.H.C. & Oving, A.B. (2003). *Tactile torso display as countermeasure to reduce night vision goggles induced drift*. NATO / RTO on 'spatial disorientation in military vehicles: causes, consequences and cures' Spain 15-17 April 2002. RTO-MP-086. p 49.1 - 49.8.

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Van Erp, J.B.F. (2000). Direction estimation with vibro-tactile stimuli presented to the torso: a search for the tactile ego-centre.

Van Erp, J.B.F. (2001). Effect of timing parameters on the vibrotactile spatial acuity of the torso.

Van Erp, J.B.F. (2002). Multiple processing systems for vibrotactile spatiotemporal patterns.

Van Erp, J.B.F. (2004). Functional model for the processing of vibrotactile spatiotemporal patterns.

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Van Erp, J.B.F. & De Vries, S.C. (2003). Coding principles for driver's seat tactile directional warnings.

Van Erp, J.B.F. & Van den Dobbelsteen, J.J. (1998). On the design of tactile displays.

Van Erp, J.B.F. & Duistermaat, M. (2005). Tactile guidance for land navigation.

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Van Erp, J.B.F., Meppelink, R. & Van Veen, H.A.H.C. (2002). A touchy car.

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Van Erp, J.B.F., Ruijsendaal, M., H.A.H.C. van Veen, & Kranenborg, K. (2004). Ontwikkeling van een tactiel oriëntatiedisplay voor het internationale ruimtestation.

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Van Erp, J.B.F. & Van Veen, H.A.H.C. (2002). Coderingsprincipes voor tactiele torso displays: spatio-temporele patronen.

Van Erp, J.B.F. & Van Veen, H.A.H.C. (2002). Lokalisatie van tactiele stimuli op de torso.

Van Erp, J.B.F., Van Veen, H.A.H.C. & Oving, A.B. (2002). Een tactiel vest vermindert drift bij hoveren.

Van Erp, J.B.F. & Verschoor, M.H. (2000). Uni and cross modal tracking of visual and vibro-tactile stimuli.

Van Erp, J.B.F. & Vogels, I.M.L.C. (1998). Vibrotactile perception: a literature review.

Van Erp, J.B.F. & Werkhoven P.J., (1999). Spatial characteristics of vibro-tactile perception on the torso.

Samenvatting

Er zijn situaties, bijvoorbeeld tijdens het autorijden, waarin we eigenlijk ogen en oren tekort komen. Terwijl we in gesprek zijn met onze passagiers en tegelijkertijd de autoradio instellen besteden we misschien wel te weinig aandacht aan wat er op de weg voor ons gebeurt. Om in dit soort situaties de veiligheid, efficiëntie en het comfort te verbeteren zijn ontwerpers van mens-machine systemen continu op zoek naar nieuwe manieren om informatie aan te bieden. Eén van de mogelijkheden hierbij is een tactiel display. Een tactiel display is een display voor de huid zoals een beeldscherm een display voor de ogen is. Een bekend voorbeeld van een eenvoudig tactiel display is de mobiele telefoon met één trilelement die via de huid laat weten dat er een telefoontje of SMS bericht binnenkomt. Dit proefschrift gaat over de vraag of geavanceerde tactiele displays met veel trilelementjes verspreid over borst en rug (trilvest) iets kunnen betekenen in het domein van stuur- en regeltaken; de relatief snelle processen zoals het koers houden bij autorijden en het onderscheppen van vijandelijke doelen in een jachtvliegtuig.

Soms komen we ogen, oren, en mentale reserves te kort om alle informatie om ons heen te verwerken (links). Een trilvest (rechts) gebruikt de huid om informatie over te brengen en ontlast zo de ogen en oren. Bovendien werkt een trilvest als een 'tikje op de schouder' en zorgt ervoor dat we informatie kunnen verwerken zonder dat we er bij na hoeven te denken.

In hoofdstuk 1 brengen we deze problemen verder in kaart. We doen dit aan de hand van een model (prenav) dat een beschrijving geeft van de regelprocessen bij sturen en navigeren. Uit prenav komen twee potentiële knelpunten naar voren: sensorische en cognitieve overbelasting. Sensorische overbelasting betekent dat er (te-) veel informatie wordt aangeboden via de ogen en de oren, cognitieve overbelasting betekent dat de gebruiker niet genoeg capaciteit heeft om alle aangeboden informatie goed en tijdig te verwerken. Als mogelijke oplossing voor beide knelpunten introduceren we het trilvest. Omdat dit tactiele display de huid als communicatie kanaal gebruikt kunnen we de ogen en oren ontlasten. Daarnaast kan een trilvest als het ware een tikje op de schouder geven om zo iemand de goede richting in te sturen of te vertellen in welke richting een vijandelijk doel zich bevindt. Omdat dit tikje op de schouder intuïtief begrepen wordt, dus zonder er bij na te hoeven denken, kunnen we ook het risico op cognitieve overbelasting verkleinen.

In dit proefschrift komen de volgende onderwerpen aan de orde. In experiment 1 kijken we als eerste naar de spatiële resolutie van de torso voor trilsignalen. Met andere woorden: hoe dicht kunnen trillertjes naast elkaar zitten om ze nog uit elkaar te kunnen houden, en is dit overal op de torso hetzelfde? Het blijkt dat trillers 3 - 4 cm uit elkaar moeten zitten. Alleen in de buurt van de middenlijn (de verticale lijn door ruggenmerg (achter) en navel (voor)) kunnen trillers dichter bij elkaar zitten. Dit effect hangt waarschijnlijk samen met de manier waarop de hersenen signalen van dit gedeelte van de torso verwerken. In experiment 2 kijken we naar het effect van aanbiedingsduur op de spatiële resolutie. Stuur- en regeltaken zijn immers snelle processen waarbij signalen mogelijk kort aangeboden worden of snel van positie veranderen. Het blijkt dat de trilling heel kort kan duren en dat het vooral belangrijk is hoeveel tijd er tussen twee trilsignalen zit: hoe meer tijd tussen twee trillingen, hoe beter je ze uit elkaar kunt houden.

In deze eerste twee experimenten gaat het om het uit elkaar houden van twee trillocaties. In experiment 3 onderzoeken we hoe goed mensen de plaats van een trilling op hun lichaam kunnen bepalen. Als we de wereld als het ware op de torso willen projecteren is dit een belangrijk aspect: als we een doel aangeven met een trilling op 2 uur (wijzer van de klok), maar de gebruiker lokaliseert de trilling op 1 uur kan dit tot problemen leiden. We vinden echter dat mensen de plek van een trilling behoorlijk goed kunnen bepalen. Dat klopt ook wel met de ervaring dat we een stekende mug gelukkig ook in een fractie van een seconde kunnen raken. In experiment 4 kijken we naar hoe goed mensen een trilling op de torso om kunnen zetten in een richting en hoe ze dat doen. Het lijkt logisch dat een trilling bij de navel een richting rechtuit aangeeft, maar welke richting hoort er dan bij 10 cm rechts van de navel? Experiment 4 levert een drietal interessante bevindingen op. Ten eerste blijkt dat we behoorlijk goed zijn in het koppelen van een richting aan een trilling op de torso. De variatie in onze antwoorden valt ruim binnen het voorbeeld van de 12 uren van de klok. Mensen hebben echter wel een systematische afwijking: we zijn geneigd richtingen meer van recht van voren of van recht van achteren waar te nemen (respectievelijk voor de voorste en achterste helft van onze torso). Hier kunnen we echter makkelijk rekening mee houden als een hoge nauwkeurigheid vereist is. Ten slotte is het interessant om te kijken hoe mensen in staat zijn om richting waar te nemen. Een (tril-) punt bevat immers geen richtingsinformatie. Het lijkt erop alsof we richting waarnemen door een tweede punt als intern referentiepunt te gebruiken. Dit kennen we ook uit de visuele waarneming, waar we praten over het cyclopisch oog. Onze cyclopische huid ligt echter niet -zoals we vooraf voorspelde- op de lichaamsas. We concluderen dat er twee van dergelijke interne referentiepunten zijn: een voor iedere lichaamshelft. Ook dit is verklaarbaar door te kijken naar de manier waarop de hersenen trilsignalen verwerken. De linker en rechter torsohelften worden door de hersenen namelijk als aparte lichaamsdelen beschouwd, en hebben dus ook beide hun eigen cyclopische huid.

Omdat tactiele displays vaak gebruikt zullen worden samen met of als aanvulling op een visueel display (bijvoorbeeld om de kans op visuele overbelasting te verminderen) is het zinnig om te kijken hoe we visuele en tactiele displays goed op elkaar af moeten stemmen. In hoeverre klopt wat we zien en wat we voelen met elkaar? En hoe goed kunnen we informatie van voelen en van zien naar elkaar vertalen? In experiment 5 en experiment 6 onderzoeken we de crossmodale perceptie van tijd en ruimte. Het blijkt dat we net zo goed zijn in het vergelijken van informatie in dezelfde modaliteit als tussen twee verschillende modaliteiten. Opnieuw zijn er wel systematische afwijkingen (zo lijkt de tijd tussen visuele gebeurtenissen korter te duren dan tussen tactiele), maar hier kunnen we opnieuw makkelijk rekening mee houden bij het presenteren van informatie.

Deze eerste zes experimenten waren gericht op de waarneming van signalen van een trilvest. De experimenten erna zijn gericht op gedrag, prestatie en werklast bij het gebruik van een trilvest. Kunnen gebruikers op basis van informatie van het trilvest bijvoorbeeld hun weg vinden en vijandelijke vliegtuigen onderscheppen? En kost het inderdaad minder mentale inspanning om zulke taken uit te voeren met een trilvest dan met een traditioneel visueel display? We onderzoeken deze vragen in acht experimenten, onderverdeeld in vier categorieën. De eerste categorie is (waypoint) navigatie, met andere woorden: kunnen mensen een route langs een aantal punten afleggen op basis van tactiele informatie. We beginnen eenvoudig met lopen. Proefpersonen kregen een gordel met acht trillers om en moesten de richting van de trilling volgen om van A naar B, naar C etc. te lopen. Met het aan-uit ritme van de trilling werd de afstand tot het waypoint aangegeven. Het blijkt dat deze manier van navigeren goed werkt: alle routes werden goed gelopen met een normale loopsnelheid. Het blijkt ook dat afstandsinformatie niet belangrijk is, maar een waarschuwing vlak voor het bereiken van het waypoint wel. Dit principe testten we verder met een helicopter piloot en een speedboat bestuurder. Dit zijn wat we noemen 'uitdagende omgevingen', waarbij fysieke stress (b.v. trillingen) en mentale stress een rol spelen. Het is niet vanzelfsprekend dat in dergelijke situaties een tactiel display ook nog goed werkt, bijvoorbeeld omdat voertuigtrillingen kunnen interfereren met de trilsignalen van het vest. De resultaten bewijzen echter dat dit geen probleem is: ook in deze uitdagende omgevingen kan het tactiel display adequaat gebruikt worden voor waypoint navigatie.

Tenslotte testen we waypoint navigatie ook in een groter rijsimulator experiment. Deelnemers moesten een route door de stad rijden en kregen route-informatie via een standaard visueel display en/of via trillingen in de autostoel. De ene helft van de deelnemers deed dit in normale omstandigheden, de andere helft in een situatie met een hoge werkbelasting. Opnieuw blijkt dat het tactiele display goed werkt. Mensen reageren eerder op de navigatie boodschappen en vinden het display minder inspannend. Bovendien presteert de groep met de hoge belasting niet slechter mits ze een tactiel display hebben. Als ze alleen een visueel display hebben is hun prestatie echter wel slechter dan de groep met de normale werklast. Dit is een indicatie dat een tactiel display intuïtief is, en gebruikt kan worden als de chauffeur druk is met andere taken, terwijl dit niet lukt met een visueel display.

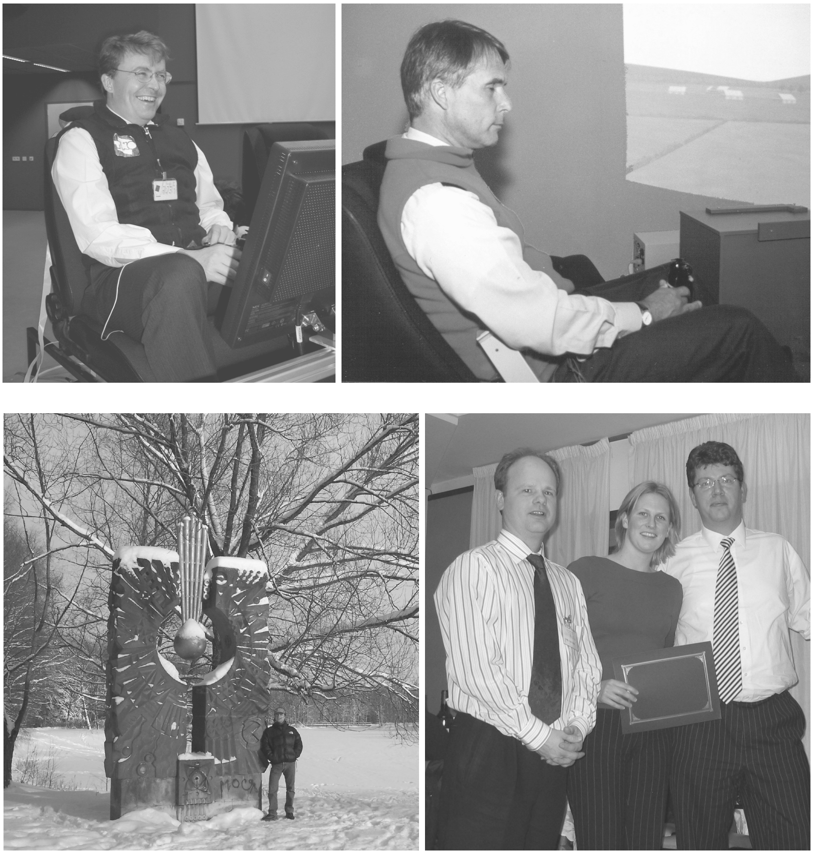
De resultaten van deze drie experimenten laten zien dat gebruikers met een tactiel display kunnen navigeren in het platte vlak. Sommige gebruikers, zoals vliegers en duikers, moeten echter navigeren in de 3D ruimte. In hoofdstuk 7 breiden we de trilgordel daarom uit naar een trilvest waarbij we naast richtingen in het horizontale vlak ook richting in het verticale vlak aan kunnen geven. We testen dit in twee studies in een helicopter simulator. Opnieuw manipuleren we ook de werklast van de vlieger om te kijken of een tactiel display de gebruiker inderdaad 'immuun' maakt voor de mentale werkbelasting. In experiment 10 testen we of we vliegers kunnen helpen om op een bepaalde hoogte te blijven in de achtervolging van een tank op de grond. We vinden dat het trilvest hierbij uitstekend helpt: de hoogtefout wordt gehalveerd zodra de vlieger tactiele ondersteuning krijgt. In tegenstelling tot het autorijden vinden we niet de voorspelde effecten van de extra werkbelasting. Ook met een tactiel vest vermindert de prestatie. In experiment 11 combineren we de horizontale en verticale informatie in één taak, een zogenaamde hover taak. Hierbij moet de vlieger de helicopter stil houden op een vaste plek, een moeilijke taak, zeker onder slechte zichtomstandigheden zoals 's nachts of bij opwaaiend zand. Ook hier vinden we dat het trilvest de prestatie aanzienlijk verbetert: de positiefout wordt opnieuw gehalveerd. Bovendien laten de resultaten zien dat de verslechtering als gevolg van de extra taken veel minder is als de vlieger geholpen wordt met een trilvest.

Naast navigatie (waar ben ik ten opzichte van mijn doel en hoe kom ik daar, gerelateerd aan translaties), is ook oriëntatie belangrijk (gerelateerd aan rotaties, b.v. wat is beneden en wat is boven). Deze vraag is van belang voor onder andere duikers, astronauten en vliegers. Zo belangrijk zelfs dat spatiële desoriëntatie gezien wordt als een belangrijke oorzaak van ongelukken in de (militaire) luchtvaart. In experiment 12 onderzoeken we of een trilvest ook kan helpen bij oriëntatietaken. Allereerst in een 2D situatie waarbij we een situatie van spatiële desoriëntatie creëren. We doen dit door mensen in het donker om hun lichaamsas te roteren en dan plotseling stil te zetten, een situatie die lijkt op wat in de luchtvaart bekend staat als een graveyard spin. Vervolgens moeten ze proberen zichzelf stil te houden met of zonder de hulp van een trilvest. Zonder trilvest blijkt dit onmogelijk te zijn, en raken mensen direct in een graveyard spin. Met een trilvest lukt het de proefpersonen echter wel om uit een spin te blijven. Vervolgens maken we ook voor oriëntatietaken de stap van een 2D omgeving naar een 3D omgeving. Experiment 13 was een case study in het internationale ruimtestation ISS. Ook hier is oriënteren van groot belang, maar door het gebrek aan zwaartekracht moeilijk. Eén ESA astronaut heeft tijdens zijn adaptatieperiode aan gewichtloosheid een aantal oriëntatie-experimenten gedaan. Op basis van de verzamelde gegevens en zijn subjectieve beoordelingen kunnen we zeggen dat een trilvest oriëntatie sneller, beter en makkelijker maakt. Dit kan van belang zijn tijdens het dagelijkse leven in het ISS, maar vooral ook in kritische situaties zoals tijdens een ruimtewandeling of een noodevacuatie. Tenslotte testen we in het viertiende en laatste experiment de ondersteuning van straaljagervliegers bij het onderscheppen van vijandelijke doelen. We doen dit in een simulator die in staat is om tot 9 keer de zwaartekracht op te wekken tijdens het vliegen. Op dit moment zijn er in veel moderne jachtvliegtuigen al zeer geavanceerde visuele displays aanwezig voor dit soort taken. De uitdaging ligt dus vooral in het aantonen van meerwaarde van een tactiel vest in deze omstandigheden. De resultaten laten zien dat die meerwaarde er is in de initiële reactietijd, en in het onderscheppen van doelen die achter het eigen vliegtuig verschijnen.

De experimenten in dit proefschrift tonen aan dat een tactiel display een belangrijk hulpmiddel kan zijn bij het navigeren en oriënteren. We hebben laten zien dat het sensorisch systeem van de torso voldoende capaciteit heeft om de trilsignalen van een trilvest te verwerken en dat gebruikers goed in staat zijn om de ruimtelijke informatie die we met het trilvest op de torso projecteren te interpreteren. We vinden in experimenten met rijden, vliegen en varen dat gebruikers beter presteren, de taken minder belastend vinden en minder last hebben van situaties met een hoge mentale werkbelasting.

Dankwoord

Het traject dat leidde tot dit proefschrift was plezierig. Het relatief onontgonnen gebied waar collega's en ik ons tien jaar geleden instortte gaf ons vaak het gevoel eenoog in het land der blinden te zijn: wij weten bijna niets, maar net iets meer dan de rest van de wereld. We vonden onszelf natuurlijk ook 'gelovers' op een missie (feeling is believing!). Het bezoeken van bijzondere plaatsen en het ontmoeten van bijzondere mensen maakte missies meer dan eens opwindend. Redenen genoeg om me bevoorrecht te voelen.



Boven: bijzondere mensen op bezoek: van lachende prins (ZKH J.F. van Oranje-Nassau) tot de op gevoel vliegende militair (huidige Chef Defensiestaf Generaal D.L. Berlijn). Beneden: bijzondere plaatsen (Start City, Moskou) en gebeurtenissen (best demo award met de 'vogeltjesdans demo', worldhaptics Pisa).

Niet allen dit traject, maar ook het proefschrift is het resultaat van teamwork. Mijn allereerste dank gaat uit naar promotor en co-promotor, Peter en HJ. Peter, met je besmettelijke enthousiasme heb je me erin geluisd met tactiel onderzoek aan de gang te gaan, en jouw crossmodale illusie van de vallende druppels uit je lekkende dak was de directe aanleiding voor onze eerste gezamenlijke experimenten. Het is mij een oprecht genoegen om bijna 10 jaar later onder jouw supervisie dit proefschrift te verdedigen. HJ, behept met een minstens net zo besmettelijk enthousiasme en voorliefde voor avontuur, je verdient zonder enige twijfel de eer van co-promotor. Vaak hebben we missies gedeeld. De zoektochten naar Indiaas eten -een goede gewoonte sinds de 'death by chocolate' ervaring in Glasgow- horen daar zeker bij. 'Gewapend' met onze demokoffer hebben we menig X-ray inspecteur op tilt doen slaan. Direct na 11 september wist jij de argwanende Amerikaanse inspecteurs er gelukkig van te overtuigen dat er een 'big vibrator for the skin' in zat, en dat dat alles met wetenschap te maken had en niets met een bomgordel. Mede daardoor heb ik dit proefschrift in alle vrijheid af kunnen maken. Rest me nog maar één vraag: wanneer gaan we *nature* bellen?

Nog veel meer TNO collega's hebben een belangrijk bijdrage geleverd aan dit werk - werkelijk teveel om allemaal op te noemen. Sjouke, Antoon, Jan en Obbe verdienen het echter zondermeer om genoemd te worden. Als technici, knutselaars en wizards onontbeerlijk voor het bouwen van het lab en het optuigen en programmeren van de experimenten. Hetzelfde geldt ook voor Bernd en andere betrokken geldschieters. Belangrijke teamgenoten bij de experimenten en het tactiele werk waren onder andere Arjen, Chris, Maaike, Mark, Sjoerd, Wouter, Wytze, nu en dan aangevuld met stagiaires: Arjen, John, Migh, Marc, Ian, Robert, Steven, Edward en Dennis. Gelukkig heeft tenminste één van jullie zijn doctors titel eerder behaald dan ik. Verder waren er de vele anonieme collega's die ik van de gang sleepte om 'even' een pilotexperimentje te doen. RB, JH, AO, NB, AdV. Het is mijn geloofwaardigheid niet, maar men dankbaarheid wel degelijk ten goede gekomen. Hierbij dus. Verder zijn er veel leermeesters, kamergenoten, carpoolers, treinmaatjes, en bridgers: Pieter, Leo, Sjoerd, Nico, Alexander, Martin, Tony, Wytze, Jan, Richard. Jullie waren onontbeerlijk om sociaal en wetenschappelijk te groeien en om sommige vormen van noodzakelijk kwaad te verzachten.

Professionele ondersteuning kwam er ook van buiten TNO. A special thanks goes to Trevor who read through many manuscripts and gave valuable suggestions for improvements. I am also grateful for the opportunities to make many friends who joined us on our missions: Lars, Otto, Linda, Brian, Brad, Bill, Bob, Angus, Sharon. And last but certainly not least, I would like to acknowledge the members of the advisory committee: Anton, Astrid, Charles, Roger and Susan.

Maar er is, zelfs tijdens het schrijven van een proefschrift, meer dan werk. Rust komt er nu ook eindelijk voor de potige dame Dunya die menig passage voor haar rekening nam als het niet snel genoeg ging, maar wiens bijdrage achteraf bezien toch meestal werd geschrapt. Je vier pootjes komen beter tot zijn recht naast dan op het toetsenbord. Hetzelfde gold trouwens ook voor Mustapha Pasha. Heel, heel bijzonder zijn de mensen die me na staan; zij verdienen zondermeer het laatste dankwoord. Gebrek aan idee waar ik nu precies allemaal mee bezig was heeft jullie vertrouwen op een goede afloop niet kunnen beïnvloeden. Daan, Bas, David en laatste loodjes Liesbeth: ik ben blij dat jullie kunnen delen in de oogst. Mijn grootste dank gaat uit naar de overlevers van het eerste uur: Kees, Ineke, Tiem, Arthur, Heleen en (niet voor niets paranimf) Marianne.

Curriculum Vitae

Jan van Erp was born on the 9th of June 1969 in Lisse, The Netherlands. He finished his Atheneum B education at the Fioretti College in Lisse at the age of 18. After finishing his first year degree (propaedeutics) in civil engineering at the Delft University of Technology, he completed his Master's degree in Experimental Psychology at Leiden University, The Netherlands in 1994. After his military service he started working at TNO Human Factors in 1995 as researcher and project manager in the Steering and Control Task group. He became head of the same research group in 2004 and Chief Scientist of the Department Human Interfaces in 2005. Over the past years, he has written more than 100 reports and papers, organised international scientific meetings, has served as a member of programme committees of international conferences and scientific groups, has been a member of expert teams for ETSI and NATO, reviewed many papers for conferences and scientific journals, and coached MSc and PhD students at TNO. Jan is currently chair of the Committee on experimental methods and statistics of TNO Human Factors, chair of the NATO Task Group on tactile displays for orientation, navigation, and communication in Air, Land and Sea environments, editor of the NATO publication on tactile displays, editor of the ISO international standard on haptic and tactile interaction, member of the board of the Netherlands Psychonomics Society, member of the ISO expert group on tactile and haptic interaction, and chair of the trans disciplinary study group on man-machine interaction of the Netherlands Study Centre for Technology's project images of the brain.