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?

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

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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

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[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.

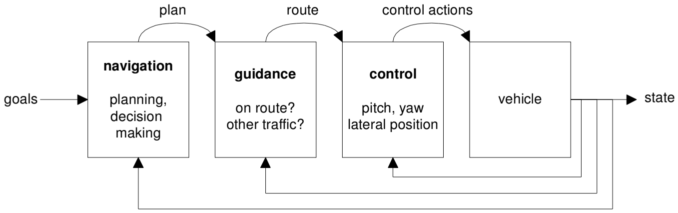

Figure 1.2. Sheridan’s model of (supervisory) vehicle control.

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.

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[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.

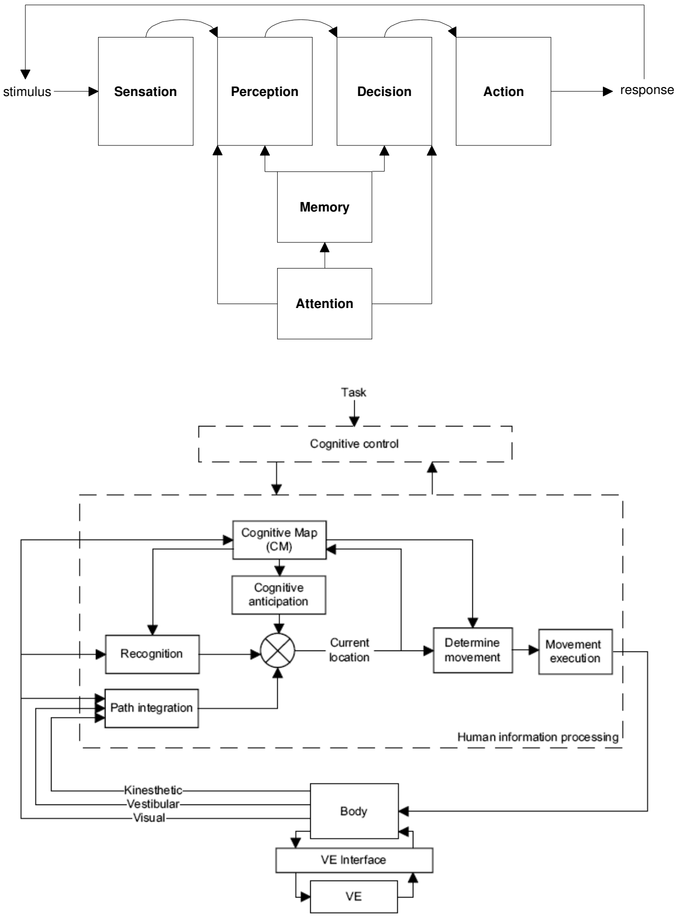

Figure 1.3. Wickens' model of information processing (upper panel) and Bakker's FIND framework (lower panel; from Bakker, 2001).

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.

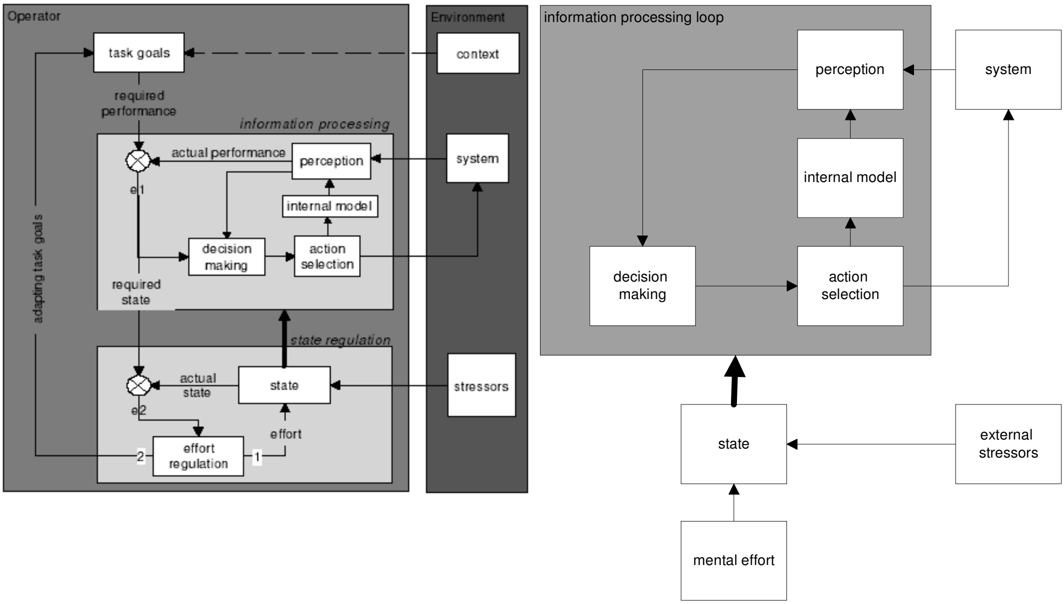

Figure 1.4. Complete (left) and simplified version (right) of the workload framework of Veltman and Jansen.

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.

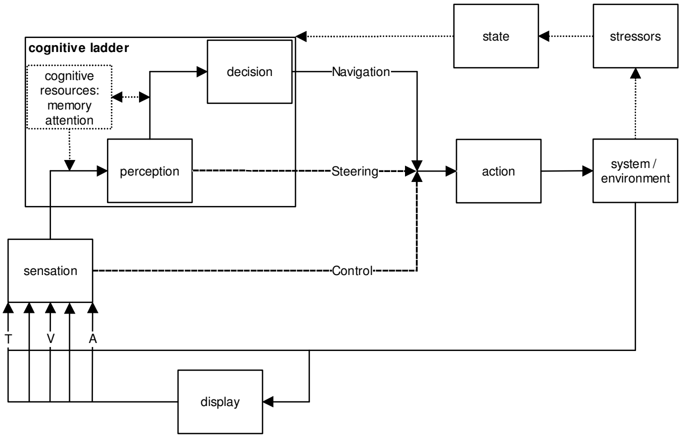

Figure 1.5. The prenav model for human behaviour in platform navigation and control. See text for explanation.

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.

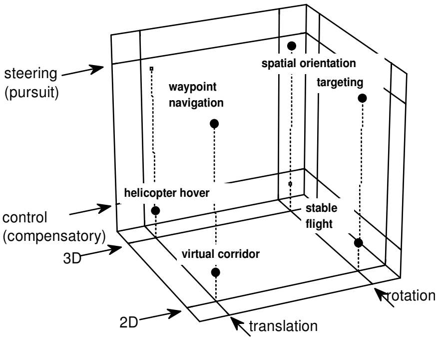

Figure 1.6. The local guidance task space can be divided along three dimensions: the controlled parameters: translation vs. rotation, the dimensionality of the environment: 2D vs. 3D, and the task level: control (or compensatory tracking) vs. steering (pursuit tracking). Tasks at the marked locations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

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[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).

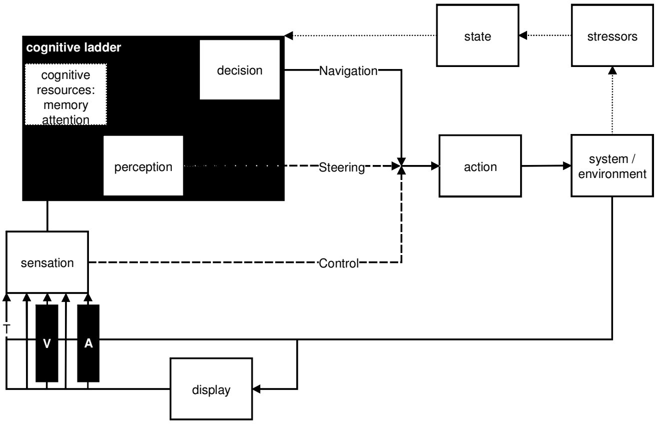

Figure 1.7. The prenav model with the predicted potential bottlenecks marked.

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;

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[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.

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[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.

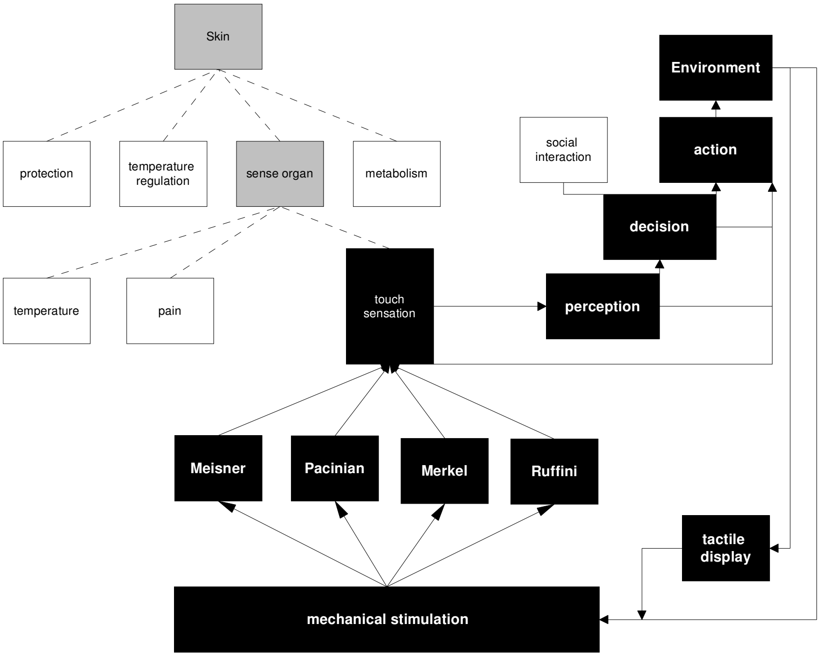

Figure 1.8. The sense of touch can be considered as a subfunction of the skin as sensory organ, which is one of the many functions the human skin has. The black marked cells relate to the prenav model. Mechanical stimulation of the skin may evoke responses in one or more of the four main types of mechanoreceptors: 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

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[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

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[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).

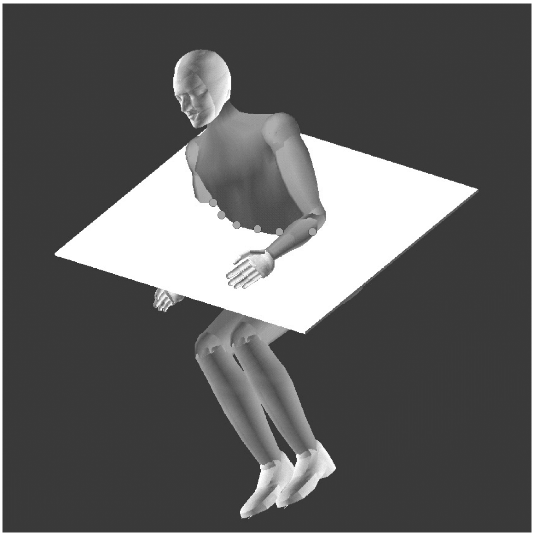

Figure 1.9. An example of local guidance information presented by a tactile torso display: an artificial horizon indicated by a slanted ring of vibrating elements.

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.

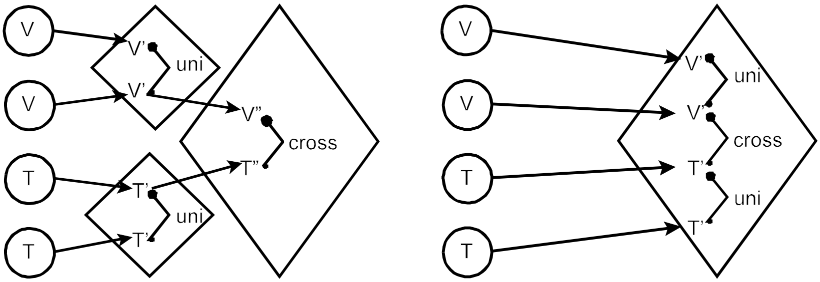

Figure 1.10. Two models for unimodal and crossmodal comparisons of visual (V) and tactile (T) information. The model on the left has a modality specific representation in which the unimodal comparisons are made. Crossmodal comparisons can only be made after the unimodal representations are translated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