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.

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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

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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).

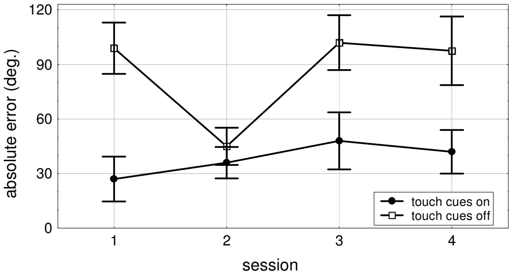

Figure 9.3. Objective performance (absolute error) in the first task as function of the sensory cue and the test session (averaged over ten repetitions). Without the tactile cues, performance is at the guessing level of 90°. Error bars present the standard error of the mean.

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.

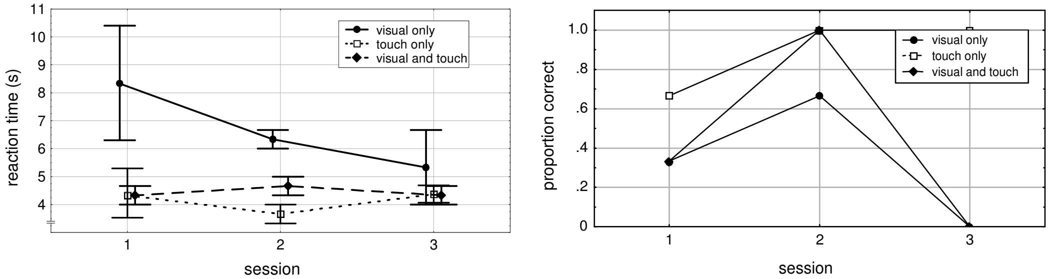

Figure 9.4. Objective performance in the second task as function of the sensory cue and session. Left the reaction time to report the section of down (averaged over three repetitions, bars present the standard error of the mean). Right the proportion correct responses.

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.