Institute of Cognitive Science

Bachelor thesis

The impact of the vibro-tactile sensory augmentation device
“feelSpace belt” on spatial orientation and navigation of blind
people

by
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Declaration of Authorship

I hereby certify that the work presented here is, to the best of my knowledge and belief, original and the result of my own investigations, except as acknowledged, and has not been submitted, either in part or whole, for a degree at this or any other university.

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Abstract

Spatial orientation and navigation require cognitive skills, but most of all depend primarily on vision. Blind, visually impaired and deaf-blind people do not have this fast source of information about their environment available. To facilitate and enhance orientation and navigation and to make travelling outdoors safer for people deprived of visual input, the “feelSpace belt” can be used. The belt gives its wearer information about the magnetic north via vibrotactile stimulation around the waist. The aim of this study is to investigate to what extent the belt has an impact on the orientation and navigation abilities of blind people. Congenitally blind and late-blind subjects wore the belt for seven weeks in everyday situations and five of them additionally took part in behavioural experiments. Two deaf-blind subjects wore the belt for three to four weeks. The experimental tasks took place before and in the middle of the participants’ training period. They consisted of a straight-line walking task to evaluate the belt’s effect on blind people trying to keep to the direction in which they are heading, an angular rotation task to examine the development of the egocentric orientation capabilities of the participants and a triangle completion navigation task to test whether the belt helps to take shortcuts. Weekly questionnaires gave an insight into the subjective experiences and evaluations of the participants. Overall, the belt’s information on cardinal directions proved to have intuitively a positive effect on the participants, facilitating especially orientation but also navigation. The results suggest that egocentric route-based navigation, which has been shown in previous studies to be the favoured navigation strategy of blind people, was still preferred when the participants wore the belt but, due to the belt, was further extended by increased use of also the allocentric reference frame.

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1 Introduction

1.1 Challenges of blind people outdoors in known and unknown environments

Finding one's way seems to be very simple since this ability is used and needed every day and in many situations. However, it is a highly complex activity that depends on a person's spatio-cognitive abilities (i.e. understanding space and manipulating it mentally) (Passini, 1990). Orientation and navigation outdoors are particularly challenging for visually impaired and blind people as they cannot rely on the main and fastest source of information for these tasks: vision.

Our world is based on visual information and thus, infrastructure is a challenge for blind people. Blind and visually impaired people are in particular danger when confronted with traffic. Taking crossing a street as an example: blind people have to first detect the street, find a place to cross the street (preferably at pedestrian traffic lights), align to the curb, find the right moment to cross the road, cross the road in a straight line so as to reach the opposite side of the road and then cross rapidly before traffic starts again. Each step affords them to be aware of their own position relative to the traffic. Without a sense of vision, they need to rely on their auditory sense to determine the direction in which traffic flows and to make out potential crossing gaps, and further use the haptic information from the cane during each step of the process. Crossing a street thus becomes a stressful high concentration task. Rounded curbs at crossings, pedestrian traffic lights with no or misleading auditory signalling and not straight crosswalks (Barlow et al., 2005) add to the already existing difficulties. Other difficult situations include crossing a large square in a straight line, walking along train platforms or the like. Nowadays, electric vehicles that make only little noise also provide a source of danger. In all these tasks keeping track of their orientation and navigation information towards the goal they are heading. Before presenting technical aids that help blind and visually impaired people in the above-mentioned situations, it is necessary to take a closer look at the concepts and biological processes underlying orientation and navigation and the differences between sighted and blind people to understand how these technical devices can be useful.

1.2 Differentiation between orientation and navigation

In this section I would like to define and distinguish between spatial orientation and spatial navigation and present the underlying concepts for these mechanisms in light of the challenges blind people face.

Orientation

Suterko (1973) defined orientation as being a cognitive process in which all sensory information is used to compute one's own position relative to other objects in the environment. Human beings orientate with the help of four main factors: senses, memory, cognition and general rules of environments. Visual, vestibular, proprioceptive, auditory and somatosensory information give us knowledge about our surrounding environment and our place in it. However, our senses alone are not sufficient for orientation. Memorizing specific landmarks in our environment is essential if we change our position in the environment. At the same time, we need cognition to choose relevant landmarks and to combine the position of landmarks to each other and to ourselves. For orientation we also make use of specific rules/laws in our environment. Let us suppose we are in a new town and want to explore it. A typical relevant and salient landmark could be a church which we know to be often in the centre of town. When wandering around, we keep track of our position in the environment by remembering the position of the church relative to us. The church is a relevant landmark for orientation opposed to a street lamp since it is unique and follows the rule of being in the centre of town. Orientation is

therefore a complex cognitive process which requires the integration of multiple sources of information.

Navigation

Navigation goes one step further than orientation. Navigation is associated with directed movement in which one's position in the environment has to be located with respect to a destination, i.e. not merely exploring (as in orientation) but moving towards a certain goal. One part of navigation is path integration. Path integration means that a person needs to always keep track of and update his/her position and orientation during self-motion (Chrastil et al., 2019). It is an internal process. A classic experimental paradigm to test for path integration skills in animals and humans is the homing task. The subject starts at a starting point, walks along a path and at an end point has to return back to the starting point as directly as possible. Path integration abilities have been shown in insects e.g. ants (Wittlinger et al., 2006), but also in humans (Wiener et al., 2011). However, the mechanisms underlying path integration between animals and humans are assumed to be different: Whereas animals are thought to continuously update their homing vector during their outdoors activities, humans store representations of route segments in their working memory and only calculate a homing vector when necessary (Wiener et al., 2011). Both in animals and humans, navigation incorporates the abilities needed for orientation and adds the quality of goal-directed movement.

Spatial representations of navigation processes

The exact mental representations underlying spatial navigation is still a topic of present ongoing research and discussion. Researchers agree on the existence of spatial representations during navigation, but not on the extent and in which situations they are used. The two most commonly referred to spatial representations are the route and the survey representation of space. The term route representation implies that route segments are sequentially processed according to landmarks or decision points during navigation (Loomis et al., 1993). Tolman (1948) was the first to propose that animals and humans represent their spatial surrounding as "cognitive maps", a survey representation. How this survey representation / cognitive map is actually used during navigation is still disputed. Researchers mainly agree that the somewhat misleading term "cognitive map" does not mean that one constantly has a complete map of the environment in one's mind but that a map can be constructed piecewise if necessary, due to the knowledge gained by experience of specific routes and landmarks (Passini et al., 1990; Loomis et al., 1993). This construction can then enable e.g. taking previously unknown shortcuts. One can hypothesise that the route representation is a prerequisite for the construction of a more complex and efficient survey representation.

Reference frames for spatial orientation

In addition to mental representations of space, it is widely accepted that humans utilize two main reference frames in the environment for spatial orientation and navigation: the egocentric reference frame to process one's own position relative to the environment and the allocentric reference frame for information about the position of objects relative to each other in the environment (Klatzky, 1998). The egocentric reference frame is associated with a route representation while navigating since route segments are sequentially processed according to landmarks or decision points. The allocentric understanding leads to a survey representation of the route – a cognitive map (Tolman, 1948; Passini et al., 1990; Loomis et al., 1993). The extent to which an egocentric or an allocentric reference frame is dominant during navigation and if there exist specific tasks in which only one reference frame is utilised is still debated. Ekstrom et al. (2014) postulate that orientation and locomotion rely on an egocentric reference frame and therefore propose navigation to also primarily depend on egocentric

processing. They further propose the egocentric representation to influence the allocentric representation and therefore view navigation as an interaction of the two mechanisms. However, they also admit that the primary use of one strategy over another may depend on personal preferences of the individual to solve a navigation task and may even change during the task. During orientation and navigation, the individual therefore presumably mainly relies on the egocentric reference frame.

Spatial representations and reference frames during navigation/orientation as employed by blind people

For sighted people, updating their spatial representation through visual information of their environment requires little effort. For blind or visually impaired people who have to rely on touch, hearing and smell to compensate for lack or loss of vision, navigation is a difficult, time- and effort-consuming task (Espinosa et al., 1998). It has been shown in previous research that blind people use mostly route strategies when navigating (Fletcher, 1980; Cuturi, 2016) and therefore rely on egocentric coordinates. Examining the brain of blind people during complex navigation tasks in a functional magnetic resonance imaging (fMRI) study, Halko et al. (2014) found brain areas associated with egocentric navigation particularly active. The study proves from a neurobiological perspective that egocentric navigation strategies are primarily used by blind people in spatial navigation. These findings, however, do not prove that blind people cannot make use of allocentric navigation strategies or construct survey representations. Researchers have shown that congenitally blind subjects can develop survey representations of their environment via alternative senses (i.e. hearing, smell and touch), but that this takes more time and effort than in sighted people (Espinosa et al., 1998). This time-lag and additional effort can be explained with the differences between modalities in processing information. When perceiving several objects visually, the information can be processed simultaneously. Auditory and haptic perception have to be processed sequentially. Simultaneous processing of a large amount of information via other senses than vision can therefore not be processed as efficiently in congenitally blind people as in sighted people (Cattaneo et al., 2008). Late blind participants likely profit from the knowledge of allocentric relations in familiar environments, which they acquired before turning blind. One can conclude that blind people use mainly an egocentric reference frame and a route representation during spatial navigation since sequential processing of spatial information via other senses than vision makes the formation of an allocentric reference frame and a survey representation more difficult.

1.3 Sensory substitution devices

Sensory substitution devices try to compensate for the loss of one sensory modality by other substituting modalities. The plasticity of the brain is a necessary prerequisite for sensory substitution. Brain imaging studies have shown that upon visual impairments and blindness (especially in the first 12-16 years of life) the visual cortices undergo a huge functional reorganization such that they are activated by other sensory modalities (Cohen et al., 1999; Sadato et al., 2002; Collignon et al., 2007). Congenitally blind and people that lost their sight at an early age are therefore able to use the visual cortical areas for other compensatory modalities due to cortical plasticity. The brain is particularly plastic during infancy until puberty, but plasticity does not stop with adulthood, making substitution devices also useful when growing blind at an older age (Pascual-Leaone et al., 2005; Ptito et al., 2005). The first sensory substitution device was developed by Bach-y-Rita (1969). A tactile image on the back of six blind participants enabled them to perceive visual input and therefore discriminate between individuals and objects. A particularly important and successful vision-to-tactile substitution system for blind people is Braille (Bach-y-Rita et al., 2003). By using their fingertips to read, blind people compensate for their loss of sight. Bach-Y-Rita et al. (2003) even suggest that a prior sensory

substitution system is hidden in a person's ability to read since reading is a learnt ability that "visually presents auditory information (the spoken word)" (Bach-Y-Rita et al., 2003, p.541). Neuronal activity in the occipital lobe of blind people during Braille reading proves the existence of cross-modal plasticity as mentioned above. The visual cortex can be used for a spatio-tactile task such as Braille reading (Hamilton et al., 1998). Another device that can be considered as a successful sensory substitution device with very practical everyday use for blind people is the cane (Bach-y-Rita et al., 2003). The blind person perceives a stimulus at the end of the cane, rather than in the hand holding the cane. To move independently and safely through known and unknown environments, blind people have to rely heavily on such travel and orientation aids as the cane and training is necessary. A downside of sensory substitution devices is that attention and other sensory modalities have to be devoted to them, leading to yet another source of information that has to be processed.

1.4 Sensory augmentation with the feelSpace belt

The idea behind sensory augmentation devices is learning a new sense. The brain is supposed to learn to interpret unchanging, rule-based new sensory input from the augmentation device. Instead of using other sensory modalities to compensate the loss of another – as is the case in sensory substitution devices – new sensory information is given. In the case of the sensory augmentation device “feelSpace belt”, the new information consists of a vibrotactile signal about the direction of the magnetic north. The feelSpace belt has first been used by Nagel et al. (2005). Since then, it was used in several studies (e.g. Kärcher et al., 2012; Kaspar et al., 2014) and made a product for the blind. The person wearing the belt receives permanent tactile information about the magnetic field of the earth (Nagel et al., 2005) - information that is not innate in humans and therefore provides information exceeding that of our sensory organs.

Research conducted with sighted participants focussed on investigating whether a new modality is formed when wearing the belt (Nagel et al., 2005), whether new sensory-motor contingencies are formed (Nagel et al., 2005; Kaspar et al., 2014; König et al., 2016) and whether the augmented information from the belt can be integrated in the already existing native sensory information (Goecke et al., 2016). Nagel et al. (2005) report that training with the feelSpace belt improved performance in outdoor navigation tasks and leads to a subjective new experience of spatial perception. Furthermore, they showed that little attention needs to be devoted to the belt and therefore suggest that new sensory-motor contingencies (SMCs) are formed when training with the belt over a longer period of time. The concept of sensory motor contingencies claims that the quality of perception is determined by the knowledge of how sensory information changes when one acts in the world. They further propose that the meta-modality spatial perception - a secondary modality that takes the information of the primary modalities into account for more natural perception of the environment - is modified when wearing the belt. The meta-modality is formed due to the formation of SMCs. No new modality as such is formed since one does not sense the earth's magnetic field without the belt. In a study built solely on subjective experiences of subjects wearing the belt over a seven-week period, Kaspar et al. (2014) support the findings of Nagel et al. (2005) that new SMCs are formed by wearing the sensory augmentation device. Results indicate that participants experienced perceptual changes of the belt's information. The vibrating signal turned into spatial information during the experimental period. Altogether, the belt induced changes in navigation behaviour and spatial perception. König et al. (2016) support the development of new SMCs when wearing the belt with EEG and fMRI data. Participants in the study of König et al. (2016) and those in the study of Goecke et al. (2016) report that participants rely on the belt's information. Participants tend to find the signal of the belt more reliable than the sometimes more accurate native orientation strategies, as Goecke et al. (2016) have shown in an angle estimation task. This subjective feeling of the participants may be due to the signal of the belt being

easy information access because of its absolute coordinate system Goeke et al. (2016) hypothesise. The developed enhanced navigational skills with the belt, however, only last as long as the belt is worn. Kaspar et al. (2014) found that the effects of the belt faded in the following weeks after their study. The improvement seems to be tied to experiencing the signal of the belt continuously. All in all, the sensory augmentation device has proven in several experimental setups to give an easy to understand and useful signal which informs the wearer about his/her relative position to the magnetic north. In contrast to the sensory substitution devices, the feelSpace belt provides additional information without attracting too much attention from other important sensory organs during orientation and navigation.

1.5 FeelSpace belt for blind people

The above-mentioned results of studies with the feelSpace belt with sighted participants could only partly be replicated in the case study with a late blind subject by Kärcher et al. (2012). As with sighted participants, the signal of the belt gave additional helpful information during spatial navigation. Kärcher et al. (2012) proved that the feelSpace belt was used by a late blind subject partly without attentional resources. Kärcher et al. (2012), however, found no evidence of the formation of a new modality nor a change in the perception of the belt's signal which would indicate the formation of new SMCs in the late blind participant but they do not exclude its feasibility. A further case study by Schumann (2012) with one congenitally blind participant showed, that new spatial relationships can be learned with the help of the belt in familiar environments. All researchers working with the belt have reported a positive influence of the belt on navigation abilities and positive emotions of sighted as well as of visually impaired and sightless participants towards the belt (Kärcher et al., 2012; Kaspar et al., 2014; Nagel et al., 2005 etc.).

1.6 Current study

In this current study my focus lies on investigating in how far the feelSpace belt as a sensory augmentation device is of help for blind people when orientating or navigating and how intuitively the belt can be used. The research of Kärcher et al. (2012) served as a source of inspiration for the present study design. One part of the study consists of two experiment days on which the same three experiments (straight-line-walking, angular rotation and a combination of triangle completion and pointing task) were conducted. These experiments provide the behavioural data to investigate the orientation and navigation abilities of the participants. The other part is a long-term study of seven weeks in which the blind participants wear the belt in their individual everyday situations. Weekly questionnaires give information about the belt's use in everyday situations and gave the subjects the opportunity to share their experiences, concerns and wishes. The value of the belt user's evaluation became especially evident in the study by Kaspar et al. (2014). The weekly questionnaire used in this study was successfully used in the study by Kärcher et al. (2012) and was only slightly modified. Prior experimental studies with the belt were either conducted as a case study with one blind participant or with blindfolded sighted participants. The larger number of blind participants in this study will give a clearer picture as to the impact of the belt on the spatial orientation and navigation abilities of blind people. The data will also be used to uncover possible downsides of the device from which improvements for future versions of the belt can be deduced.

2 Methods

2.1 Participants

22 subjects signed up for the 7-week study in which the participants wore the belt in everyday life. 11 out of the 22 subjects fully participated in the long-term study. Five people out of these 11 additionally took part in experimental tasks. Two participants were deaf-blind and are going to be analysed separately from the other blind participants. Nine participants had to be completely or partly excluded from the study. The participants were either members of the “Blinden- und Sehbehindertenverband Niedersachsen” (BVN) or of the “Deutschen Blinden- und Sehbehindertenverband e.V.” (DBSV). Both are organisations for blind and visually impaired people on the level of Lower Saxony or throughout Germany respectively.

Figure 1: Overview of the participants in this study.

Five participants that took part in the experiments and the long-term study

	P1	P2	P3	P4	P5
Gender	masculine	masculine	masculine	masculine	feminine
Age	48	34	68	73	57
Blindness	late	congenitally	late	late	late
Duration of blindness	34 years	34 years	45 years	60 years	34 years
Sight	-	-	left eye: 0.01	-	-
Eye disease	Infantile glaucoma	Missing optic nerve	Retinitis pigmentosa	Retinitis pigmentosa	Glaucoma
Aid devices	Cane Compass Accompanying person	Cane Accompanying person	Cane	Cane	Cane Guide dog
Orientation strategies	Traffic noise Smartphone Guiding lines Hearing and smelling	Traffic noise Smartphone Guiding lines Hearing and smelling	Traffic noise Smartphone Guiding lines Tactile maps	Traffic noise Smartphone Guiding lines Hearing and smelling	Traffic noise
Mobility training	50 hrs	>50 hrs	25-50 hrs	50 hrs	>50 hrs
Knowledge of cardinal directions,	yes	yes	yes	yes	yes

degrees and angles					
Job	Pedagogue	Social worker	Voluntary association official	Retired	Physio-therapist
Activities	Walks Traveling	Walks Traveling Sport in fitness centre	Walks	Walks and hikes Tandem bike rides Plays the piano	Walks Organisation of seminars Technology
Traversing big crossings	seldom	regularly	sometimes	regularly	never
Crossing a road	regularly	regularly	regularly	regularly	never
Walking along train platforms	regularly	regularly	sometimes	regularly	only when accompanied and when there is no alternative, seldom
Crossing a large square	sometimes	sometimes	only if there is no alternative	sometimes	seldom

Table 1: Information on the five subjects that participated in the behavioural and long-term study.

Since five participants (four late blind and one congenitally blind) took part in both the behavioural as well as in the long-term study, a particularly detailed analysis of these participants is possible (**Table 1**). These five subjects are all active and mobile people that have received orientation and mobility training (lessons in which orientation skills are taught to blind or visually impaired people) prior to this study and have been blind for several years. They know cardinal directions, angles and degrees, which are essential prerequisites to be able to interpret and understand the vibration signal of the belt towards the north. All use the cane as an aid in outdoor activities and use traffic noise for guidance. Whilst participant five (P5) has little experience in traversing large crossroads, roads, open spaces or walking along train platforms because she lives and works in the countryside with little infrastructure, the other four participants (P1-P4) are familiar with such urban challenging everyday situations. The participants rated their sense of orientation from quite good to very good before the study.

Additional six participants for the long-term study

The six additional participants (P6-P11) of the seven-week long-term study (three female, four congenitally blind) had comparable abilities and experiences to the five subjects described above. They, too, were active people that liked going for walks. All received orientation and mobility training prior to this study (range 25-300 hours). Although there is a large discrepancy in training hours, the absolute amount is not to be weighted too strongly, since factors such as the age of onset of blindness, the previous visual experience and the amount of preparation in terms of training hours before the sometimes foreseeable blindness, as well as the personal gain from such training hours have an influence on the actual number. In general, one can be sure that all participants have had some mobility training prior to the study. They all knew cardinal directions, angles and degrees and rated their own orientation abilities from quite good to very good.

For the long-term study, the 11 participants are seen and analysed as a group (four female, mean age 54.36 years, SD = 11.96, range 34-73). Five participants were congenitally blind (two female, blindness

for mean 44.8 years, $SD = 6.61$, range 34-51 years) and the remaining six participants were late blind (two female, blindness for *mean* 39.5, $SD = 15.5$, range 20-60 years). The late blind participants form a heterogeneous group with unbalanced gender and differences in the time and age of the onset of blindness (twice early puberty (13 and 14 years old), twice early adulthood (both 23 years old) and twice middle aged (40 and 53 years old)) and degree of blindness (four subjects have no sight at all and two subjects can differentiate between light and dark with one of them being able to detect a curb in good light conditions). The group of late blind subjects form a heterogeneous group in contrast to the more homogeneous congenitally blind group of participants. None of the participants had any neurologic, psychiatric or chronic diseases. Their health condition was asked after every week. On average, the participants were highly motivated to partake in this study and all very curious and excited about their experience with the feelSpace belt. The thought of wearing the belt did not disturb or unsettle nine of the participants at all and two participants only slightly.

As a side note - I presented the participants by dividing them into two groups according to whether they had at one point used their vision (late blind subjects) or never experienced visual input in their life (congenitally blind subjects). This was done because recent research has found that the age at which one turns blind and therefore the amount of prior visual experience has an influence on the precision of integrating different senses (Scheller et al., 2019) and on the non-visual use of the occipital cortex (Bedny et al., 2012). One must therefore assume that congenitally blind and late blind people have fundamentally different mental images of their surroundings, orientation strategies and mental processes.

The two deaf-blind participants

The two deaf-blind participants were male, 56 and 63 years old and both were born with the Usher-syndrome. Both have suffered from severe visual impairment for 14 and 13 years, but can see differences between light and dark, are deaf and both have slight vestibular problems. They were both able to answer questionnaires written in easier language by sending us experimenters and e-mail with their answers, which requires a certain degree of technical knowledge. Outdoors, they use a cane and tactile guiding lines. Both have a knowledge of cardinal directions, angles and degrees, which is necessary to be able to interpret the signal of the belt (see blind participants). Like the blind participants, the deaf-blind subjects were motivated to participate in the study and were curious and not unsettled about their first experience with the belt in this present study.

Excluded participants from the study

Five blind participants had to be excluded from the analysis of this study for different reasons: One participant could participate no longer after one week because of a stay in hospital; one participant had technical trouble with filling in the weekly questionnaires after only being blind for four years (telephone calls to help with the answering of the questionnaires were not answered); one participant only filled in the questionnaires sporadically leaving us with missing data that could not be compensated for and one subject quitted the study because of too little time to get acquainted with the belt. The fifth participant had relatively recently turned blind and had problems with interpreting the signals of the belt adequately. Due to his short time of blindness the belt signal distracted his attention too much and it felt like a "signal from outside" and secondly that he had difficulties in general with tactile information. Of one further blind participant (P12) only the pre- and post-questionnaire, but not the weekly questionnaires could be evaluated. Three out of five deaf-blind participants could not fill in the questionnaires and had to be excluded.

2.2 Technical setup

The FeelSpace belt

Figure 2: Left image: The belt is worn around the abdomen and one vibromotor of the belt indicates the direction of the magnetic north. Right image: The belt has a control box with four buttons which can be felt by touch. From bottom left to top right one can see the on/off button, the pause button, a button linked to the belt's navigation application and the compass button to switch between modes.

The FeelSpace belt (**Figure 2**) is a sensory augmentation device enabling people to sense direction tactically, which is especially valuable for people who are unable to rely on vision for orientation. The belt, first developed by Nagel et al. (2005), provides directional information of the magnetic north via vibrotactile stimulation around the waist. The present version of the device is equipped with 16 small integrated vibrating motors that are evenly spaced around the waist such that 360° are covered – each module covers 22.5°. A compass passes the information of the magnetic north onto the vibromotors. Only one motor vibrates at a time to prevent irritation (Nagel et al., 2005). The choice of a belt as a sensory augmentation device is rooted in the abdomen being a stable and important body site for processing one's orientation relative to the environment and at the same time being sensitive enough to locate and process vibrotactile signals at different sites (Cholewiak et al., 2004). The prototype of the belt had 13 vibromotors (Nagel et al., 2005). FeelSpace further improved the belt by surrounding the vibromotors with a skin friendly and weather proof envelope for more comfort for the wearer and protection of the equipment and by adding a control box which is usable for congenitally and late blind people and by equipping the belt with batteries lasting for 9-15 hours. The number of vibromotors was recently reduced from 30 to 16. A trade-off between precision of information and cognitive demand is needed for the optimal number of vibrotactile motors (Cholewiak et al., 2004). The belt has two main modes: The standard mode is the compass mode in which the direction of the magnetic north is indicated via the continuous vibration of one of the motors. The belt's signal of the magnetic north remains constant while the participant experiences the vibration traveling around his / her abdomen when turning. The second mode is the road-crossing mode. When one activates the latter mode by pressing the compass button twice, the motor element at the naval vibrates in short sequences to indicate the direction when the blind person wants to walk straight ahead. If the blind person diverges from the straight line, he / she is informed via vibrosignals on the left- or right-hand side of the central vibromotor. This mode is supposed to be an advantage when wishing to cross a road in a straight line since the naval is a sensitive region of the abdomen (Cholewiak et al., 2004). The belt can be also connected to the feelSpace smartphone application so as to be able to use the vibration of the belt's modules for navigation. This function, however, is not in the focus of this present study. The feelSpace belt therefore allows the wearer to follow his / her gut feeling in the literal sense.

The “Compass Experiment” application

In order to measure the turning degrees and the turning direction of the participants, the application “Compass Experiment” was developed. The experimental conditions of the angular rotation and triangle completion task could be uploaded by the experimenters as json files to the application on an Android smartphone (for the conditions see 2.4.1 Experimental tasks). During the angular rotation task, the application on the smartphone gave pre-programmed instructions to the participant in which direction to turn. The participant held the smartphone himself / herself and pressed the screen to receive the next instruction. The feelSpace belt could be connected to the application during the experimental tasks, which then recorded the time needed for turning, the present orientation, the difference in turning degree to the start orientation and the orientation at the end of the last turn, the turning degree and the turning direction (left or right). With this information, turning errors could be calculated. The design of the application can be seen in the appendix (A8).

2.3 Study procedure

Study Procedure

* Experiment days with only five participants

Figure 3: The overall schedule and structure of the study

Five participants came to the Westerberg Campus of the University of Osnabrück on their first experiment day. After having been informed about the procedure of the study (**Figure 3**) and then having given their consent to participate in the study (**Appendix A1**), they filled in the pre-questionnaire (**Appendix A3**) with one of the experimenters. Then they received their belt and were introduced to the belt’s functions (**Appendix A2**). First the subjects completed a straight-line walking, then an angular rotation task and finally did a combination of a triangle completion and pointing task. Every task was performed under a variety of conditions: with the belt in either compass mode or in road-crossing mode or without the belt and with or without distraction tasks. After each condition in every task two questions were posed (**Appendix A6**): The first question addressed the feeling of security after the respective condition compared to a similar situation in everyday life and the second question asked how sure the participant was that he had succeeded in performing the respective task. These two questions were Likert scaled questions. A subjective estimation of performance is compared with the behavioural data in one of the other experimenter’s bachelor thesis. The exactly same three experiments were performed again on a second experiment day after the participants had trained for 4-6 weeks with the belt.

The start of the seven-week study was announced via e-mail. All 11 participants, including the five subjects that took part one to two weeks earlier in the experimental tasks, started the seven-week period at the same time. The seven (including P12) participants who did not partake in the experimental tasks received their belt via post, filled in the pre-questionnaire online and were informed about the procedure of the study, the way their data was handled and the functions of the belt via telephone. All participants gave their written consent before participating in this study. Over the weeks, the participants trained independently with the belt and wore it in known and unknown environments. Each week they filled in the weekly questionnaire with questions regarding different situations in which they had to orientate and navigate and their feelings regarding the belt (**Appendix A4**). These questions remained the same every week so as to be able to view changes over the weeks. After seven weeks, the participants filled in a final post-questionnaire (**Appendix A5**). The questionnaires were all designed in surveymonkey, an online platform for designing barrier-free questionnaires. The participants were sent a link to the questionnaires on surveymonkey. However, most of the participants preferred to answer the questions via e-mail.

Due to the Covid-19 pandemic virus outbreak, specific safety measures had to be taken for the experiment days in accordance with the Corona policy in Germany and Lower Saxony of 22nd March 2020 (**Appendix A7**). We experimenters, as well as the participants, wore masks during the whole experiment and kept a distance of at least 1,5m. Furthermore, each participant had contact to only one of the experimenters during the experiment so as to further diminish the risk of infection. Hands and utilities were disinfected before / after every participant and the experimenters wore gloves during the experiments.

2.4 Study design

The goal of this study is to determine how the belt effects blind people when orientating and navigating in everyday situations. To investigate the belt's effect, three experimental tasks were designed: a straight-line walking task, an angular rotation task and a combination of a triangle completion and pointing task. The aim was to keep the experiments as near to a natural situation as possible. To gain a larger picture, the behavioural data was reinforced with subjective quantitative and qualitative data from questionnaires. This combination of measured data on two experiment days and the subjective impressions and experiences of seven weeks wearing the belt give a clearer and deeper understanding of the effects of the belt on the participants. For five participants, combining these study methods was possible. For the remaining six participants, only subjective reports are available.

2.4.1 Experimental tasks

Straight-line walking task

The straight-line walking task, in which the participants try to keep a straight direction, aims at mimicking the crossing of a large street or an open space. This is a very challenging task for blind subjects, but is also a necessary ability to not only remain orientated and to reach one's destination but also to move around safely in towns and cities. Sighted people use visual landmarks to keep a straight line. Blind people have to solely rely on auditory and tactile white cane information about their environment, which is not as reliable. Taking the crossing of a street as an example, it is vital for a blind person to align to the curb so as to reach the other side of the road. Once the person starts crossing the road, it is difficult to correct the direction in which he or she is heading without visual feedback.

Figure 4: The general set-up of the straight-line walking task is depicted. The field was 50m long and 6m wide. The dotted lines indicate the ideal walking lane. Deviations from this walking lane were documented every 5m (A) in 50cm steps (B). The trials could be started from both sides of the field.

Straight-line walking task	
<i>Conditions</i>	<i>Trials</i>
(1) Without belt with distraction (2) Without belt without distraction	* each of the conditions twice
(3) With belt in compass mode with distraction (4) With belt in compass mode without distraction	
(5) With belt in road-crossing mode with distraction (6) With belt in road-crossing mode without distraction	* *
* Two conditions are kept together while the order of the three groups are randomized.	

Table 2: Conditions of the straight-line walking task.

For the straight-line walking task, an area of 50m x 6m was chosen as an experimental field outdoors without any obstacles in the way (the area in front of the canteen of the University of Osnabrück). The 50m walking line ran in a north-south direction. The participant had to start from a starting point and walk 50m as directly as possible toward the finishing line (**Figure 4A+B**). In half of the trials, a dual task paradigm was applied: to draw the participant's attention away from the task, the experimenters required the subject to count backwards from a number equal or smaller than 1000 in steps of three. The straight-line walking task was sub-divided into six conditions which were each repeated twice (12 trials) (**Table 2**). The order of conditions without belt (1&2), with belt in compass mode (3&4) and with belt in road-crossing mode (5&6) was randomized for each participant. The distraction task was always performed first to reduce the probability of a training effect and therefore of less attention needed anyway after two walks without distraction. The participants were allowed to use their cane during the task since this is an aid they use and rely on outdoors. To indicate the direction in which to head and give the start signal, one of the experiment conductors gave a "go"-signal from the finishing point. During the trials, the time was measured from the beginning to the end of the trail. The idea is that the participant walks faster when feeling more certain about the direction in which he / she is heading. Two practice runs, one with belt without distraction and one without belt without distraction, were conducted to get the participant acquainted with the procedure of the task. The experiment was video recorded.

The questions to answer with this task design are whether the tactile signal of the belt helps blind people to keep to the direction in which they are heading and whether the road-crossing function of the belt is a helpful feature for keeping to a straight line. If the belt signal helps, does it help on the very first day of the experiments without the person having experienced the signal of the belt before, indicating an intuitive functioning of the belt, or does it help after some training or does it help in either case?

Angular rotation task

In order to measure the orientation abilities of the participants with and without belt, the angular rotation task was designed. Specifically, the effect of the belt on egocentric orientation is examined. Without the guidance of visual cues, the blind subjects have to rely on auditory information or, if little to no stable auditory cues are available, on their own knowledge of turning degree, which they have gained in orientation and mobility lessons.

Figure 5: During the angular rotation task the participant stood at the centre of a circle. Via the Compass Experiment application, the participant was told in which direction and how far to turn from his initial position. The absolute turning error could then be calculated by taking the absolute value of the subtraction of the actual turning angle from the supposed turning angle.

Angular rotation task	
Conditions	Trials
(1) Without belt	1) Quarter turn to the right
(2) With belt in compass mode	2) Half turn to the left
	3) Whole turn to the right
	4) Quarter turn to the left
	5) Half turn to the right
	6) Whole turn to the left
	7) Quarter turn to the right
	8) Half turn to the left
	9) Whole turn to the right
	10) Quarter turn to the left
	11) Half turn to the right
	12) Whole turn to the left

Table 3: Conditions and trials of the angular rotation task.

The participant's belt was connected to the "Compass Experiment" application. The participant held the smartphone in his/her hand. Via the application, he/she was instructed to either do a quarter turn, half a turn or a whole turn either to the left or the right. All in all, the subject did 12 turns without the belt and 12 turns with the belt in compass mode (**Table 3, Figure 5**). The order of the conditions without belt and with belt was randomized. The initial orientation of the participant was also random. The

reason for the application to give the instructions and not one of the experiment instructors was that, in this way, there was no external reference point that the participant could use as an auditory cue during the task. Four practice turns – two without the belt signal and two with the belt signal – were performed beforehand to introduce the subjects to the application and the type of instructions. The hypothesis to test is whether the signal of the belt enhances the egocentric orientation abilities of the participants and if so, whether training is needed or not.

Triangle completion

The third experiment is a variation of the widely used triangle completion task. The triangle completion task has been used frequently in previous research (Loomis et al., 1993; Wiener et al., 2011) to test the navigation / path integration abilities and mental representations of the environment of participants and is a simplified homing task, which was originally performed with animals. Subjects are led along two sides of a triangle and then have to complete the triangle by returning to the starting point as directly as possible. Path integration is already challenging for sighted people, in for example a town, but for blind people even a small-scale path integration task as a triangle completion task as needed when wanting to take short cuts is even more of a challenge. In navigation, visual landmarks and memory / recollection of these are by far the most relevant information for sighted people, which blind people do not have. In this study the participants do not have to walk back to the starting point but only have to point back. The reason for this experiment set-up is that, in contrast to previous research (e.g. Loomis et al., 1993), we are not interested in the walking length to, but only in the direction of the starting point. The aim is to test the usefulness of the belt signal for the subject. The belt only gives information about direction and not about distance.

Figure 6: The participants were led along the sides of the three triangles with inner angles of 90° (right-angled triangle), 150° (isosceles triangle) and 30° in the order of the red numbers (A). The turns which the participants had to perform are depicted in (B). At the finishing point, the participants had to turn back to the starting point. The absolute value of the subtraction of the actual turn which the participant performed from the supposed turn results in the absolute turning error (B).

Triangle completion	
Conditions	Trials
(1) Without belt with distraction	1) 90° internal angle on the right
(2) Without belt without distraction	2) 150° internal angle on the left
(3) With belt in compass mode with distraction	3) 30° internal angle on the right
(4) With belt in compass mode without distraction	4) 90° internal angle on the left
(5) With belt in road-crossing mode with distraction	5) 150° internal angle on the right
(6) With belt in road-crossing mode without distraction	6) 30° internal angle on the left

* Two conditions are kept together while the order of the three groups are randomized.

Table 4: Conditions and trials of the triangle completion / pointing task.

Three triangles were drawn on the floor with varying inner angles (90°, 150° and 30°) (**Figure 6A**). The participants were led along two sides of the triangles by holding one end of a stick and the experimenter holding the other end. At the end of the second side, the experimenter took down the stick, which was the cue for the participant to turn back to the estimated starting point (**Figure 6B**). A stick was used to exclude the possibility of the experimenter giving the participant any kind of cues. The turning degree of the participant from the end point back to the starting point was recorded with the help of the “Compass Experiment” application and the belt connected to it. Another experimenter stood at the end point and pressed a button in the application to record the participant’s orientation at the finish point. After the participant turned, the experimenter pressed the button again to record the orientation in with the participant pointed. The participant was asked to turn his/her whole body toward the estimated starting point so the application could record the direction via the belt. Additionally, the participant was supposed to point so the experimenters could judge whether the pointing direction matched the body position. The recorded data could later be used to calculate the absolute turning error (**Figure 6B**). Four conditions for the participants to walk along the two sides of the triangles were designed (**Table 4**). The distraction task was the same as in the straight-line walking task (mathematical calculations). The order of the conditions without belt (1&2) and with belt (3&4) was randomized. Each condition consisted of six trials since the sides of the three triangles were traversed twice from different sides such that the internal angle was once on the left and once on the right side (**Figure 6A**).

The aim of this task is to determine whether the belt has an effect on the spatial navigation abilities of the blind participants.

2.4.2 Questionnaires

In order to receive more information about the participant's experience with the belt in everyday situations and to deduce how helpful the belt is in the participant's natural environment, the experimenters designed questionnaires. The questionnaires consisted of multiple-choice questions, matrix questions with quantitative Likert scales and open-ended qualitative questions. The questionnaires can be found in the appendix (A3-A5).

A pre-questionnaire served as a source of information about the participants that took part in the study. The length and degree of blindness, the orientation aids (such as a cane, dog etc.) and orientation strategies (e.g. listening to traffic, smartphone etc.) of the subject, their willingness to explore new environments, their subjective estimation of how good their sense of orientation is and how often they come across certain situations outdoors were only a few of the questions posed to gain an impression of the participants and their orientation and navigation experiences.

The weekly questionnaire is mainly based on that of Kärcher et al. (2012). The questions can be subdivided into four categories: the perception of the belt during the week, questions concerning emotions and motivation, changes in orientation abilities and the use of attentional resources. I will focus on the questions concerning the orientation abilities in my bachelor thesis.

The post-questionnaire at the end of the study picks up questions from the pre-questionnaire to allow a before and after comparison. Additionally, the participants could give their final feedback on the feelSpace belt and on the study design and procedure.

All questionnaires were additionally approved by a rehab teacher working at a school for blind people.

2.5 Data analysis

Quantitative data from the experiments and the questionnaires was analysed with nonparametric statistics due to the small sample size. The five participants who took part in the behavioural experiments were first analysed individually in a case-study manner. Mainly descriptive statistics were employed, for which Excel 2019 was used. To test for statistical significance, the Wilcoxon sign rank test was used. As a second step the participants were analysed as a group. Here the focus was also laid on descriptive statistics due to the small number of subjects. To test for statistical significance and at the same time to take account of inter-subject differences, a two-way analysis of variance (ANOVA) was performed in MATLAB R2020a.

Quantitative data from the Likert scaled questions in the questionnaires was also analysed individually for each subject. Descriptive analysis was performed. The open-ended questions served the purpose of gathering the participants' experiences, problems and wishes and served as a source of subjective impressions.

I refrained from making inter-person comparisons when analysing the belt's effect for two reasons: Firstly, because the aim of this study is to inspect the developing effect of the belt on the individual participants and from these findings deduce similarities and secondly, because blind people are a very heterogenous group in which each person has individual strategies to cope with his / her impediment and experience with being blind such that a direct comparison of two participants is not useful.

3 Results

3.1 Experimental results concerning the impact of the belt on orientation abilities

In the following, the results of the behavioural data of the two experiment days will be presented.

3.1.1 Straight-line walking task results

With the help of the straight-line walking task I test the hypothesis that the feelSpace belt helps blind people keep to the direction in which they are heading when walking. Furthermore, the hypothesis that the belt's signal can be intuitively used and the hypothesis that the road-crossing function of the belt is a particularly helpful tool to keep to the direction in which one is heading were examined. In order to verify or falsify these hypotheses I analysed the participants' performance according to seven factors: reaching the finishing line, the precision of reaching the goal, the maximal deviation on the walking path, the size of the walking corridor, the summed-up amount of deviations, the longest straight-line walking distance and the time needed to reach the finishing line.

Finishing line reached

Figure 7: The bar chart depicts how often the finishing line was reached by the five participants in each condition. Since each participant performed each condition twice, 10 trials mean that the finishing line was always reached (dotted line).

Figure 8: (A) The absolute number of trials in which each participant reached the goal is depicted in the bar chart. Each participant performed each of the six conditions twice leading to 12 trials all in all. (B)+(C) In which of the six conditions (D) the participants reached the finishing line is shown for the first and second experiment day respectively.

The first and main factor is to ascertain whether the participant reached the finishing line. On the first day, all five participants reached the finishing line every time when following the signal of the belt in compass mode, except for one trial of one participant in the condition with belt in compass mode without distraction (Figure 7). In the conditions without belt and with belt in road-crossing mode, the participants taken together reached the finishing line four to five times out of ten on the first day (Figure 7). The results clearly indicate that the belt in compass-mode is immediately helpful to reach a goal lying straight ahead of the blind person, even when a distraction task is present.

Comparing the baseline condition of the participants walking the distance without the belt with the condition in which the participants wore the belt in road-crossing mode on the first experiment day (Figure 8B), one can detect differences between the participants: two subjects reached the finishing line more often with the belt in road-crossing mode (P2 & P3), one participant performed almost

equally well without and with the belt (P4) and two participants reached the finishing line without the belt more often (P1 & P5). One can deduce that two participants could immediately use the road-crossing signal at the naval to keep walking in a straight line, one participant could either also use the signal, or the signal at least did not distract him from keeping his track, and two participants could not profit from the belt's signal in that mode. The road-crossing mode was therefore only partially helpful to keep a straight line while the belt in compass mode led to increased performance in every participant in maintaining the direction in which they were heading on the first experiment day.

Examining the two participants that could keep to the direction in which they were heading with the belt in compass mode but not with the belt in road-crossing mode (P1 & P5), one can detect that P1 only reached the finishing line one out of four times in road-crossing mode, but was also stopped by the experimenter twice after 35m and once after 40m. At these distances, the participant would have already crossed a road safely. The other participant (P5) was less sensitive in the naval region than at the spine due to surgery. This explains her preference for the compass mode over the road-crossing mode because in the compass mode the participants walk south with the vibrating signal at their spine. On the second day, in all but one trials in road-crossing mode without distraction, the participants reached the finishing line (**Figure 7**). With the belt in compass mode and without the belt without distraction, the participants reached the finishing line in half of the trials (**Figure 7**). In compass mode four out of five participants either reached the goal or were stopped at 30m or later. Without wearing the belt this only holds for two participants. Three subjects reached the finishing line more often with belt in compass-mode than without belt (P1, P3 & P5). One participant (P2) did not reach the goal as often with the belt in compass-mode as without the belt but was stopped at a later point with the belt than without (30m, 40m and 45m). Wearing the belt in either mode, P4 only reached the finishing line in the conditions without distraction (**Figure 8C**). In the condition without belt he performed best by always reaching the finish line and without the distraction task, the participant reached the finishing line in compass mode once out of two times and in road-crossing mode every time. The results of GR have to be seen in light of the fact that he disapproved of the experimental set-up and especially of the distraction trials on the second day (see paragraph on subjective impressions below). The belt's signal also helped him on the second day to reach the finishing line.

Comparing the two experiment days, one can see that three out of five participants (P1, P3 & P5) reached the finishing line more often on the second day than on the first day (**Figure 7**) indicating a positive effect of training in the weeks between the two experiment days. The same three participants reached the finishing line with the belt in road-crossing mode on the second day more often than on the first day, P2 performed equally well on both days and P4 improved in the road-crossing condition without distraction for reasons mentioned below in the subjective impressions paragraph. The performance with the belt in road-crossing mode therefore improved over time. However, the performance of the participants with the belt in compass mode decreased from the first to the second day (**Figure 7**). Three participants reached the finishing line less often on the second day than on the first day and two participants performed equally well on both days (**Figure 8B+C**). Without the belt, two participants (P2 & P3) reached the finishing line more often on the second day than on the first day. The other participants' performances without the belt stayed almost stable. Taking an average of the participants and number of trials in which the finishing line was reached without the belt, one can detect a slight improvement in performance from the first to the second experiment day.

Deviation from the goal point

Figure 9: The bar chart indicates the precision with which the goal was reached i.e. a high deviation means low precision. The average deviation of the five participants was taken.

The second factor is the precision in which the goal was reached. The aim of the participant was to reach the point after 50m from which the “go”-signal was given by one of the experimenters. On the first day, four out of five participants had the least deviation at the finishing line from the goal point with the belt in compass mode. The deviations of the trials without belt and with belt in road-crossing mode were comparable (**Figure 9**). Together with the results from the above section one can deduce that the participants do not only reach the finishing line with the belt in compass mode but are also most precise at reaching the goal point in that mode compared to the baseline conditions without the belt or with the belt in road-crossing mode.

On the second experiment day, the participants showed higher precision at reaching the goal in one of the conditions wearing the belt than without the belt. Without belt and without distraction, the participants were almost as precise at reaching the goal as with the belt in compass mode (**Figure 9**). Comparing the first and the second day, one can see that the deviation from the goal point is drastically lower on the second experiment day than on the first day in all six conditions (**Figure 9**). In the two conditions in which the belt was in compass mode, the deviation is almost halved on the second day. In the road-crossing conditions the deviation is reduced by a third (distraction condition) or slightly more than a third (no distraction condition). The conditions without belt reveal nearly a third reduction in deviation in the distraction condition and more than half the deviation in the no distraction condition on the second day compared to the first day (**Figure 9**).

At this point one can already identify the tendency of the belt in compass mode as being particularly useful on the first experiment day since the finishing line was almost always reached (**Figure 7**) and that with a high rate of precision of on average less than 1m from the goal point (**Figure 9**). The road-crossing mode improves with respect to helpfulness on the second experiment day according to the number of trials in which the finishing line was reached (**Figure 7**) as well as in precision (**Figure 9**). Although the finishing line was not reached as often on the second day as on the first day, the trials in which the finishing line was reached showed higher precision compared to the first day.

Maximal deviation, size of walking corridor, summed-up amount of deviations and longest straight stretch of path

Figure 10: The average distance covered by the five participants when walking in an absolutely straight line without deviations is depicted in the bar chart.

The remaining four factors examine the deviations of the participants during their walk: the maximal deviation on the path, the size of the walking corridor, the summed-up amount of deviations and the longest straight-line walking distance. While the maximal deviation and the size of the corridor give actual information about the amount of deviation, the summed-up amount of deviation and the longest straight-line walking distance indicate how straight the participants moved. For this purpose, the deviation from the optimal line (the straight line) is measured in the course of the 50m walk every 5m. These measures are introduced here to examine the effect of the belt on the walking behaviour of the participants. The results without belt serve as a baseline. On average, the participants have the least maximal deviation (2m), the narrowest width of the walking corridor (2.25m without distraction and 2.45m with distraction) and the longest straight-line walking distance (15m without distraction and 17m with distraction (**Figure 10**) with the belt in compass mode on the first experiment day. These results suggest that it is easiest to maintain a direction heading straight on with the help of the belt in compass mode. The results of the baseline conditions without belt and the road-crossing mode are comparable with higher average results than with the belt in compass mode. The lowest average values of the summed-up amount of deviation are found in the conditions without belt with distraction and with belt in compass mode without distraction. The highest values are found in the exact opposite conditions without belt without distraction and with belt in compass mode with distraction. The low values in either condition with or without belt indicate that the participant walked in a relatively straight line with few deviances. High values have different implications for the conditions without belt and with belt: A high value without belt indicates natural deviations during walking; a high value with belt, however, can mean natural deviations or a correction of the direction of walking due to the signal of the belt. The cause of the deviations with belt cannot be shown with this measurement. From the first to the second experiment day, the average results of the road-crossing mode improved: deviations were reduced and the straight-line walking distance was prolonged.

Time needed to reach the finishing line

A seventh factor measured was the time needed in each condition. If a trial was terminated by one of the experimenters because of the participant deviating from the experimental corridor, the time was extrapolated depending on how far the participant had walked. The idea was that the participants walked faster if they were sure about the direction in which they were heading due to the continuous feedback via the belt's signal. This hypothesis, however, could not be verified by the behavioural data. Nevertheless, the subjective impressions of the participants on the experiment days was that they walked faster when wearing the belt due to the continuous feedback via the signal of the belt.

Summing up the results of the straight-line walking task in which the participants walked in north-south directions, the belt in compass mode helped the participants to keep a direction heading straight on on the first experiment day without them having trained with the belt beforehand. On the second day, the performance of the participants in the conditions with the belt in compass mode worsened whilst the performance with the belt in road-crossing mode strongly improved compared to the first day. From the first to the second day, the participants' performance without the belt either remained stable or slightly improved. The hypothesis that the belt's signal in general is helpful to walk a straight line due to the participant receiving permanent feedback from the belt is verified by these results. The results further revealed that the signal of the belt in compass mode can be intuitively processed, interpreted and used during walking with or without being distracted on the way, from the first day onwards. However, the road-crossing mode does not seem to be as intuitive as the compass mode, indicated by fewer trials in which the finishing line was reached and high deviations from the goal and on the way. Some training seems to be necessary to perform equally well in road-crossing mode as in compass mode. A reason for required training is that it is vital in the road-crossing mode to be exactly aligned in the direction of the goal before switching the road-crossing mode on. If this is not the case, the participant will deviate very quickly away from the optimal straight line to the goal, all the while following the "straight ahead" signal. The called "go"-signal from the other end of the field can only partially indicate the direction in which to head for the participant. The vibration at the naval in the road-crossing mode did not show superior performance over the vibration signal at the spine in the compass mode.

Subjective impressions of the participants and observations of the experimenters during the task

P3 mentioned on the second day after walking the trials with the belt in compass mode that it is difficult to return back to the initial straight line once one deviated from it. This impression is supported by the experimental data of not only P3 but of all participants.

P4 has to be considered independently from the others on the second experiment day since he did not approve of the experiments as such because he found the set-up too artificial and not comparable to everyday life situations. The subject was therefore not motivated at all to give his best, which was displayed in the results. Since he particularly disapproved of the distraction trials, the results show that he did not reach the goal in either belt mode with distraction, mirroring his attitude. In the condition with belt in road-crossing mode and with distraction, P4 commented that in an everyday situation he would take the belt off because this combination is an impediment for him. In the conditions without distraction and with belt, however, the belt's signal was seen to be very helpful by the participant. In these conditions, he did not use his cane in rhythmic intervals as usual but relied on the permanent feedback of the belt with occasional tappings with the cane for auditory information about the surrounding buildings. He additionally had the subjective impression that he walked faster since

wearing the belt. His conclusion with respect to this task was that the information of the belt clearly helps in everyday situations such as crossing a road and in situations in which traffic is involved. He said that in general, the belt helped in constantly changing environments, but that the experimental set-up of this study, especially with the unnatural distraction, did not represent his experiences with the belt in everyday life.

The slight worsening in performance from the first to the second day when the belt was in compass mode can have several reasons with respect to the participants reaching the finish line: In the case of P4 it can be explained by his lack of motivation to give his best on the second day. Additionally, there exists a natural fluctuation in performance from day to day due to the participants' levels of concentration, motivation, fatigue etc. P2, for example, arrived on the second experiment day by himself by navigating with the help of the feelSpace belt. The walking exercise of reaching the University campus might have had an influence on his directly performing the straight-line walking task with the belt in compass mode. Such natural factors have to be taken into consideration here. They are, however, factors on which we as experimenters have no influence.

3.1.2 Angular rotation task results

The angular rotation task was performed to test the direction estimation accuracy and therefore the egocentric body-centred orientation abilities of the participants. The hypothesis to be verified is that the belt has a positive impact on the turning accuracy of the participants. In the following, each person is first considered individually due to different performances on and developments between the two experiment days. In a second step, general results will be presented.

Figure 11: Comparisons of each participant's median turning error without or with belt in compass mode on the first (A) and second experiment day (B) were performed. A directed Wilcoxon sign rank test was calculated per person to compare the two belt conditions. One asterisk indicates a significant ($p < 0.05$) lower absolute turning error and therefore a significant higher precision at turning of the lower bar compared to the higher one. Two asterisks indicate a highly significant ($p < 0.01$) lower absolute turning error of the lower bar compared to the higher bar.

Figure 12: Comparisons of each participant's median turning error between the two experiment days separated into the conditions without belt (A) and with belt (B) were performed. A directed Wilcoxon sign rank test was calculated per person to compare the two experiment days. One asterisk indicates a significant ($p < 0.05$) lower absolute turning error and therefore a significant higher precision at turning of the lower bar compared to the higher one. Two asterisks indicate a highly significant ($p < 0.01$) lower absolute turning error of the lower bar compared to the higher bar.

The median of the absolute turning error of each person's 12 turns with the belt in compass mode and 12 turns without the belt was calculated to compare intra-person turning accuracy differences between the two conditions. The median was chosen as a measure instead of the mean as it is more resilient to outliers in the data. The median absolute deviation (MAD) as a robust measure of statistical dispersion serves as an indicator of uncertainty of a subject in performing the angular turns. The Wilcoxon sign rank test was used to test for statistical significance between the belt wearing conditions on each experiment day and to compare the development of each of the two conditions from the first to the second experiment days.

P1

On the first experiment day, P1 made smaller angular turning errors and fewer deviations in errors without the belt than with the belt (**Figure 11A**). On the second day, the same effect could be seen and P1 was significantly more precise without the belt than with the belt ($p = 0.0442$) (**Figure 11B**). Moreover, the medians of the turning error in both conditions were more than halved on the second day compared to the first day (**Figure 12A+B**). The subject was highly significantly more accurate without the belt ($p = 0.0081$) and significantly more accurate with the belt ($p = 0.0269$) at turning on the second experiment day than on the first day. One can deduce that P1 is more precise at turning without belt than with belt. Nevertheless, the training with the belt over the weeks between the two experiment days seems to have reduced the overall turning error. Each vibrating motor in the belt covers 22.5° turning degrees. P1 makes only small mistakes at interpreting the position of the vibrating motor in the belt on the first day and even fewer mistakes on the second day. This indicates a training effect over the weeks between the experiment days and additionally provides evidence that the belt's signal could also be used intuitively on the first experiment day. Training with the belt therefore has a positive impact on the subject in the sense that his already good estimation of turning is further improved.

Figure 13: Comparison of median and absolute median deviation values of the absolute turning errors. On the first experiment day the two statistical measures show supporting values (e.g. low median and low MAD in the without belt condition). On the second day there is a discrepancy in the values in the with belt condition (low median and high MAD).

On P2's first experiment day, the median absolute turning error was clearly lower without the belt than with the belt (**Figure 11A**). The Wilcoxon sign rank test showed that P2 was highly significantly better without the belt than with the belt ($p=0.0034$). Absolute turning errors were particularly high for 360° turns – up to almost half a turn (172°). The median absolute deviation was also extremely high in the with belt condition ($MAD=41.917^\circ$) and especially when the participant did a whole turn ($MAD=53.25^\circ$). The participant made a mistake at interpreting the position of the vibromotor 9 out of 12 times with the belt; seven times he turned two or more vibromotors too far or too little. A low median turning error and a low median absolute deviation in the without belt condition (**Figure 13**) show precision and certainty in the participant's turns. The belt's signal could not be used to estimate the angular turn by the participant, which is shown by the high values for median and deviation in the with belt condition (**Figure 13**).

On the second experiment day, the median of the absolute turning errors doubled for the condition without belt compared to the first day and decreased for the condition with belt to $\frac{1}{4}$ of the median turning error of day one. The median absolute deviation also increased for the condition without belt and decreased for the condition with belt. The values of the median and the deviation therefore show opposite tendencies (**Figure 13**). Whole turns have the highest turning errors.

Comparing the two experiment days, one can recognise that P2 made fewer mistakes at interpreting the position of the vibromotor signal. A relatively high median and median deviation in the condition without belt on the second day reveals less precision and certainty of turns than on the first day. The low median and high deviation in errors on the second day with the belt indicate high uncertainty at performing the turns (**Figure 13**). The results reveal that the belt's signal cannot be used by the participant to estimate his turning degree. The high deviations on both days during 360° turns with the belt indicate that the concept of the belt is not understood by the subject: the same vibromotor should be signalling before and after the turn.

P3

P3 has a lower median turning error and less deviation in the errors with the belt compared to without the belt on the first experiment day (**Figure 11A**). The Wilcoxon sign rank test proves that the difference is significant ($p=0.0122$). On the second day, P3 had a median error of 9° in both conditions (**Figure 11B**). This means that the participant significantly improved in both conditions (*without belt highly significantly: $p=0.0012$; with belt significantly: $p=0.0337$*) on the second day. Misinterpretations of the position of the belt's signal was reduced to zero on the second day. The belt's signal could be used intuitively from the first day onwards. Training with the belt further improved the estimation of turning angles in both conditions.

P4

On the first experiment day, P4 had the lowest median error (**Figure 11A**) and error deviation with the belt. With the belt, P4 was almost significantly more precise in his turns than without belt ($p=0.0542$). The second day revealed the opposite results: P4 made fewer turning errors (**Figure 11B**) and had fewer deviations in his turning errors without the belt than with the belt. Compared to the first day, he made mistakes in terms of the position of the vibromotor more often than on the second day. He was however highly significantly more precise on the second day without the belt than on the first day ($p=0.0073$). The belt was of help directly on the first day. The results of the second day are slightly skewed due to his lack of motivation on that day. The without belt condition improved from the first to the second day (**Figure 12A**).

P5

P5 showed a very similar performance on both experiment days and in the development from the first to the second experiment day to that of P4. On the first day, she was more precise with the belt in every aspect than without the belt: median turning error (**Figure 11A**), deviation of errors and no misinterpretations of the vibromotor signal. She performed highly significantly better with the belt compared to without the belt on the first day ($p=0.0029$), but on the second day the condition without belt was significantly better than with belt ($p=0.0408$) and she misinterpreted the position of the vibromotor slightly more often. Like P4, P5 improved in turning precision from day 1 to day 2 without the belt. With the belt she was however significantly more precise on the first day compared to the second ($p=0.0161$). She could intuitively make use of the belt's signal on the first experiment day. On the second day, she was less concentrated at performing the task compared to the first day due to a strenuous week at work. The without belt condition, however, improved on the second day.

Group analysis

Since P2 did not fully comprehend the turning concept of the belt, he is excluded from the following analysis and only the late blind participants are examined.

Figure 14: The median absolute turning error of the late blind subjects was calculated for when the participants wore the belt and when they did not. This was done for each experiment day **(A)**. The median calculated in **(A)** is further subdivided into angular turns (90°, 180° and 360°) in **(B)**. Furthermore, six ANOVAs were calculated separately for each of the angular turns in each condition to test for significant differences between the two experiment days. While no significant differences in the with belt condition were detected, a significant difference ($p < 0.05$, one asterisk) in 360° turns without the belt and highly significant differences ($p < 0.01$, two asterisks) in 90° and 180° turns without the belt can be seen when comparing the two experiment days **(B)**.

Figure 15: Boxplots are a statistical measure to graphically present the distribution of data. The “box” of the boxplot holds the data between the first (25%) and the third (75%) quartile, i.e. the middle 50% of the data. The line within the box indicates the second quartile i.e. the median of the data. The length of the “whiskers” is the interquartile range (IQR) between the first and third quartile multiplied by 1.5 for the upper whisker and by -1.5 for the lower whisker. By convention, the last data point within the calculated whisker is the end of the whisker. The dots indicate outliers in the data.

These boxplots give a more detailed overview over the distribution of the absolute turning errors of the four late blind participants. The two experiment days can be compared with respect to the belt conditions. Deviations of the absolute turning errors are fewer on the second experiment day than on the first in both belt conditions.

Taking the median of the absolute turning errors of the late blind subjects, one can see an improvement in turning precision without the belt from the first to the second experiment day while the median remains constant for the with-belt condition (**Figure 14A**). The MAD is more than halved on the second day compared to the first day in both belt conditions. Fewer deviations were made on the second day compared to the first day (**Figure 15**).

Further subdividing the errors into angular turns (90°, 180° and 360°), one can observe that on both experiment days and in both conditions, quarter and whole turns were performed more accurately than half turns. Without the belt, accuracy was highest for 90° followed by 360° and lastly 180° turns on both experiment days. This effect was also evident on the first experiment day with the belt. However, on the second day, according to the median turning errors, 360° turns were more precise than 90° turns with the belt (**Figure 14B**). ANOVA significance tests revealed the following.

On the first and second experiment days, the participants’ performance of 90° without belt, 180° without belt, 360° without belt, 90° with belt, 180° with belt and 360° with belt turns are highly significantly different (*day 1*: $p=0.0025$; *day 2* $p=0.0092$) according to the 2-way ANOVA of turning errors of the participants. Therefore, to avoid committing a systematic error in the analysis, three separate ANOVA for the turning degrees were calculated to test for significant differences between the with and without belt conditions. No significance between the two belt conditions were found on the first day. In general, each turn could be performed with the belt as precise as without the belt. With respect to the median, the participants were slightly more precise with the belt than without.

On the second day, however, a significant difference between the two belt conditions in the 90° turning errors was found ($p=0.0284$). Median and MAD of the turning errors were lower when the late blind participants performed the turnings without the belt. The participants were therefore more precise at

90° angular turns without the belt than with the belt on the second experiment day. No significant difference could be seen for the 180° and 360° turns.

Comparing the two experiment days in the condition without belt, the turning errors of all three turns are significantly to highly significantly different (90°: $p=0.0029$; 180°: $p=0.0067$; 360°: $p=0.0415$) (**Figure 14B**). Significant inter-person differences were revealed in the 180° and 360° turns ($p < 0.05$). All late blind participants had a lower median and a lower median absolute deviation in turning errors on the second day and therefore performed more precise turns compared to the first day. In the condition with belt, the two experiment days do not differ significantly (this aspect is going to be further analysed in the paragraph below on turning errors in terms of vibromotors, p.30).

The turning direction to the left or to the right showed a slight difference in performance between the two experiment days. On the first experiment day, turns to the right were performed more accurately while on the second day turns to the left were performed more precisely according to the median of the turning errors of both belt conditions. However, the median of right turns compared to left turns differed only in 4 - 5.5° on both experiment days. The MAD from the first to the second experiment day decreased in right turns and was halved when the late blind participants performed left turns. No clear preference in the late blind participants' turning direction can be detected in the angular rotation task but precision in performing the turns increased from the first to the second experiment day.

Turning errors in terms of vibromotors

Absolute turning errors which the late blind participants made in the angular rotation task can also be analysed by taking the vibromotors of the feelSpace belt into account. Each vibromotor covers 22.5°. An angular turn in the range of 22.5° with the belt would therefore activate the same vibromotor and with that gives the participant some leeway in performing the turn. An angular turning error of more than 22.5° therefore activates a neighbouring vibromotor of the appropriate one and leads to a mistake of one vibromotor. In the following, turning errors with respect to vibromotors are going to be analysed.

Figure 16: Boxplots are a statistical measure to graphically present the distribution of data. The “box” of the boxplot holds the data between the first (25%) and the third (75%) quartile, i.e. the middle 50% of the data. The line within the box indicates the second quartile i.e. the median of the data. The length of the “whiskers” is the interquartile range (IQR) between the first and third quartile multiplied by 1.5 for the upper whisker and by -1.5 for the lower whisker. By convention, the last data point within the calculated whisker is the end of the whisker. The dots indicate outliers in the data.

These boxplots give a more detailed overview over the absolute turning errors of the late blind participants when wearing the belt as already depicted in **Figure 14B** *right-hand part of the diagram*. As above, the absolute turning errors are sorted by turning degrees. In the case of 90° and 360° turns on both experiment days, more than 50% of the absolute turning errors are below 22.5°. Since each vibromotor has some leeway of 22.5°, the participants did not make any mistakes in terms of activating the appropriate vibromotor in more than 50% of all turns regarding 90° and 360° turns.

In contrast to the without-belt condition, no significant difference between the two experiment days could be detected when calculating ANOVAs in the with-belt condition as already mentioned in the paragraph above. Solely regarding the median in the with-belt condition, one could get the impression that the late participants were less precise in their turns on the second day than on the first day (**Figure 14B**, **Figure 16**). Taking a closer look at the distributions of the absolute turning errors of the individual turning degrees (**Figure 16**), one can, however, see that deviations seem to be less on the second day compared to the first experiment day. In the case of 90° and 360° turns on both experiment days, more than 50% of the participants’ turns were errors of equal or less to 22.5°. Since each vibromotor has some leeway of 22.5°, the participants did not make any mistakes in terms of activating the appropriate vibromotor in more than 75% of all 90° and 360° turns (**Figure 16**). From the first experiment day onwards, mistakes in activating the appropriate vibromotor in quarter and whole turns were seldom made such that performance on both days is comparable with even slightly less deviations on the second day.

180° turns, in general less precise compared to the other turning degrees, were also performed with less deviations on the second day than on the first day with the participants only once making a mistake by more than one vibromotor (>45°) on the second day.

Figure 17: The late blind participants' turning accuracy in terms of vibromotors is depicted. One vibromotor of the feelSpace belt covers 22.5°, meaning that on making a larger turn than 22.5° the neighbouring vibromotor would be activated. The left-hand side of the graph shows the late blind participants' percentage of turns in which they turned so precisely such that the appropriate vibromotor was active, i.e. turning errors less than 22.5° were performed for each condition respectively. On the right-hand side of the graph the percentage of turns in which the participants turned less or equal to 45° and thereby either made no error or an error of one vibromotor is depicted. Differences with respect to the conditions (with or without belt) on each individual experiment day as well as developments from the first to the second day can be observed.

After having analysed the absolute turning errors according to some leeway the belt gives the wearer in performing the turns in detail, the focus of this following paragraph is laid on comparing the belt conditions under the light of the existing imprecision of the belt.

To compare the without-belt condition with the with-belt condition, the spectrum of 22.5° is also applied to the without-belt condition. On the first experiment day, 58.33% of the turns without the belt and 75% of all the turns of all four late blind participants with the belt had errors of less or equal to 22.5° (**Figure 17 left-hand part of the diagram**). This is equivalent to making a turn such that the appropriate vibromotor is active for the angular turn performed by the late blind participants. These results show that more precise turns could be performed when wearing the belt which reveals that the belt is intuitively useful. Regarding turning errors of less or equal to 45°, which is equivalent to making a mistake by one vibromotor or less, the percentage of turns in the two conditions were comparable (*without belt*: 85.42%; *with belt*: 89.58%) (**Figure 17 right-hand part of the diagram**). These results together with those above indicate that on the first day the late blind participants could already perform more precise turns when wearing the belt than without the belt but they were also quite precise at performing their turns without the belt.

On the second experiment day, 87.5% of the turns without the belt and 79.17% of the turns with the belt were in the spectrum of 22.5° (the appropriate vibromotor) (**Figure 17 left-hand part of diagram**). Mistakes by only one vibromotor or less were made in 97.92% of the turns without the belt and 95.83% with the belt (**Figure 17 right-hand part of diagram**). Angular turns without the belt were therefore more precise than with the belt on the second day.

From the first experiment day to the second experiment day, the late blind participants made less mistakes in terms of vibromotors and smaller absolute angular turning errors in both conditions. An especially large increase in precision can be seen in the without-belt condition which surpasses the also positive trend of the with-belt condition (**Figure 17**).

Summing up the results of the angular rotation task, the individual analysis of the participants suggests that the belt's signal could be intuitively understood and used on the first experiment day by all late blind participants. The congenitally blind participant did not profit from the belt's signal probably due to not understanding the information of the belt relative to his body turns. While wearing the belt for the turning improved the angular turning precision from the first to the second day in only two cases, three out of four late blind participants highly significantly improved in the without belt condition. The two late blind participants with fewer precise turnings on the second day compared to the first day with the belt were, however, not motivated or could not concentrate on the second experiment day, which has to be kept in mind. Regarding the late blind participants as a group, one can see more clearly the significant to highly significant difference between the two experiment days in the without-belt condition according to angular turns whereas no significant difference can be detected in the with-belt condition. Quarter and whole turns are overall more precise than half turns independent of the belt condition and the experiment day, but only on the second day did the performance in 90° turns differ significantly between the two belt conditions. The median absolute turning error was lower without the belt, indicating the participants being more precise at quarter turns without the belt than with the belt. The MAD was in both belt conditions and irrespective of the turning directions lower on the second day than on the first day showing an increase in certainty at performing the turns. Analysing the turning errors in terms of whether the appropriate vibromotor for a specific turn was active or not, one can observe a high precision in activating the right vibromotor on both experiment days in quarter and whole turns when the late blind participants wore the belt. From the first to the second experiment day, the participants improved their performance in both belt conditions but especially in the without-belt condition. One can deduce from the above results that the belt improves the direction estimation accuracy and therefore the egocentric orientation skills of the participants that understand the relation between their body turns and the movement of the belt's signal relative to themselves.

3.1.3 Triangle completion task results

With the triangle completion task the impact of the feelSpace belt on the navigation abilities of the blind participants is tested. More precisely, the question to be answered is whether the belt helps the participants to keep track of their positions whilst moving in an environment, allowing them to take shortcuts. The participants traversed two sides of the triangles and had to point back towards their estimated starting point. As in the two tasks presented above, the aspect of the intuitive use of the belt's signal is also investigated. As a first step, the participants are going to be examined individually since their performances differed.

As in the angular rotation task, the median of the absolute turning error serves to compare the performance of each participant in the four conditions and in the different triangles (see **Table 3** for conditions and trials). The median absolute error is chosen as a statistical measure of the deviation within the absolute errors. This indicates the certainty of the participants at performing the turns back to the starting point.

Figure 18: Every participant performed the triangle completion task in four conditions (**C**). Each participant's median turning errors in the four conditions depicted for the first experiment day (**A**) and the second experiment day (**B**) respectively. The two diagrams are used to compare each participant's performance in the four conditions as well as on the two experiment days.

P1

On the first experiment day, P1 had a high median absolute error value and high deviations within the errors especially in the two conditions with belt, but also in the without belt with distraction condition. The smaller errors were performed without belt without distraction (**Figure 18A**). These results indicate that the task was considered a difficult task by the participant and the belt's information did not help the participant. On the second day, however, the median errors and the deviations drastically decreased compared to the first day. The lowest median errors were performed with the belt, but the medians of the two without belt conditions were comparable (**Figure 18B**). The median absolute deviation revealed the most drastic decrease in the condition with belt with distraction: the value of the first day ($MAD=39^\circ$) is reduced by factor seven on the second day ($MAD=5.33^\circ$). In the distraction conditions, the participant improved significantly from the first to the second day according to the Wilcoxon sign rank test (*without belt*: $p=0.0313$; *with belt*: $p=0.0469$). One can therefore see a great improvement of the participant at performing the triangle completion task from the first to the second day. The improvement is most prominent especially in the with belt conditions. These results reveal that the belt's signal could be used in a helpful manner to perform the navigation task on the second day. Moreover, since the condition with belt with distraction was the condition in which the participant was especially precise at turning back, little attention seemed necessary to perform the task. However, part of the improved performance from the first to the second experiment day is due to the participant recognising the triangles from the first day, as he admitted after having performed the conditions.

Figure 19: The absolute turning errors of participant P2 during the triangle completion task regarding the inner angle of the three triangles (30°, 90° & 150°) is depicted. The median absolute error is depicted as a red line and labelled. For comparison, this is done for experiment day 1 (**A**) and experiment 2 (**B**).

In the case of the congenitally blind subject P2, the median errors and deviations were very high in all conditions except for the with belt without distraction on the first day. In that condition, the values were relatively low compared to the other three conditions (**Figure 18A**). Examining the data more closely, one can observe especially high precision in turning in the triangles with an inner angle of 90° and 150° with the belt without distraction (**Figure 19A**). On the second day, P2 improved at performing the navigation task in the conditions without distraction according to the median errors and deviations. Regarding the single trials, one can, however, see a general improvement in all four conditions in the 90° and 150° triangles from the first to the second day (**Figure 19A+B**). In the with belt conditions the participant was more precise than in the without belt conditions on the second day according to the absolute turning errors. High estimation errors of the direction back to the starting point were committed in the 30° triangle in all four conditions on the second day (**Figure 19B**). P2 showed a preference for the triangle with a 90° inner angle and the isosceles triangle with the 150° inner angle on both experiment days. The clearly higher errors in the 30° triangle skewed the values of the descriptive statistical methods (even though they are as such robust methods) such that the individual turning errors of the trials had to be examined. In the triangles preferred by the participant, the belt's signal was of help on the first day in the condition without distraction and on the second day in both conditions with the belt. P2 also improved in the without belt conditions (especially in the condition with distraction) from the first to the second day. All in all, the navigation task was a difficult task for the participant. Training with the belt during the weeks between the two experiment days resulted in improved precision with and without the belt only in the preferred triangles (90° & 150°).

P3

P3 showed a high precision of turning back to the starting point on the first day according to the median of absolute turning errors (**Figure 18A**) and deviations of the errors. Especially in the conditions with the belt and the condition without the belt without distraction, P3 made few errors. The belt's signal could be intuitively processed and used for this navigation task. On the second day, the participant further improved his precision at turning back to the starting point in the without belt conditions by halving the value of the median errors and the deviations of the errors. In the conditions with belt, the participant was less precise on the second day compared to the first day. In the condition with belt with distraction the results remained comparable to the first day whilst his precision was apparently lower in the without distraction condition (**Figure 18A+B**). The Wilcoxon sign rank test revealed that the participant was significantly more precise in the condition without belt with distraction compared to the with belt with distraction ($p=0.0313$), underlining the improved performance without the belt. The without distraction comparison of with and without the belt also revealed that the task was performed more precisely without the belt. However, the result is not quite significant ($p=0.0781$). While the belt's information could be used by P3 to estimate the direction from which he started more precisely on the first day, the same effect cannot be seen on the second day. The without belt conditions, however, improved from the first to the second day.

P4

On P4's first experiment day, he committed high errors when estimating the starting direction, which can be shown by the high value of the median of absolute turning errors in all four conditions (**Figure 18A**). The MAD of the turning errors was also high but a little less so for the conditions without belt. High medians paired with low deviations of the errors in the without belt conditions indicate that the participant has an erroneous but constant estimation of the starting point. On the second day, the median errors, as well as the median absolute deviation of the errors in all conditions decreased compared to the first day (**Figure 18A+B**). As with P3, especially the without belt conditions improved in precision: the median absolute turning error was halved on the second day compared to the first day in the without belt conditions. On the first day, P4 had a stable but erroneous estimation of the starting point without the belt and the belt did not help him to make more precise estimations. However, the estimations improved on the second day so one can hypothesise that training with the belt during the weeks between the two experiment days had a positive influence on the overall precision of navigation.

P5

P5's estimations of the starting point were error prone. She had a high median absolute error in all four conditions (**Figure 18A**), but in the conditions without belt with distraction and with belt without distraction a low MAD of the turning errors on the first experiment day. On the second day, the median turning errors remained high except for when she wore the belt and had no distraction (**Figure 18B**). Excluding one high outlier, one can see that she also had the fewest deviations in errors in the same condition. The task was very difficult for P5. On the first day, the belt did not help in this navigation task. However, she had more problems with comprehending the task as such than with the signal of the belt since without distraction she had a low MAD value with the belt (see subjective impressions on page 36). On the second day, the belt's signal could be used for the navigation task whenever she was able to concentrate on the task and the belt's signal.

Group analysis

Figure 20: The median absolute turning errors of all five participants is depicted for the first and second experiment day in the four task conditions. An ANOVA for each condition comparing the two experiment days was calculated. In the conditions with distraction there is a significant difference between the two experiment days ($p < 0.05$, one asterisk) while no significant difference can be seen in conditions without distraction between the two experiment days.

Figure 21: Boxplots are a statistical measure to graphically present the distribution of data. The “box” of the boxplot holds the data between the first (25%) and the third (75%) quartile, i.e. the middle 50% of the data. The line within the box indicates the second quartile i.e. the median of the data. The length of the “whiskers” is the interquartile range (IQR) between the first and third quartile multiplied by 1.5 for the upper whisker and by -1.5 for the lower whisker. By convention, the last data point within the calculated whisker is the end of the whisker. The dots indicate outliers in the data.

These boxplots give a more detailed overview over the distribution of the absolute turning errors of the five participants. The two experiment days can be compared with respect to the belt conditions. As already stated and depicted in **Figure 20**, one can observe significant differences in the participants’ performance on the two experiment days in the tasks with distraction as calculated with an ANOVA for each condition ($p < 0.05$, one asterisk).

Considering the median absolute turning error of all five participants in the four task conditions, it can be established that more accurate estimations were given on the second experiment day compared to the first (**Figure 20**). In the conditions with distraction, the difference in performance was significantly different between the two experiment days (*without belt*: $p=0.0275$; *with belt*: $p=0.0488$). On the first experiment day, the distributions of turning errors were larger in the conditions with distraction compared to those without distraction. While the absolute turning errors from the first to the second experiment day lessened in the conditions with distraction, the distributions without distraction remained comparable (**Figure 21**). Regarding the experiment days separately, no major differences can be seen between the conditions regarding the median errors (**Figure 20**). Three out of five participants improved especially in the without belt conditions from the first to the second experiment day.

Figure 22: The absolute turning errors of the five participants sorted according to the three triangles with an inner angle of 30°, 90° and 150° respectively are depicted for the first (**A**) and second experiment day (**B**). The median stresses the difference between the turning accuracy depending on the triangle.

P2, showed extreme preferences in his estimations when traversing right-angles and isosceles triangles inducing one to examine the effect on all participants. Examining the results of the absolute errors more closely, one can detect differences in all the participants' performances between the three triangles (inner angle 30°, 90°, 150°) independent of the belt and distraction conditions and independent of the experiment days (**Figure 22A+B**). The participants have smaller absolute turning errors after having traversed the triangles with an inner angle of 90° and 150° than the triangle with an inner angle of 30°. These two triangles have special properties: one is right-angled and the other is isosceles (150°). The difference between the accuracy in path integration becomes more prominent on the second experiment day (**Figure 22B**). From the first to the second experiment day, the median of the absolute turning errors is reduced (**Figure 22A+B**). Right-angled and isosceles triangles are therefore easier path integration tasks than a triangle with none of those properties (30°).

Figure 23: The absolute turning errors of all five participants are pooled according to the inner angle of the triangles (30°, 90° and 150°) and whether the inner angles were on the right-hand or left-hand side of them while walking along the sides of the triangles. The four diagrams allow a comparison between the inner angle being on the right-hand side (**A+C**) and the inner angle being on the left-hand side (**B+D**) and a comparison between the first experiment day (**A+B**) and the second experiment day (**C+D**). The median is the statistical measure chosen to compare the results.

The participants walked along the side of each of the three triangles twice with the inner angle once being on the right-hand side and once being on the left-hand side. A bias towards more precise estimations when the inner angle was on the right-hand side of the participant during the walk compared to when the angle was on the left-hand side can be seen. Pooling according to the three inner angles of the triangles and examining the two triangles with the properties of either having a right angle or being isosceles (150°), one can also detect differences according to the side of the inner angle with respect to the participant: On the first as well as on the second experiment day, the starting point was estimated more precisely when the inner angle was on the right-hand side of the participant (**Figure 23A+C**). The isosceles triangle did not show a bias on the first experiment day, but on the second day participants were more precise in their estimations when the angle was on the right-hand side (**Figure 23C+D**). According to the median absolute turning error, the participants made more than

50% larger angular turns if the angle was on the left-hand side. No such clear bias towards right-hand turns can be seen in the triangle with the 30° inner angle. Right-angled and isosceles triangles are therefore not only easier triangle tasks but additionally show higher estimation accuracy of the starting point if the inner angle is on the right-hand side of the participant.

Since the triangles differ in many factors (the size of the inner angle and whether it is on the right- or left-hand side of the participant when walking the triangle, the turning angle back to the starting point, the turning direction chosen by the participant to turn back to the starting point and the length of the sides of the triangles) and each trial was only performed once, performing significance tests in the form of an ANOVA did not seem appropriate at this point.

Turning errors in terms of vibromotors

Figure 24: The five participants' turning accuracy in terms of vibromotors is depicted. One vibromotor of the feelSpace belt covers 22.5°, meaning that on making a larger turn than 22.5° the neighbouring vibromotor would be activated. The left-hand side of the graph shows the blind participants' percentage of turns back to the starting point in which they turned so precisely such that the appropriate vibromotor was active, i.e. turning errors less than 22.5° were performed for each of the four conditions respectively. On the right-hand side of the graph the percentage of turns back to the starting point in which the participants turned less or equal to 45° and thereby either made no error or an error of one vibromotor is depicted. Differences with respect to the conditions on each individual experiment day as well as developments from the first to the second day can be observed.

As in the axis rotation task above, the turning errors with respect to mistakes in vibromotors are going to be analysed in the following.

On the first experiment day, the five participants estimated the starting point correctly (less or equal to 22.5° turning error and therefore correct vibromotor) in 20-32.14% of all turns depending on the condition (**Figure 24 left-hand part of the diagram**). Mistakes by one or less vibromotors (less or equal to 45° turning error) occurred in 56.67-76.67% of the turns back to the starting point depending on the condition (**Figure 24 right-hand part of the diagram**). In the conditions without distraction the participants were slightly more precise. No clear difference between the conditions when the participants wore the belt to when they did not wear it can be detected. The low percentage of turns without mistakes with respect to the activated vibromotor in either condition reveals that the triangle completion task was considered a difficult task by the participants.

On the second experiment day, 46.67-53.33% of the turns back to the starting point depending on the condition were turns in which the appropriate vibromotor was activated (**Figure 24 left-hand part of the diagram**). In 76.67-86.67% of all turns depending on the condition, mistakes by one vibromotor or less occurred (**Figure 24 right-hand part of the diagram**). The participants made no mistakes in terms of vibromotors slightly more often in the conditions with distraction. However, no clear differences between the four conditions can be observed.

From the first to the second experiment day, the accuracy in activating the appropriate vibromotor increased. Especially the accuracy of the condition without the belt with distraction increased (**Figure 24**). However, in about half of all turns in any one of the conditions the appropriate vibromotor, which already gives the participants some leeway of 22.5°, was not activated.

All in all, the high median of estimation errors and the uncertainty of the participants in performing the estimations in at least one condition on both days indicates that the triangle completion task was a difficult navigation task for the participants. P3 was the only participant who not only showed reasonable results without the belt but could also use the signal of the belt directly on the first experiment day for more precise estimations of the navigation task. P1, who could not give precise estimations on the first day, showed great improvement in precision especially with the belt on the second day. The three remaining participants revealed a slight improvement in their estimations on the second day. The belt's signal / information could not be as intuitively of use for most subjects as in the above two tasks. However, with training in the weeks between the two experiment days, the performance in every condition improved in general as the median of absolute turning errors of all five participants as well as the mistakes in terms of vibromotors reveal. Significant differences between the two experiment days in the conditions with distraction can be seen with an improvement in precision on the second day. The results of the triangle completion task reveal a slight improvement in the navigation abilities and / or spatial mental representations of the participants through wearing the belt. Independent of the four task conditions and the experiment days, more accurate estimations of the starting point could be given when the triangles were either right-angled or isosceles.

Subjective impressions of the participants and observations of the experimenters during the two experiment days

On the first experiment day, P5 noticed during the triangle completion task that she still had to actively process the signal of the belt. She found the task strenuous since she had to concentrate strongly on the signal. The belt was not considered helpful at that point in time. These subjective impressions are also manifested in the behavioural data – the estimation of the starting point was not more precise when she wore the belt. However, in contrast to her subjective impression that she could concentrate better on the task without the belt as an additional source of information on the second day, her estimations were more precise with the belt without distraction. In general, P5 considered the task to be extremely difficult since she could not construct a mental image of the layout of the triangles, she explained. She understood the task as such but was unable to imagine the triangles she was walking. The triangle completion task also occupied her thoughts after the experiment on the first day and on the following days, so she admitted to the experimenters on the second experiment day. She discussed the task with her family and even dreamt about it because she could not mentally represent the task. For this reason, the task was explained to her in detail on the second day after the actual experimental trials.

P3 also expressed his feeling that the information of the belt was difficult to use for this task. According to him, the belt was first of all helpful when walking the sides of the triangles but not to orientate back

to the starting position. This impression fits in with the results that the participant performed more precise estimations without the belt on the second day than with the belt.

3.2 Evaluation of the questionnaires

In the section above, the results of the behavioural data of the two experiment days were presented. They give us detailed and as objective as possible data about the helpfulness of the belt at two points in time in this study: before wearing the belt and in the middle of the study after having trained individually with the belt for about 4 weeks. The questionnaires give an insight into subjective experiences in everyday situations during the seven-week period. They will be analysed quantitatively and then qualitatively in the following.

3.2.1 Quantitative evaluation of the questionnaires

Since detailed behavioural data of five participants was collected and analysed on the experiment days, those five participants are also going to be examined individually and separately from the remaining participants of the long-term study. In the following, I am going to focus on the questions regarding changes in the participants' orientation abilities. The questions that are going to be evaluated are structured according to a 5-point Likert scale from strongly agree to not agree. The results will be presented purely descriptively due to the small number of participants.

P1

P1 is a late-blind participant, 48 years of age who has been blind for 34 years due to an infantile glaucoma leaving him with no sight at all. He uses a cane and sometimes a compass or an accompanying person as aids. He orientates with the help of flowing traffic, guiding lines and in general with his auditory and olfactory senses. For navigation, he uses navigation apps on his smartphone such as BlindSquare (an app particularly for blind and visually impaired people) and Google maps. He is a pedagogue and likes to travel and go for walks. On average, he is outdoors for one to two hours each day. He rates his sense of orientation as very good. When orientating, he strongly agrees that he has a sequence of landmarks in his head and also an inner map of his surroundings in his mind. He sometimes explores new environments and does not avoid new surroundings actively. Concerning his experience with difficult situations outdoors when orientating, he seldom crosses large crossings, regularly crosses roads and walks along train platforms and sometimes crosses large open spaces such as squares. He only partly agrees that it is difficult for him to tell if he is walking round a long bend. This information was gathered in the pre-questionnaire before the study. He was highly motivated and curious before his first experience with the feelSpace belt and not at all unsettled about the idea of wearing the belt. Over the seven weeks when P1 wore the belt it was of particular interest to see how his subjective sense of orientation developed. Starting from a subjectively felt very good sense of orientation already without the belt, he had on average the impression over the weeks that the belt moderately improved his orientation abilities. In weeks three and four he did not have the impression that the belt helped his orientation abilities, which matches his lack of motivation to wear the belt in the third week. His conclusion in the post-questionnaire is in accordance with his average impression over the weeks that the belt moderately improved his orientation abilities. Taking off the belt did not lead to a worsening of his spatial orientation abilities over the weeks except for moderately in the last week. In general, his subjective opinion was that his orientation abilities were not worsened by wearing the belt and that contrarily, the belt rather helped him to orientate. P1 only partially agrees that the belt had no

influence on his orientation behaviour and strategies and moderately that the belt is a good complement to his already existing orientation abilities. The latter impressions indicate that the belt induced changes in the participant's orientation strategies. In the light of his very good orientation abilities already previous to the study, wearing the belt had a further positive impact on his orientation abilities.

Turning to P1's mental representations when orientating, he strongly agreed that he had a sequence of landmarks in his mind implying a route based mental representation. He, however, also agreed to that he had an inner map of his environment also indicating the existence of a map representation prior to wearing the belt. This subjective impression remained after the seven weeks of wearing the belt. Even though he was more aware of the cardinal directions since he wore the belt, he only moderately agreed in the post-questionnaire that the cardinal directions helped him to orientate and only agreed a little that his inner map was oriented towards the magnetic north. The participant was well aware of the cardinal directions due to the belt's information, but could not use that information for his survey representation.

The following three questions in the weekly questionnaire can be used to infer the development of the participant's reference frame over the weeks of wearing the belt. P1 strongly agreed over the whole seven weeks that he was well aware at every point in time of where he was relative to his home when wearing the belt. The participant's knowledge of his relation to a relevant object (his home) points towards a strong egocentric reference frame. P1 on average moderately agreed to rather agreed that it was easier with the belt than without it to estimate the position of different places to each other (except for in the third week in which he only agreed a little). His estimation of the position of roads to each other was also, on average, met with the same sentiment. These questions indirectly test for the development of the allocentric reference frame of P1. The belt leads to an improvement in estimating the position of different objects to each other and therefore improved the allocentric reference frame.

P1 explored new environments moderately, often without the belt. With the belt in the first four weeks of the study he found it a little easier to moderately easier to find his way in unknown environments; from the fourth week onwards, he found it moderately to rather easier. One can see a positive trend over the weeks. For him, the belt was very helpful in unknown environments. In familiar environments the belt helped a little. The amount of time P1 wore the belt in unknown environments was particularly high in the fourth and fifth weeks. In these weeks the participant also found it easier to orientate in unknown environments. One can therefore deduce that, with training, the belt's signal seemed to be of particular use for the participant to orientate and navigate in unknown environments and in surroundings he does not know.

When walking outside, P1 stated that for him it was moderately difficult to notice when he was walking round a long gradual bend without the belt. On average during the seven weeks, GS found that with the belt it was rather easier to notice that he was walking round a long bend, which was also his final impression in the post-questionnaire.

To sum up, P1 was both aware of the information the belt gives of the cardinal directions and he also used the information as information about direction and inferred relations of places with respect to his position as well as in relation to each other. He therefore used the information of the belt for his egocentric and allocentric reference frames. The belt had little impact on the cardinal alignment of the participant's inner map. It was easier for P1 to notice large bends in the road when walking. In general, the belt was experienced as having a positive effect on the orientation abilities in especially unknown environments.

P2 is a congenitally blind participant, 34 years of age and blind for just as long due to missing optic nerves. He uses a cane and an accompanying person as aids and orientates with the help of traffic and guiding lines outdoors. Additionally, he uses his auditory and olfactory senses for orientation. For navigation he uses his smartphone. P2 is a social worker who likes travelling and going for walks and to the fitness studio to do sport. On average, he spends half an hour to one hour outside per day. He rates his sense of orientation as very good and strongly agrees that he has a sequence of landmarks in his mind when he orientates and also an inner map. He frequently explores new environments and does not avoid them. Furthermore, he frequently traverses large crossings, crosses roads and walks on train platforms and sometimes crosses open spaces. P2 declares that he has no problem at recognising if the road has a long bend. He was highly motivated and curious and not at all unsettled about wearing the belt for a longer time in this study. Before this study, he first came in contact with the belt at an exhibition for aids for blind people and tested the belt on one day in the centre of Osnabrück under real conditions. This study is, however, the first time that he wears the belt over a longer period of time.

P2 estimated his sense of orientation as being very good before the study i.e. without the belt. Over the weeks, he on average recognised a strong improvement in his orientation abilities since he wore the belt and this was also his final conclusion in the post-questionnaire. Starting from the first week of wearing the belt, P2 had the subjective impression that his orientation abilities worsened when taking the belt off. He states that his sense of orientation strongly improved through wearing the belt and negates the statement that his sense of orientation has not changed over the weeks. He further has the impression that the belt's signal can be well integrated into his usual orientation strategies. The participant therefore sees the belt as a device which greatly ameliorates his orientation abilities and to such an extent, that he feels his orientation abilities decrease when taking the belt off.

After having stated in the pre-questionnaire that he had a sequence of landmarks in his mind and an inner map of his surrounding when orientating, he found that the prior estimation remained after the seven-week period but the latter did not. He concluded that he did not have an inner map of the surroundings after all. Since wearing the belt, he was very much aware of cardinal directions in every week except for the outlier in week four where he ticked the box, that he was not aware of cardinal directions. Before and after the study the participant has a route representation.

P2's opinion on whether he was aware of his own position relative to his home fluctuated from moderate to quite good over the weeks. He, however, quite to very much agreed that it was easier for him to estimate the position of places and roads to each other when wearing the belt. His allocentric reference frame seems to have improved with the belt.

Before the study began, P2 often explored new environments. With the help of the belt it is rather easier for him to orientate in new surroundings. Nevertheless, he feels that the belt helped more in known than in unknown environments. This impression may be due to him wearing the belt in total more than double as long in known compared to unknown surroundings.

P2's subjective impression of having no problems at noticing when he walks around a long bend before the study stands somewhat in contrast to his strong agreement with the statement that it is easier for him with the belt than without to notice that he is walking around a bend. Also, in the post-questionnaire he strongly agreed to this statement. This difference between the answer in the pre-questionnaire and during the weeks of the study can be seen as proof that he really did not notice long bends previously.

Summing up, P2 found that the feelSpace belt greatly enhanced his orientation abilities in general. The belt's information was helpful in particular in known but also in unknown environments. An enhancement can be seen in his allocentric reference frame. The belt also seemed to correct his

previous estimations and views before the study for example him noticing when he walked around long bends and that his not having an inner map of his surroundings.

P3

P3 is 68 years old and a late blind participant. He had been blind for 45 years at the time of the study due to the illness retinitis pigmentosa. He has slight vision of 0.01 on the left eye and can therefore see dark-light contrasts. As an aid outdoors, he uses a cane and for orientation he uses guiding lines and tactile maps and listens to traffic. For navigation, he uses the app BlindSquare on his smartphone. He works as a voluntary association official and goes for walks, does nordic walking and goes shopping in his spare time. On average he spends one to two hours a day outside. He quite agrees that he has a good sense of orientation. When orientating, he has a sequence of landmarks in his mind and also an inner map of the environment that is aligned to cardinal directions. He often explores new environments and does not avoid new surroundings. Concerning his experience with difficult outdoor situations for blind and visually impaired people, he frequently crosses roads, sometimes traverses large crossings and walks along train platforms and only if there is no other possibility does he cross open squares. He fully agrees to the statement that it is sometimes difficult for him to realise that he is walking around a long bend. P3 was very motivated and curious and not unsettled about his first experience with the belt.

P3 subjectively evaluated his sense of orientation to be quite good already without the belt. Over the weeks he did not have the impression that the belt enhanced his orientation abilities and his conclusion was that the belt helped him a little. He neither had the feeling that his sense of orientation worsened when taking the belt off nor in the course of the study. He, however, strongly agreed that the belt helped to orientate and could be well integrated in his orientation strategies. Furthermore, he negated the question that the belt had no influence on his orientation behaviour and strategies. P3 would not go so far as to say that his orientation abilities have improved since wearing the belt, but he does see the belt as a helpful device for orientation.

In the pre-questionnaire, P3 stated that he had a sequence of landmarks in his mind as well as an inner map of his surroundings in his mind. The impression of having an inner map was agreed to more strongly in the post-questionnaire after having worn the belt for seven weeks. Moreover, his inner map is more strongly aligned to cardinal directions after the study than before. Over the weeks he rather agrees that he is more aware of cardinal directions since wearing the belt. However, the cardinal directions only help a little when orientating. While he preserves his route representation, his survey representation seems to be enhanced through wearing the belt. Cardinal directions are transferred into feedback about direction and are not used as such.

P3 does not know at any point in time outdoors in which direction his home is from where he stands when wearing the belt. He stated that the belt gives him too little information in that respect. He would have to constantly count his steps to then calculate his position to his home which is not the sense he sees in wearing the belt. He, however, partially agrees that with the belt it was easier to estimate the position of places and roads to each other. The allocentric reference frame seems to have improved moderately.

Before the study he often explored new environments. In the first week it was not easier for him to orientate in unknown surroundings with the belt. From week two to four it was easier for him with the belt and in the last three weeks it was moderately easier. His conclusion was that the belt helped a little in unknown environments and quite a bit in known environments. Since he also wore the belt mostly in known surroundings, the results are not surprising.

P3 strongly agreed that it was sometimes difficult for him to notice when he was walking round a large bend prior to this study i.e. without the belt. On average, the belt strongly helped in this respect.

In general, P3 saw the belt as a helpful device for orientation and the belt's information as easily to integrate into his already existing orientation strategies. His survey representation was enhanced by the belt as well as his allocentric reference frame.

P4

Another late blind participant is P4. He is 73 years old and has been totally blind due to retinitis pigmentosa for 60 years. He uses a cane outdoors and orientates with the help of traffic noise, guiding lines, acoustic fixpoints and olfactory information. Smartphone apps such as BlindSquare, Google maps are used for navigation. He is retired and likes playing the piano, goes for walks and hikes and rides tandem. He is outside for more than three hours per day and frequently explores new environments without wanting to avoid them. His sense of orientation is subjectively estimated as being good and he orientates with a sequence of landmarks in his mind. He partially agrees that he has an inner map of his surroundings in his mind when orientating; however, this representation is strongly aligned to cardinal directions. P4 regularly traverses large crossings, crosses roads and walks along train platforms and sometimes crosses open squares. He strongly agrees that it is sometimes difficult for him to notice a long bend while walking. Although he has some previous experience with the belt, he is still very motivated and curious and not unsettled about participating and wearing the belt. It is, however, the first time he wears the belt for as long as seven weeks. Prior to this study, he came in contact with the feelSpace belt only for short tests.

Subjectively, P4 estimated his sense of orientation as being quite good. In the first three weeks his impression that the belt helped his sense of orientation improved from moderate to very much. In the following weeks it remained constant at quite helpful. His conclusion in the post-questionnaire was that he strongly agreed to the statement that his orientation abilities had improved since wearing the belt. A similar positive trend can be seen regarding the statement that his orientation abilities worsen when taking the belt off. In the first three weeks he moderately to quite agreed and in the following weeks he on average agreed very much, indicating a dependence of his orientation abilities on the belt. He also strongly agreed that the belt helped when orientating and that the belt was a good supplement to his already existing orientation strategies. In known as well as in unknown environments the belt was experienced as helpful. The belt therefore had a positive impact on his orientation abilities in general.

As stated in the pre-questionnaire, P4 still orientates with a sequence of landmarks in his mind; he has a route representation. Whilst he denoted that he can only moderately agree to having an inner map before the study, he strongly agrees to having an inner map and therefore a survey representation when orientating after the study. However, this inner map is not aligned to cardinal directions. This statement stands in contrast to his strongly agreeing to having an inner map aligned to cardinal directions in the pre-questionnaire. From the first week onwards, P4 was very aware of cardinal directions, which helped him to orientate. In his case, cardinal directions as such carried helpful information for orientating.

With respect to the development of P4's reference frames while wearing the belt, his egocentric reference frame improved since he was aware at every point in time where his position was in relation to his home. Relations of places and roads to each other were easier to estimate with the belt than without in his opinion, and therefore indicates an enhancement of the allocentric reference frame of the participant. His egocentric and allocentric reference frame improved with the belt.

Before the study, P4 often explored new surroundings. From the first week onwards, it was easier for him to orientate in unknown environments with the belt. The belt was felt to help in known as well as in unknown environments.

P4 strongly agreed that it was sometimes difficult for him to notice when he was walking round a large bend before the study. The belt strongly helped in this respect.

P4 saw a great enhancement in his orientation abilities when wearing the belt. His reference frames and survey representation improved and the information of cardinal directions from the belt was used for orientation.

P5

P5 is 57 years of age and has been totally blind for 34 years due to a glaucoma. She uses a cane and a guide dog as aids outdoors. For orientation she mainly listens to traffic noise. She works as a physiotherapist, organises seminars and likes to occupy herself with technology and goes for walks. Per day, she is outside for about half an hour to one hour. Her sense of orientation is quite good and she has a sequence of landmarks as well as an inner map of the environment in her mind when orientating, according to her own estimation. Her inner map is not aligned to cardinal directions. She moderately agrees that she explores new environments and does not avoid them. Since she lives in the country, she states that she never crosses large crossings or roads. She seldom walks along train platforms and then only with an accompanying person and if there is no other alternative. Open spaces are also only seldom crossed. She agrees that it is sometimes difficult for her to notice when she is walking round a large bend. In this study she has her first experience with the feelSpace belt and she is highly motivated and curious and has no worries about trying out the belt.

P5 estimated her sense of orientation as quite good prior to the study. On average she had the impression that her orientation abilities improved in the weeks of wearing the belt and concluded the study by strongly agreeing that her orientation ability had improved due to the belt. The belt also helped her to orientate and the belt could be integrated into her usual orientation strategies. Her good sense of orientation was therefore even further improved by the belt as well as her orientation abilities.

Without the belt before the study and after the study, she orientates with a sequence of landmarks in her mind and additionally with an inner map of her surroundings, indicating a route and a survey representation. While her inner map was not aligned to cardinal directions before the study, it is moderately so after the study. Since wearing the belt, she has been very aware of cardinal directions, which helped her to orientate. For her, cardinal directions as such carry information helpful for orientation. The information of the belt about cardinal directions is therefore for her not exclusively an indicator of in which direction to turn.

P5 quite to strongly agrees that she is permanently aware of her position relative to her home when wearing the belt. This indicates her use of the egocentric reference frame. Additionally, her allocentric reference frame was improved by the belt since she quite agreed that it was easier for her to estimate the position of places and the position of roads to each other when wearing the belt.

Prior to the study, she moderately often explored new surroundings. She quite to very much agrees that it was easier for her to orientate in unknown environments with the belt. The belt's signal helped in known as well as in unknown environments. It is noticeable how often she wore the belt. On average, she wore it 61 hours per week and therefore almost continuously and mostly in known surroundings. In the pre-questionnaire she quite agreed that it was sometimes difficult for her to notice that she was walking around long bend. In the first week of the study, it was quite easy and in the later weeks very much easier to notice a bend with than without the belt.

In total, the belt had a positive effect on P5's sense of orientation and abilities to orientate. The fact that P5 wore the belt for such long periods of time indicates that the belt was so helpful for her that she wanted to wear it constantly and, moreover, that it was comfortable to wear for a long time.

Group analysis of all the participants in the long-term study

After the detailed description of the five participants who participated in the long-term study as well as in the experiments, the aim of this section is to sum up the results of all 11 participants in the long-term study in order to obtain general results.

In the questionnaires, one could not find any differences in the results of the participants when filtering them according to gender, age, hours of orientation and mobility training, total blindness vs. ability to see light-dark differences, time spent outdoors before the study or total amount of time wearing the belt during the study. The length of blindness only revealed a difference in results between P9 and P10 and the rest of the participants concerning their feelings when thinking about wearing the belt over a seven-week period. Being blind for 20 and 15 years and therefore those participants that were blind for the shortest amount of time in this study, they were only a little concerned while the rest of the participants were not worried at all. No differences in the results of the five congenitally blind vs. six late blind participants could be detected. In the above description of the participants I mentioned that the group of congenitally blind participants were quite homogenous in contrast to the heterogenous group of late blind subjects regarding gender and onset, time and degree of blindness. The heterogeneity can be neglected for the following analysis since no differences in the results according to these factors could be detected. The focus of this section will therefore be laid on the questions regarding orientation and navigation abilities and space perception.

Sense of Orientation

My spatial orientation abilities have subjectively improved since wearing the belt

Figure 25: The above four diagrams present the degree of agreement of the 11 participants to the question whether their spatial orientation abilities have subjectively improved since wearing the belt. 1 stands for do not agree and 5 for strongly agree. 6 indicates that the participant did not give his opinion. In the top left-hand corner, the diagram shows participants that agreed strongly, in the top right-hand corner participants that agreed moderately strong, in the bottom left-hand corner participants that agreed a little to not at all to the question in the post-questionnaire and finally in the bottom right-hand corner P10 as a special case is depicted. Additionally, individual opinions of the participants in the course of the seven weeks can be seen.

All participants estimate their sense of orientation to be quite to very good before the study. Regarding the question whether their spatial orientation abilities improved since wearing the belt, the participants were of different opinions (**Figure 25**). Four subjects agreed strongly to this statement in the post-questionnaire. While the four participants agreed moderately to quite strongly in the first week, as from the third week their opinion remained constantly between quite strong and strongly, showing a slight positive trend over the first few weeks. Four participants agree moderately in the post-questionnaire with high fluctuations of impressions over the weeks in two cases. In two cases (P6, P3) do not see any improvement in their orientation abilities. P10 presents a special case: In the first four weeks he only sees a slight improvement in his orientation abilities which improve to moderate in the last three weeks. However, in the post-questionnaire he states that his orientation abilities did not profit from the belt at all. P6 and P10 further see no difference between their orientation abilities before and after wearing the belt. They have the impression that the belt did not have any effect on their orientation behaviour and strategies. Whilst most participants (independently of whether they

are congenitally or late blind) have the subjective impression that the belt helped their orientation abilities and had an effect on their orientation behaviour and strategies, a few (two to three subjects) do not see an improvement nor an effect. None of the participants sees a worsening of his/her orientation abilities due to wearing the belt.

When taking the belt off, those four participants that saw a strong improvement in their orientation abilities also, on average, moderately to quite agree that their orientation abilities worsened. P4 even strongly agrees that his orientation abilities worsened when taking the belt off in weeks four to six. The remaining seven participants moderately to do not agree at all that their orientation abilities worsened in week seven. The results indicate on average, a little to moderate dependency of the participants' orientation abilities on the belt over the weeks. Nine out of twelve participants do not support the statement that the belt had no influence on their orientation behaviour or abilities.

Mental representations

Figure 26: The participants' agreement from do not agree (1) to strongly agree (5) to the question whether they have an inner map of their surroundings in their heads before and after wearing the belt for seven weeks is depicted.

Examining the participants' mental representations, one can detect that all participants use a route representation when orientating. The sequential processing of landmarks was affirmed by the participants before the study as well as after the study. The belt has little to no influence on their already present route representation. Regarding the participants' survey representations, all participants moderately to strongly agreed to having an inner map before the study (**Figure 26**). Those three participants who only moderately agreed before the study agreed more to the statement after having worn the belt for seven weeks. Five participants (including P12) that quite or strongly agreed before the study did not change their opinions after the study. In three cases the participants agreed less to the statement after the study than before. An interesting development is that of P2 since he declared before the study that he had an inner map and after the study that he did not have one (**Figure 26**).

Building upon the participants' impressions of having an inner map, the question whether this inner map is aligned to cardinal directions poses itself. Six participants were well aware of cardinal directions while wearing the belt, but stated that the cardinal directions only helped a little to moderately much to orientate. In three cases the participants were very aware of cardinal directions, which also strongly helped them to orientate. P6 was the only participant who was aware of cardinal directions only a little

to moderately much over the weeks and who could not use the cardinal directions for orientation. Being well aware of the cardinal directions had at least a small impact on all participants when orientating except for one participant. However, from being more aware of the cardinal directions and using them for orientation it does not necessarily follow that inner maps are aligned accordingly. While some participants indicated that having information about cardinal directions through the belt helped only a little to orientate, they, at the same time, declared that their inner map was strongly aligned to cardinal directions whilst other participants answered in the opposite manner. The belt had therefore different effects on the participants' survey representations: Being aware of cardinal directions either helped to orientate or to align one's inner map or in 2 cases both (P5, P11).

Reference frames

Figure 27: The participants' agreement from do not agree (1) to strongly agree (5) to the question whether when wearing the belt, they are aware of where they are positioned relative to their home at any point in time over the course of the seven weeks is depicted.

Three questions give information about how the belt influences the participants' reference frames. The question whether the participant is aware of his / her position relative to his / her home at any point in time when wearing the belt examines the egocentric reference frame (**Figure 27**). Two clearly separated groups can be seen over the whole course of the seven weeks starting from the first week. Seven participants on average quite strongly to strongly agreed in the affirmative while three participants (P3, P6, P10) negated the effect of the belt (**Figure 27**). The egocentric reference frame in the case of seven participants was clearly enhanced by the belt while the belt had no effect in three cases.

It is easier for me with the belt than without to estimate the position of places to each other

Figure 28: The participants' agreement from do not agree (1) to strongly agree (5) to the question whether it is easier for them with the belt than without it to estimate the position of places to each other over the course of the seven weeks is depicted. In the diagram (A), eight participants quite to strongly agreed to the question in the first and last weeks. In the diagram (B), three participants with different opinions at the beginning and in the course of the study compared to the rest are depicted.

The effect of the belt on the allocentric reference frames of the participants was tested with the questions whether it was easier for the participant with the belt compared to without to estimate the position of different places or to estimate the position of different roads to each other. Slight differences in the answers to these questions can be seen.

In the first week of the study, all but three participants agreed quite strongly to strongly that the belt helped them to estimate the position of different places to each other (**Figure 28A**). One participant moderately (P5) and one participant slightly agreed (P10) and one participant did not agree (P3). These three participants agreed more strongly in the second week (**Figure 28B**). In the third and fourth weeks, two participants (P1 & P2) agreed less to the statement than in the first week (**Figure 28A**). As from the fifth week onwards, nine participants quite to strongly felt that the belt helped in their estimation of the position of places to each other, one participant moderately agreed and P10 did not agree (**Figure 28A+B**). P10 saw the belt as being moderately to quite helpful in weeks two to four but not at all in the last three weeks (**Figure 28B**). All in all, the majority of participants found it easier to estimate the position of places to each other with the belt than without over the whole study period of seven weeks.

It is easier for me with the belt than without to estimate the position of roads to each other

Figure 29: The participants' agreement from do not agree (1) to strongly agree (5) to the question whether it is easier for them with the belt than without it to estimate the position of roads to each other over the course of the seven weeks is depicted. 6 means that the participant did not give his opinion. All but one participant partially to strongly agreed during the whole course of the seven-week study to the question **(A+B)**.

Concerning the estimation of the position of roads to each other, all 11 participants except for P10 moderately to strongly agreed that it was easier with the belt than without. Their opinions, on average, stayed constant over the whole study period (**Figure 29A**). P10's opinion fluctuated over the weeks but in the last two weeks he also moderately agreed to the statement (**Figure 29B**). The allocentric reference frame of every participant except for P10 was clearly improved due to wearing the belt. Estimating the position of roads to each other was slightly easier than estimating the relation of places to each other for the participants.

Exploration of new surroundings

In order to test how much help the belt is in unfamiliar situations and surroundings, the participants were asked in the pre-questionnaire how often they explored unknown environments prior to the study, during the study whether it was easier for them to orientate with the belt compared to without the belt in new surroundings and after the seven weeks whether the belt helped especially in known or unknown environments.

Four participants quite to strongly agreed that they often explore new environments, five participants moderately agreed and two participants agreed a little in the pre-questionnaire. During the seven weeks, the two participants that seldom explored new environments prior to the study on average quite agreed that it was easier for them to find their way in an unknown environment with the belt than without it. In the post-questionnaire they moderately to quite agreed that the belt helped especially in unknown environments and a little less in known environments. The belt helped them from the first week onwards in unfamiliar environments. Three out of five participants that moderately often explored new surroundings prior to the study, quite to strongly agreed that they found it easier to find one's way in unknown surroundings with the belt than without it from the first to the sixth week and strongly agreed in the seventh. P1's impression fluctuated in the first four weeks between finding it a little to moderately easier with the belt. From the fifth to the seventh week he moderately to quite agreed to the statement. These four participants quite to strongly supported the statement of mainly profiting from the belt in unknown environments. Two of them additionally also greatly

profited in known environments, according to their own impressions. P10 did not find it easier to find his way with the belt in unknown environments in the whole course of the study and neither profited from the belt in unknown nor in known surroundings. The remaining four participants who often explored new environments prior to the study show different results compared to the above-mentioned subjects and differing results among each other. P4 strongly agreed that it was easier for him to find his way in unknown surroundings thanks to the belt and that the information of the belt helped just as much in unknown as in known environments. P2 and P3 had similar opinions as from the second week. In the first week, P3 did not find it easier to orientate with the belt in unknown environments, but, as from week two to week four, he found it quite a bit easier with the belt and in the last three weeks, moderately easier. P2 found it quite a bit easier on average. In contrast to the other participants, P2 and P3 found the belt especially useful in known environments and only a little to moderately helpful in unknown environments. P6's impression alternated between not finding it easier with the belt at all to finding it a little easier to find his way in unknown environments. His conclusion that the belt helped him especially in unknown environments and not at all in known environments stands somewhat in contrast to his evaluations of the belt over the weeks. The four participants that started out in the study with more experience at exploring unknown environments showed very different feelings regarding the helpfulness of the belt in unfamiliar surroundings and differed in the environments in which they found the belt to be most helpful (known or unknown). Averaging over all participants in the seven-week study, the belt helped most in unknown environments. Especially those participants that did not often explore unfamiliar terrain before this study found the belt's information helpful in unknown surroundings. Experienced explorers tended to find the belt particularly helpful in known environments.

Wearing time of the belt

Figure 30: The amount of the 11 participants' belt wearing time during the seven weeks in known and unknown environments is shown.

On average, all the participants wore the belt more in known than in unknown environments. One reason for the comparably little time spent in unknown environments is the outbreak of the Corona virus during the time of this study. The time spent outside in general was reduced due to the virus. P5

wore the belt the whole day and, by far, wore the belt the most. However, the absolute wearing time in known and unknown environments does not coincide with finding the belt most helpful in those respective surroundings. How helpful the belt is felt to be depends most likely on multiple interacting factors such as prior experience at exploring unknown surroundings, orientation abilities, sense of orientation, hours of mobility training etc. Moreover, it depends on how intense the training with the belt during the wearing time is and not merely on the absolute wearing time of the belt.

Noticing a long bend in a road

Figure 31: In the pre-questionnaire the 12 participants were asked whether they sometimes found it difficult to notice when a road made a long bend. During the seven weeks of wearing the belt 11 subjects (P12 not included) were asked whether it was easier for them to notice when they were walking around a long bend with the belt compared to without the belt. This same question in the weekly questionnaires was also posed in the post-questionnaire and was answered by 12 participants. The participants' agreement ranges from do not agree (1) to strongly agree (5) and 6 stands for no opinion.

Before the study, eight out of twelve participants agreed that they sometimes found it difficult to notice if a road makes a long bend. The remaining four participants estimated that they had moderate to no difficulty at all in that respect (**Figure 31**). During the weeks and averaging over all participants, the result was that the participants strongly agreed to finding it easier with the belt compared to without it to notice when one was walking around a bend. In the fourth week, P2 displays a varying opinion from the others by not noticing a bend more easily with the belt in that week. In the post-questionnaire all the participants concluded that the belt made it easier to notice that one was walking around a bend (**Figure 31**). It is worth mentioning, that P2 and P8 stated before the study that they had no to little difficulty at noticing bends in a road. However, just like the other participants, they found the belt very helpful in noticing bends over the weeks and this was also their conclusion at the end of the study. This hints at them recognizing that they really did not notice prior to the study if they had walked around a long bend. The participants all agree that the belt is helpful to notice when one is walking around bends and therefore is useful for keeping track of directions in which they are heading.

3.2.2 The participants' experience during the training period

The open-ended questions in the weekly questionnaires and the post-questionnaire are structured as such that the citations are assigned to categories and sub-categories. Only the citations concerning orientation and navigation, space perception and the perception of the belt will be presented in the following.

Focussing first on the belt perception and especially on the quality of the perception of the belt's signal, all the participants had a tactile sensation. An additional acoustic quality due to the vibrating motors of the belt was perceived in particularly quiet surroundings such as during walks in the woods (P6). P4 directly transferred the information of the belt into spatial information. *"One directly transfers the signal into direction"* („Man wandelt das Signal gleich in eine Richtung um“), P4 stated in the first week. Secondly, some participants mentioned situations in which the belt's information helped them in understanding spatial relations in their surroundings and therefore had an effect on space perception. These spatial relations were either experienced egocentrically (that is, the participant's position relative to an object) or allocentrically (that is, the relation of objects to each other) or the participant aligned to cardinal directions. The participants mostly used the belt's signal for an egocentric estimation: P7, for example, to estimate his position on a playground in front of his house relative to the door of the house or relative to the roads. The belt facilitated orientation from an egocentric perspective because *"[...] I was at every point in time aware of the either planned or actual direction in which I was moving"* („[...] ich mir zu jederzeit über geplante und tatsächliche Bewegungsrichtung bewusst war“) according to P7. P3 found the belt's signal helpful when gardening: *"one turns around a lot and then one walks in one direction and ends up somewhere else than expected. With the belt this does not happen."* („umdrehen beim gartenarbeiten, man geht in eine richtung und landet woanders als man denkt. Mit gürtel passiert das nicht. [sic!]“) P1 finds the belt's signal helpful to position himself relative to a road he wants to cross. In the fifth week he learned a new way to walk to work via a large triangular complicated crossroad and through the woods; both situations in which he would not act by himself without the belt, he admitted. *"I used a complicated triangular crossroad several times and learnt with the help of the direction signal, to safely cross"* (P1) („Ich habe mehrfach ein unübersichtliche dreieckige Kreuzung genutzt und gelernt, mich anhand des Richtungssignals sicher über die Stelle zu bringen. [sic!]“). According to his statements on walking in the woods, one can deduce that he used his egocentric reference frame but also his allocentric reference frame to keep track of new paths relative to the exit out of the woods. For P6, the belt caused him to set roads and places more into relation to each other. As a specific situation he mentioned the belt being helpful to put the relation of paths in the wood into relation to each other and also to compare the orientation of salient points according to cardinal directions to each other. It is certainly clear that his allocentric reference frame was enhanced and he made use of the belt's information of cardinal directions to understand his spatial surroundings better. P7 described a situation in the first week of the study in which the belt helped him to find his way from the baker's within a discount store to the entrance / exit: *"On entering I knew that the entrance was situated to the west. Therefore, I could start off on my way back well and with the knowledge that I was walking in the right direction."* („Beim eintritt wusste ich, dass der Eingang richtung westen gerichtet war, Dadurch konnte ich meinen rückweg von Beginn an gut und mit dem wissen in die richtige Richtung zu laufen antreten. [sic!]“) He memorized the alignment of the entrance with respect to cardinal directions – information the belt gave him – and aligned accordingly on his way out of the shop. All these are examples of situations which definitely indicate that the belt gave the participants the possibility of accessing spatial information about their environment and their position in it.

Three participants made comments on how the belt positively affected their inner map / survey representation. P7 stated: *"The knowledge of always being able to get a fast and reliable feedback on my orientation conveys to me a feeling of safety and synchronises my inner map with reality."* („Das

Wissen, dass ich jederzeit ein schnelles und zuverlässiges Feedback über meine Ausrichtung bekommen kann, vermittelt mir Sicherheit und synchronisiert quasi meine innere Karte mit der Realität. [sic!]) He further said that his inner map was completed by the belt. P3 commented that his *“perception of the network of roads had improved and clarified, also in an environment that has been familiar to [him] for years.”* („Meine Vorstellungen des Straßennetzes haben sich auch in meinem seit Jahren vertrauten Umfeld verbessert und geklärt“) *“The registering of bends and turns etc. helped to better comprehend and thus to internalize a path one walked along”* („Das Registrieren von Kurven, Abzweigungen usw. hat dazu beigetragen, einen gelaufenen Weg besser nachvollziehen und damit verbunden verinnerlichen zu können. [sic!])“, P2 said when asked for situations in which the belt was of help. In all three cases, the belt’s signal enlarged the mental survey representation of the participant concerning his environment by giving permanent feedback and information about cardinal directions. Many participants made comments on the impact of the belt on their orientation and navigation process, for example, when keeping to a straight line and noticing bends etc. P7 found it interesting that the railroad track made almost a 180° turn at one point. He had only a very vague idea of the layout of the train lines before the study, he stated in the sixth week of the study. P1 found the belt’s signal very helpful to keep his direction traversing complicated crossings. P4 also stated in the third week that *“in all critical situations in traffic such as road and rail crossings as well as crossing squares the belt helped me very much.”* („In allen Verkehrskritischen Situationen wie Fahrbahn- und Gleisübergängen sowie Platzquerungen hat mir der Gürtel sehr geholfen.“) *“With no sensation of light, the belt is indispensable to monitor whether one is keeping to the right direction. When walking with the cane, the belt gives one, to a very large extent, an additional feeling of safety in known and unknown environments – especially in traffic”* („Bei keiner Lichtwahrnehmung ist der Gürtel zur Überwachung der Richtungsbeibehaltung unerlässlich. Er gibt beim Gehen mit dem Langstock ein hohes Maß an zusätzlicher Sicherheit in bekannter und unbekannter Umgebung, insbesondere im Straßenverkehr.“), P4 further concludes at the end of the study. P10 also agreed that the belt helped at pedestrian crossings but only when the pavement was parallel to the road one wanted to cross. P11 reported in the second week that the belt helped to orientate when he knowingly added an excursion to his path. Additionally, the belt helped him to cross roads and to perceive bends in paths in the woods and fields. P3 also stated that involuntary changes in direction were noticed quickly and he could correct them more accurately. Furthermore, P3 found the belt helpful to orientate in loud surroundings when he could not rely on the auditory input (for example, due to strong winds, a road sweeper, rubbish collection, construction noise). While the belt helped keeping track of the direction in which one was heading (P6, P3, P1, P2 & P11), P3 and P10 point out that one should not rely absolutely on the belt’s signal. At crossroads with pavements not aligned to the road or pedestrian crossing at an angle from the starting position, there is the danger of walking right into the middle of the crossroads if one relies on the belt’s signal and does not know the crossroads, P10 pointed out. P3 stated that he would not rely on the belt when walking along a train platform without guiding lines: *“Both the signal of the belt and its perception is not exact enough to keep a constant distance to the edge of the platform. A deviation of 10 degrees off the straight line is not noticeable with the belt; on a train platform that could, however, be deadly.”* („Sowohl das Signal des Gürtels als auch dessen Wahrnehmung ist nicht exakt genug, um einen gleichbleibenden Abstand zur Bahnsteigkante einzuhalten. Eine Abweichung von der Geraden um nur 10 Grad bekommt man über den Gürtel nicht mit; am Bahnsteig könnte sie aber tödlich sein.“) In the process of orientating and navigating in urban situations as well as in the countryside, the belt helps to keep track of the direction in which one is heading. One should, however, also bear in mind that the belt is only an aid on which one should not totally rely in every situation.

In addition to an improvement in the orientation and navigation process, one can go one step further and examine the effect of the belt on the orientation and navigation abilities of the participants. P5

saw a general improvement in orientating spatially from the first week onwards. P12 came to the same conclusion at the end of the study. Not only did the belt help them notice bends in the road, it also helped them to maintain the direction in which one was heading according to P10 and P3. P11 further found the belt helpful for “*general orientation*” with which P11 probably refers to estimating directions as the crow flies. P8 found two aspects that influenced her orientation strategies. Firstly, she could concentrate better on other things when orientating (counting the number of crossroads and crossings, finding a specific point) and secondly, she could use different paths which she had avoided previously because there were no landmarks to orientate with. P1 found that he now has the ability to orientate through the woods by himself with the help of cardinal directions which he would not have done without the belt. P2 commented that he included cardinal directions much more strongly when planning and realizing familiar or new paths by wearing the belt. He further found the belt a sensible alternative to his smartphone with the advantage that both ears stay free. Even though his smartphone is still an important tool for orientation, the directions given via headphones are a distraction in situations with traffic. P11 also positively commented on her ears and hands remaining free when wearing the belt. Being able to reorientate after having lost one’s sense of orientation and a broader comprehension of one’s surrounding are also newly found abilities due to the belt. Four participants described situations in which they had lost their sense of orientation either in a room or outdoors and could reorientate with the help of the belt. P3 even stated that he noticed that he had taken a turn onto a road instead of onto an agricultural path due to the belt and could then find his way back to the pavement to start again. Except for P6, who did not find the belt helpful in general, all participants pronounced an enhancement in their orientation behaviour, abilities and / or strategies due to the belt in the course of the study.

3.3 Results of the deaf-blind participants

The two deaf-blind participants (DBPs) did not partake in the experimental part of study but filled in weekly questionnaires. Since communication between us experimenters and the participants was difficult and pre- and weekly questionnaires were communicated via e-mail, the data that we received strongly depended on them answering. Therefore, we could only analyse the pre-questionnaires and the first three to four weeks of the weekly questionnaires. Simplified questionnaires concerning the language were designed to make them more comprehensible. The content, however, is mostly congruent to the questionnaires of the blind participants. The results will be briefly presented in the following.

Both participants subjectively evaluated their sense of orientation to be good prior to wearing the belt. From the first week of wearing the belt and onwards, both agreed that the belt enhanced their orientation abilities. Both were also very much aware of cardinal directions since wearing the belt. The belt’s positive effect on their egocentric reference frame could also be recognised: Both strongly agreed that they were always aware of where they were relative to their home when wearing the belt. Only one deaf-blind participant also found it easier to estimate the position of places and roads to each other since wearing the belt and therefore showed an increased use of his allocentric reference frame due to the belt. The other participant only agreed a little to moderately. While the participants only agreed a little to moderately that they had difficulties in noticing when they are walking around a bend prior to wearing the belt, they strongly agreed that it was easier for them to note a bend when wearing the belt. The answers of the deaf-blind participants were therefore very similar to those of the blind participants.

It was, however, in the open-ended questions that the participants’ enthusiasm for the belt and its extreme helpfulness from the very first week became evident. One deaf-blind participant (DBP1) wrote: “The naviBelt is really a great thing ... a few years ago it was unthinkable like science fiction ...

now reality ... great aid for the deaf-blind!!! Incredibly very important orientation and mobility device for deaf-blind people – indispensable” („Der Navig?rtel is wirklich eine tolle Sache ... noch vor ein paar Jahren ist das unvorstellbar wie Icience fiction ... Jetzt Realit?t ... Tolle Unterst?tzung f?r die Taubblinden!!! Unheimlich sehr wichtiges Orientierungs- und Mobilit?t-System f?r Tbl – unverzichtbar! [sic!]“). The other participant (DBF2), who was a technical designer before turning deaf-blind, strongly used the belt’s information on cardinal directions to orientate. By using cardinal directions, he reorientated when walking in a wrong direction. He also memorized routes by noting in which cardinal direction the road stretched and also in which cardinal direction he had to stand / walk relative to the cardinal directions. Both participants wrote the above comments in the first week and additionally both expressed how the belt helped to keep to the direction in which they were heading. The following citation gives a detailed insight in how DBP2 used the belt’s information and orientated and navigated with it - he mostly maked use of the road-crossing mode: “In front of the shopping centre “Rheincenter” I pressed the compass button twice. In a huge building the shopping parade is very long. This shopping parade is like a cloister. I can orientate much better than without wearing the naviBelt. For example, in the shop DM I can know immediately where the exit is. When the pulsating signal is on the left side of the belt, I am in the northern or southern shopping parade. I walk through the shopping parade clockwise: eastern, southern, western and northern shopping parade. In the past I found myself in a big labyrinth.” („Vor dem Eingang zum Einkaufszentrum „Rheincenter“ habe ich zweimal die Kompassstaste gedrückt. In einem riesigen Gebäude ist die Ladenstraße sehr lang. Diese Ladenstraße befindet sich wie im Kreuzgang. Ich kann mich viel besser darin orientieren, als ohne den naviGürtel zu tragen. Z.B. im Geschäft DM kann ich sofort wissen, wo der Ausgang. Wenn das pulsierende Siganl an der linken Seite am Gürtel ist, befinde ich mich in der nördlichen oder südlichen Ladenstraße. Ilch gehe durch die Ladenstraße im Uhrzeigersinn: Östliche, südliche, westliche und nördliche L>adenstraße. Fröherr bin ich in ein großes Labyrinth geraten. [sic!] “) The participant also used the compass signal together with the feelSpace application for the smartphone to orientate and navigate to a specific grave in a cemetery.

To sum up, it can be said that the deaf-blind participants strongly profited from the information provided by the belt and found the device extremely helpful. Especially being able to keep track of in which direction they were heading via the information on cardinal directions was appreciated.

4 Discussion

4.1 Influence of the belt on spatial orientation and navigation

In this study, the impact of the directional information of the feelSpace belt on the orientation and navigation abilities of blind people was investigated. Furthermore, the intuitive use as well as the long-term effect of the belt were examined with behavioural data from the days of the experiments and with the quantitative and qualitative data of questionnaires in everyday situations over seven weeks. From this, preferred reference frames and mental representations of the participants could be deduced. The straight-line walking task on the experiment days, mimicking the crossing of a large street or a square, and the angular rotation task, testing the precision of turns and the comprehension of the belt's signal, in general revealed an enhanced precision in reaching a goal and making turns and an intuitive use of the belt. The triangle completion task examined the participants' navigation abilities in path integration and made implications on a participant's mental representation of his / her environment possible. The belt's information was not intuitively useful, but with training over the weeks, the participants' performance in that task improved. The behavioural data of the triangle completion task, however, does not clearly show whether this improvement is due to training with the belt over the weeks between the experiment days or because the setup is known to the participants or a combination of both, since the subjects improved with as well as without the belt. Subjectively, the majority of the participants see an enhancement in their orientation and navigation abilities due to the belt and therefore feel that the belt's information is helpful to master difficult orientation and navigation problems in everyday life.

The hypothesis that the belt's information is in general helpful to keep to a direction in which one is heading could be verified by the behavioural data from the straight-line walking task and is further strengthened by the subjective impressions of the participants. Maintaining the direction in which one is heading was improved from the first day onwards by the participants and can be explained by the belt giving them permanent feedback about directions. On the first experiment day, the belts' signal in compass mode helped the participants to reach the finishing line and the goal point with high precision, revealing that the belt's signal could be intuitively processed. However, the road-crossing mode was not as intuitively usable as the compass mode and showed similar results as when the participants had the belt switched off. On the second day their performance in compass mode was less pronounced while their performance in road-crossing mode improved. To make use of the road-crossing mode some training seems to be needed. One reason why training is required is that it is vital in the road-crossing mode to be exactly aligned in the direction of the goal before switching the road-crossing mode on. If this is not the case, the participant will deviate very quickly away from the optimal straight line to the goal, all the while following the "straight" signal of the belt. Although the participants were well aligned towards the goal by us experimenters in this study, the absolute importance of not making slight tuning movements after having activated the road-crossing mode had to be made clear to the participants especially on the first experiment day. The called "go"-signal from the other end of the field, could only partially indicate the direction in which to head for the participant. Training with the belt during the weeks between the two experiment days therefore seems to have increased the precision of walking in a straight line with the road-crossing mode on the second day. The worsening in performance towards the second day when the belt is in compass mode can have several reasons: In the case of P4 it can be explained by the lack of motivation to give his best on the second day. Additionally, there exists a natural fluctuation in performance from day to day due to the amount of concentration, motivation, fatigue etc. with which the subjects participate. P2, for example, arrived on the second experiment day by himself by navigating with the help of the feelSpace belt. The walking exercise of reaching the University campus might have had an influence on his directly performing the straight-line walking task with the belt in compass mode. Such natural factors have to be taken into consideration here. They are, however, factors on which we as experimenters have no

influence. Concerning the subjective impressions of the participants, all agreed that the belt was helpful to notice when one was walking around bends and therefore acknowledged the usefulness of the belt to keep track of the direction in which they were heading. One can deduce that since they were more aware of walking around bends they were also aware when walking in a straight line. In open-ended questions the majority of the participants described situations in which the belt helped them to maintain or to keep track of the direction in which they were heading such as when crossing a road or a square. Therefore, the subjective impression strongly supports the experimental results of the belt's signal being helpful to keep to the direction in which one is heading.

An improvement in turning precision could be seen in the angular rotation task when the participants wore the belt on the first experiment day and especially without the belt on the second day. The results showed that all four late-blind participants were able to interpret the belt's signal intuitively from the first experiment day onwards. All four late blind participants were aware, that on performing a whole turn, the vibration must be in the same position before and after the turn. This indicates that they understood the concept of the belt. P2, in contrast, did not comprehend the concept, which was seen in his high absolute turning errors when he was supposed to perform 360° turns. Only considering the late blind participants, one could detect differences between the angular rotations (90°, 180° and 360°): 90° and 360° angular turns were performed more precisely than 180° turns irrespective of the belt condition and the experiment day. The results further revealed a significant difference between the quarter turns with the belt and without the belt on the second day, with the median indicating more accurate turns without the belt. 90° turns are frequently used angular turns in everyday life. Streets are often located perpendicular to each other and in buildings the corridors are usually also perpendicular to each other. Therefore, participants have formed strategies such as positioning their feet in a perpendicular fashion before the turn as such. The belt's information is therefore not of particular help because the participants are well adapted to such turns. Half turns were less precise than the other two turns, probably due to the vibration not being at one of the anchor points of the abdomen. Remembering the position of the vibration motor before the turning is performed is then more difficult.

The differences between the late blind participants and the congenitally blind participant in this study in understanding the belt's concept suggests that late blind participants have the advantage of having understood the concept of turnings in the years of sightedness and could therefore interpret the position of the vibrating motor on their bodily surface relative to their actual standing direction more precisely than the congenitally blind participant. This hypothesis has to be verified in future studies and with more congenitally blind subjects.

Especially without the belt, the late blind participants were more precise at estimating turning degrees on the second experiment day than on the first experiment day. All late blind participants improved drastically (in three cases highly significantly: P1, P3 and P4) in the estimation of their turns without the belt from the first to the second experiment day. Two participants additionally significantly improved in the with belt condition (P1 and P3). The two remaining participants that did not improve from the first to the second day with the belt had either a lack of motivation (P4) or a lack of concentration (P5) as conversations with them revealed. The halved MADs in both belt conditions from the first to the second experiment day, indicating more certainty at performing the angular turns, point towards a training effect. The increased precise estimations without the belt may partially be due to the participants knowing the experimental task on the second day. It is, however, unlikely that the significant difference between the first and the second experiment day in the without-belt condition can merely be explained by the participants knowing the set-up since there was a considerable time span of four weeks between the two experiment days. Training with the belt over the weeks between the experiment days and thereby learning to interpret and use the belt's information of direction is likely to be also a factor leading to the more precise turns with the belt. Since participants stated in

the weekly questionnaires that the belt's signal helped them to synchronise their mental map with the environment, it is well possible that wearing the belt and training with it also led to a correction of the participants' estimation of angular turns. The results of analysing the absolute turning errors with respect to mistakes in terms of vibromotors are in line with the above argumentation that the belt serves to correct turning estimations and further support it: a higher percentage of turns performed without the belt were in the range of the appropriate vibromotor (less or equal to 22.5° absolute turning error) than turns with the belt on the second day. Being already quite precise in their angular turns on the first experiment day without the belt, the late blind participants seem to have been able to use the belt's information over the weeks to correct their, prior to the study, slightly erroneous turning estimations so as to perform even more precisely without the belt than with the belt on the second day. An explanation for the without-belt condition surpassing the with-belt condition in the amount of more precise turns on the second experiment day could be that the participants rely solely on the information the belt gives them. They do not need to rely on their own bodily estimations when wearing the belt but can work out which vibromotor has to be active depending on how large the turning degree is. This gives them some leeway of 22.5° for turning leading to less precise turns than when they have to take bodily parameters into account for their turns. Angular turns become a memory task with the belt since the position of the active vibromotor prior to the turn has to be memorised to calculate which vibromotor is supposed to be active on performing a specific angular turn. On maybe memorizing the wrong vibromotor or forgetting which vibromotor was active prior to the turn, larger turning errors can occur. This effect was, however, seen less often on the second day than on the first day. All in all, training with the belt over a longer period of time seems to be very effective for blind people with prior knowledge of angular turns to correct erroneous ideas of their turnings. A prerequisite is that the blind person understands the movement of the belt's signal relative to his / her bodily turns. A future study may determine whether this correction in turning estimations has a long-lasting effect on the participants even after a longer period of not wearing the belt.

The behavioural results of the angular rotation task show a positive effect of the belt on the participants' turning precision and egocentric direction estimation. The quantitative and qualitative data of the questionnaires further reveal that all the participants in the experiments as well as the majority of the participants in the long-term study subjectively see a strong improvement in their orientation abilities. Since most participants of the long-term study found their estimation of their own position relative to their home easier with the belt from the very first week onwards, one can deduce an immediately felt improvement of the egocentric reference frame of the participants and therefore that the belt gives very intuitive and comprehensive information.

While the belt's information was intuitively of help with respect to the straight-line walking task and the angular rotation task, it is less intuitively useful for path integration and navigation tasks as the results of the triangle completion task have revealed. Only one participant (P3) could intuitively make use of the belt's signal to estimate the starting point more precisely. On the second experiment day, however, he was more precise without the belt than with the belt on the first day. Two further participants showed increased accuracy, particularly in the without-belt conditions on the second day compared to the first day. The improvement in the without-belt conditions from the first to the second day could be partially due to the participants already being familiar with the experimental set-up on the second day. It is also possible that training with the belt in the course of the weeks between the two experiment days and therefore the constant feedback of direction improved the direction estimation of the participants even without wearing the belt. Similar accuracy at activating the appropriate vibromotor on turning back to the starting point was achieved in all four conditions on either experiment day when taking all five participants into account. However, the strongest increase in precision from the first to the second day was found in the condition without the belt with distraction leading to the assumption that mainly training with the belt over the weeks could lead to

this differing effect to the other three conditions. These results together with those of the angular rotation task point towards the belt being a helpful training device to correct erroneous turning estimations when navigating without the belt.

Examining the with-belt conditions, one can observe that P3 estimated the starting point less accurately with the belt on the second experiment day than on the first day. His own explanation was that the belt helped him on the sides of the triangle to keep track of the inner angle but not to orientate back. One further participant (P1) improved greatly in precision from the first to the second day when wearing the belt and the other three participants only slightly improved. P1, however, admitted on the second experiment day that he was aware of the triangles being the same as on the first experiment day. Knowledge of the set-up therefore could partially have led to the improvement in precision. Training with the belt during the weeks between the experiment days may additionally have had an effect.

In general, the navigation task was considered to be difficult by all participants and the belt's signal could only be of moderate help during the task. A possible reason for the difficulties on especially the first experiment day is that the triangle completion task can be seen as a memory task. Participants have to keep track of their locomotion to estimate the length of the sides of the triangle and the inner turning angle. The belt's signal enables the participant to notice the angular turn between the two sides of the triangle by memorizing the position of the vibrating motor before and after the turn. However, no information about the length of the sides of the triangle is given. Estimating the starting point therefore requires the participant to keep track of the length of one side of the triangle during the walk, memorize the position of the vibrating signal before the angular turn and after the angular turn and from this information estimate the turning in degrees, keep track of the length of the second side of the triangle during the walk and finally, at the end point, integrate the information of locomotion and the belt's information of the inner angle to calculate / estimate the angular turn back to the starting point. This explanation is supported by the participants being more precise on the first experiment day without distraction than with distraction when wearing the belt. With concentration, such a memory task is possible, while it is more difficult for the participants when their attention is taken away from the navigation task. However, the additional source of information via the belt without distraction about the inner angle led to comparable starting point estimations as the without-belt-without-distraction condition according to the median and MAD values. The belt therefore did not improve the accuracy on the first day.

Significant improvements in precision from the first to the second experiment day could be observed in the conditions with a distraction task. Accuracy in the conditions without distraction remained stable from the first to the second experiment day. It seems that from the first to the second week less attention was needed to be paid to the triangle completion task independent of wearing the belt or not. This indicates that the belt's information could be subconsciously integrated in the weeks between the two experiment days. This result is in line with the results in the study by Kärcher et al. (2012).

The participants' uncertainty during the triangle completion task and their comments on the difficulty during the task point towards an egocentric reference frame and a route-based mental representation when performing the task, primarily employed in the manner as described two paragraphs above. The quantitative and qualitative data of the pre- and post-questionnaires support the implication that a route-based mental representation is employed by the blind participants. Before participating in the study and after having worn the belt this mental representation was employed for navigation, according to the answers of the participants. More participants additionally stated that they have a mental map of their surrounding after the study than before the study which indicates an increased use of a survey representation. Most participants of the long-term study also found the estimations of places and roads relative to each other easier when wearing the belt from the first week onwards. One can deduce a direct improvement of their allocentric reference frames as from the very first week.

When the P1-P5 performed the triangle completion task however, one could not deduce that an allocentric survey representation was employed. Neither the results of the triangle completion task, nor conversations with the participants gave indications in that direction. It is possible that an allocentric survey representation is used in a more natural surrounding than in the present simplified experimental set-up.

Differences in the results between the three triangles (inner angle 90°, 150° and 30°) could be detected irrespective of the belt and distraction conditions and irrespective of the experiment days. More precise estimation could be performed in the trials of the 90° and 150° triangles compared to that of the 30° triangle, which is due to their special properties of being rectangular (90°) and isosceles (150°). These results are in line with those of Wiener et al. (2011) with sighted participants. Wiener et al. (2011) could, however, not detect more precise estimations of the starting points when the inner angle was on the right-hand side of the participant as the results of the triangle completion task in this current study show. Since all five participants are right-handed, one can assume that the dominant right-hand side also leads to a more precise estimation. It is also possible that the handedness of blind people plays a special role compared to sighted people, which would explain the varying results from Wiener et al. (2011). The importance of handedness for triangle completion tasks and especially for blind people has to be studied in more detail.

Since the participants stated that the belt helped most in unknown environments, one can deduce that the additional information of the belt is helpful for the participants in unfamiliar situations. How helpful the belt is depends most likely on multiple interacting factors such as prior experience at exploring unknown surroundings, orientation abilities, sense of orientation, hours of mobility training etc. and on how intense the training with the belt during the wearing time is and not merely on the absolute wearing time of the belt. The results of Kaspar et al. (2014) with sighted belt-wearing participants also indicate that the intensity of the participants interacting with the environment and the bodily interaction are of more importance than the mere wearing time.

4.2 Comparison of the findings of this study with other studies

4.2.1 Findings concerning the feelSpace belt

Comparison with results of studies with blind participants

The results of this study are mostly congruent with those of previous studies with the feelSpace belt. As in Schumann's pilot case study with one congenitally blind subject (2012), the blind participants in this study also showed a preference for an egocentric route-based navigation strategy over an allocentric survey representation when navigating. Schumann (2012) also saw the potential of the belt to enhance the usage of the allocentric reference frame. This was proved with the results of the weekly subjective Likert scale ratings of the blind participants in this study: The participants found it easier to estimate the position of places and roads to each other when wearing the belt. In familiar surroundings, the congenitally blind participant in Schumann's study (2012) discovered new spatial relationships due to the belt's information. Especially one participant (P7) in this study also described a situation in which the belt's signal gave information about spatial relations in his surroundings and therefore helped him to orientate and navigate (finding the exit of a discounter and noticing the position of the playground in front of her house relative to the door and the road). The late blind participant in the case study by Kärcher et al. (2012) found the belt most helpful to verify and adapt his mental representation of known environments. However, the participants in the present study reveal a slightly different picture: Most participants found the belt's information most helpful in unfamiliar environments – especially those participants that do not explore new surroundings very

often. Those participants which often explore unfamiliar surroundings found the belt's information particularly helpful in familiar surroundings. It seems that the less experienced people in orientating and navigating in unknown environments find the additional information helpful in environments they do not know and those participants that have developed strategies in exploring unfamiliar environments already before wearing the belt find it helpful to enhance their spatial understanding, orientation and navigation abilities in the environments they already know. The late blind participant in the study of Kärcher et al. (2012) felt inspired by the belt to extend the radius of his tandem tours. Many participants in this study also described situations in which they tried new things with the belt – one participant even learned a new way to work via a large triangular crossroad and a path through the woods which he would not have taken without the belt, as the participant (P1) himself declared. The belt's information therefore animates and enables the participants to explore unfamiliar ground. Like the participant in the study by Kärcher et al. (2012), one participant (P7) in the present study also mentioned that his inner map was adapted due to the information provided by the belt. The belt therefore serves to correct prior inaccurate spatial estimations. While Kärcher et al. (2012) used complex polygons for their homing task, we used the simpler shape of a triangle in varying proportions. In this study we also used less shapes. This way, the beneficial effect of the belt on the without-belt condition becomes more evident than in the case study by Kärcher et al. (2012).

Similarities and differences between blind and sighted participants wearing the feelSpace belt

The effect of the belt on blind and sighted people mostly reveals similarities but also some differences. In general, the blind participants in this study had the subjective feeling that the belt enhanced their orientation abilities and had a positive effect on their orientation behaviour and strategies and did not worsen their orientation abilities. The sighted belt-wearing participants in the study by Nagel et al. (2005) and Kaspar et al. (2014) also showed improved orientation and navigation abilities compared to a control group due to the belt. The sighted participants were also more aware of spatial relationships during navigation (Nagel et al., 2005). This effect which points towards an enhancement of the allocentric reference frame was also pronounced in the blind participants of this study. In contrast to the studies of Nagel et al. (2005), Kaspar et al. (2014) and König et al. (2016), the current study with blind participants did not show a change in the participants' belt perception in the course of the long-term study. Only one participant stated that he directly translated the belt's signal into information about direction in this present study, which was also the case in the sighted belt-wearing participants in the study by Kaspar et al. (2014). While the sighted participants profited from the belt's information in unfamiliar environments in the course of the study (Kaspar et al., 2014), most blind participants profited from the belt's information from the first week onwards. Summing up, it can be said that blind as well as sighted people experienced an improvement in their orientation and navigation abilities and comprehended spatial relations in their environment better when wearing the feelSpace belt.

4.2.2 Blind people's mental representations and reference frames

The findings of this study are in line with previous findings concerning blind people's use of and preference for an egocentric reference frame and a route-based mental representation. Fletcher (1980) and Cuturi (2016) showed in their studies that blind people mostly use route representations when navigating. Furthermore, Halko et al. (2014) showed in their fMRI study that the brain areas associated with egocentric navigation were particularly active during navigation tasks. The results of this present study also revealed a preference of the blind participants for a route-based mental representation (pre- and post-questionnaires and behavioural data of the triangle completion task)

and egocentric orientation strategies (behavioural data of the angular rotation task and the weekly questionnaires) irrespective of the participants wearing the belt and/or being distracted or not. Matching and strengthening the results of the behaviour data in this study, Ekstrom et al. (2014) describe orientation and locomotion as relying on the egocentric reference frame. The feelSpace belt enhanced the precision of egocentric orientation and therefore enabled the participants to keep track of turning directions. Since navigation relies on orientation abilities and orientation strongly relies on the egocentric reference frame, navigation also primarily relies on the egocentric reference frame, according to the argumentation of Ekstrom et al. (2014). During the triangle completion navigation task, the participants also seemed to heavily rely on their egocentric reference frame. However, in everyday situations when the subjects navigated during the long-term study, all but one participant also showed a strong improvement in their allocentric reference frame through wearing the belt. Relations of places and roads to each other were easier to estimate, according to the participants. One reason, but not the exclusive reason for blind people's preference for egocentric route-based navigation strategies, could be that in orientation and mobility training – which most blind people in general and all subjects of this study receive(d) – participants learn mostly route-based strategies. Together with the findings of the other studies one can conclude that blind people mainly rely on their egocentric reference frame when orientating and on their route-based mental representation when navigating. The feelSpace belt does not change this preference, but due to the belt's signal the allocentric reference frame is also used during navigation outdoors.

4.3 Relevance for present research and future prospects

In contrast to previous studies on the feelSpace belt, this study is not a case study with one blind participant or a study with sighted or blind-folded sighted participants but examines the effect of the belt on a group of 11 blind people – congenitally blind and late blind. This study is furthermore the first study in which the effect of the belt on two deaf-blind participants is investigated. In future studies it would be helpful to have even more blind participants so that differences between congenitally and late-blind participants can be investigated in more detail. In addition to the effect of the feelSpace belt on the blind participants' orientation and navigation abilities in everyday situations outdoors, the experimental tasks as well as the questionnaires made it possible to deduce which reference frame and which mental representation is primarily employed without the belt (egocentric route-based strategies) and the belt's effect on them (enhanced use of the allocentric reference frame with the egocentric reference frame still being used most frequently). Moreover, this study is the first to clearly show that the feelSpace belt can be used as a training device. Wearing the belt for several weeks leads to an enhancement in turning accuracy even when the belt is taken off. How long this effect lasts has to be investigated in a future study.

4.4 Proposals for improvement of the FeelSpace belt

The compass in the feelSpace belt is extremely sensitive and therefore susceptible to electromagnetic disturbances e.g. near elevators, in trains and sometimes near smartphones. The belt gives the wearer a signal in such a case, indicating that the signal cannot be totally trusted at that point of time. All participants came into such a situation and some frequently when travelling a lot. This was considered extremely annoying by all participants. This problem should be considered with a high priority for future versions of the belt. A more robust compass is needed. Furthermore, more vibromotors are needed to give more precise information on direction. One vibromotor covering 22.5° does not give precise enough information when a blind participant tries to walk a longer distance in a straight line as the straight-line walking task showed. Some participants also expressed the wish for more precise and

therefore more trustworthy information through more vibromotors. As Cholewiak et al. (2004) already mentioned, a trade-off between the number of vibromotors and therefore the accuracy of the belt indicating directions on the one hand and the cognitive demand on the other hand is needed. The prototype (Nagel et al., 2005) started off with 13 vibromotors, a previous version of the belt had 30 vibromotors and the present belt has 16 vibromotors. Instead of spacing the vibromotors equally, one could also think of a version of the belt with a kind of magnifying effect at the naval. More vibromotors would be positioned at the naval for more precision in e.g. in the road-crossing mode. In addition to a more robust compass it is also important to find a next to optimal number of vibromotors for the belt. Other problems with the belt were more related to the device as such and less to its signal or the information it provides: Many participants commented on the unfortunate positioning of the slot to charge the belt. It is firstly difficult to find and secondly difficult to insert the charger because of the inconvenient position at the top of the control box behind the protecting cover of the belt. Additionally, the position of the control box slightly to the right leads to problems with participants reaching into their right trouser pockets. Individual participants wished that the belt would adapt more to the individual bodily proportions, e.g. one participant had a hollow back and could only slightly feel the vibromotors in his back even when the vibration intensity was high. Others wished for a more nonslip cover, a longer velcro strip so that the belt does not open too quickly and to adjust the size of the belt depending on which clothes are worn underneath. One participant actually asked for different colours for the belt cover. Some participants wished for a slimmer version of the belt and one wished that it was less warm when wearing it.

5 Conclusion

One can conclude that the feelSpace is a helpful aid for congenitally and late blind as well as for deaf-blind people since it has a positive impact on their orientation and navigation abilities. The belt's signal can be intuitively understood and used for orientation tasks. All participants found the belt extremely helpful to keep track of the direction in which they were heading. Especially the deaf-blind participants profited strongly from the belt's information about cardinal directions and integrated this information when navigating and memorizing routes. The signal of the belt indicating cardinal directions therefore seems to be very useful information for the participants. The behaviour data of this study further indicates that training with the belt over a longer period of time can correct erroneous estimations of turning degrees which also has an effect when the participants do not wear the belt. One can therefore deduce that the belt is a helpful training device. Most blind participants profited from the belt's information mainly in unfamiliar environments, but not exclusively. Together with previous research, this study has shown that blind people particularly rely on an egocentric reference frame when orientating and navigating and have a route-based mental representation when navigating. The belt does not change these preferences but seems to enable the blind participants to additionally use their allocentric reference frame more and therefore understand relations of places and roads better in their surrounding environment. This study has also shown how valuable it is to combine experiments that deliver quantitative behavioural data with subjective quantitative and qualitative data from questionnaires to receive a more complete picture. Future versions of the belt should be equipped with a more robust compass against interfering signals from the surroundings and more vibrotactile motors in the belt for more accurate information on direction. Future studies on the optimal number of vibrotactile motors could give helpful insights. Additionally, studies with more deaf-blind subjects could shed more light on how useful the belt could be for them in everyday life.

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Appendix

A1 Declaration of consent and data protection

Einwilligungserklärung und Datenschutz

Allgemeine Informationen

Herzlich Willkommen zu unserer feelSpace Studie. Wir danken Ihnen für Ihr Interesse an dieser Studie. Ziel dieser Studie ist es, die Funktionsweise des feelSpace Gürtels zu testen. Konkret wird untersucht, ob der Gürtel in Alltagssituationen Blinden bei der Orientierung und Navigation hilft. Durch Ihre Teilnahme unterstützen Sie uns dabei, die Funktionalität von dem feelSpace Gürtel voran zu bringen.

Ablauf der Studie

- 1) Vor dem ersten Treffen füllen Sie bitte den Vorabfragebogen und diese Einwilligungserklärung aus und schicken die Formulare an die folgende E-Mail Adresse: anluther@uni-osnabrueck.de
- 2) Beim ersten Treffen bekommen Sie Ihren feelSpace Gürtel, den Sie für den Zeitraum von sieben Wochen tragen werden. Zuerst möchten wir drei verschiedene Tests mit und ohne den Gürtel mit Ihnen zusammen durchführen. Diese Tests dienen Ihnen, um sich mit dem Gürtel vertraut zu machen, und uns, um schon einmal die Funktionsweise des Gürtels zu testen.
- 3) Nach dem ersten Treffen werden Sie einige Tage auf unseren Bescheid warten und dann für vier Wochen den Gürtel ausprobieren. Wir bitten Sie, den Gürtel möglichst ganztägig zu tragen. Nachts und bei Tätigkeiten ohne Bewegung (z.B. Arbeiten am Schreibtisch) können Sie den Gürtel ablegen. Idealerweise sind Sie täglich mindestens eine Stunde draußen unterwegs. Erkunden Sie gerne auch neue Umgebungen und Wege, während Sie den Gürtel tragen. Bitte füllen Sie einmal die Woche den wöchentlichen Fragebogen aus. Bitte dokumentieren Sie in dem wöchentlichen Fragebogen auch, wie viel Zeit Sie jeden Tag draußen waren.
- 4) Nach vier Wochen treffen wir uns wieder, wenn die Corona-Situation es erlaubt. Es werden dieselben drei Tests mit Ihnen durchgeführt wie beim ersten Treffen.
- 5) Bitte tragen Sie den Gürtel noch weitere drei Wochen.
- 6) Füllen Sie bitte anschließend den Abschlussfragebogen aus.

Freiwilligkeit und Datenschutz

Die Teilnahme an der Studie ist freiwillig.

Die Erhebung Ihrer persönlichen Daten erfolgt vollständig anonymisiert. Es ist folglich niemandem möglich, Ihre Daten mit Ihrem Namen in Verbindung zu bringen. Alle Daten werden ausschließlich zu wissenschaftlichen Zwecken erhoben und ausgewertet. Die Veröffentlichung der Studienergebnisse wird ausschließlich in anonymisierter Form erfolgen, d.h. die Studiendaten sind in keiner Weise auf Sie zurückführbar.

Abbrechen der Studie

Sie können das Experiment jederzeit abbrechen, ohne dass Nachteile für Sie entstehen.

Risiken

Die Teilnahme an der Studie führt zu keinen bekannten Risiken.

Einwilligungserklärung

Ich bin über die Studie und den Versuchsablauf aufgeklärt worden. Ich habe diese Einwilligungserklärung gelesen und verstanden. Ich bin mit der Erfassung und Verwendung meiner Angaben in anonymisierter Form zu Forschungszwecken einverstanden. Ich weiß, dass die Teilnahme an der Studie freiwillig ist.

- Ja, ich bin mit der Teilnahme an der feelSpace Studie einverstanden.
- Nein, ich bin nicht mit der Teilnahme an der feelSpace Studie einverstanden.

Datum _____

Unterschrift _____

A2 Introduction of the belt to the participants

Anziehen

Legen Sie den Gürtel um, am besten über eine leichte Stoffschicht. Der Kontrollkasten sollte zwischen rechter Hosentasche und Hosenknopf sitzen.

Nun können sie auf dem Kontrollkasten Knöpfe erfühlen. Ganz rechts ist der An-Knopf, in der Mitte der Pausenknopf und ganz hinten befindet sich der Favorit-Knopf.

Die Taste darüber ist die Kompass-Taste.

Schalten Sie den Gürtel jetzt an, in dem Sie 1 Sekunde auf an-Taste drücken. Aber vorsichtig, gleich vibriert es zweimal um den Körper. Dann gibt es die Bereitschaftsvibration. Das ist eine kurze Vibration an den Körperseiten. Das heißt, dass der Gürtel einsatzbereit ist.

Funktionen

1. Kompassfunktion

Dafür drücken Sie einmal auf den Kompass und dann vibriert das immer im Norden. Drehen sie sich doch mal, dann merken Sie, wie das Signal wandert.

2. Pausentaste

Drücken Sie die Pause-Taste (in der Mitte), dann stoppt die Vibration. Drücken Sie sie erneut geht es weiter.

3. Straßenüberquerungsfunktion

Richten sie sich im rechten Winkel zur Straße aus. Dann drücken Sie zweimal die Kompassstaste. Nun vibriert es pulsierend am Bauchnabel. Wenn es nicht direkt am Bauch vibriert, drehen Sie den Gürtel so, dass es am Bauchnabel vibriert. Drücken Sie nun einmal auf den Kompass und dann vibriert es wieder im Norden.

4. Vibrationsverstärkung

Halten Sie Pausentaste und die Kompassstaste gedrückt. Dann wird die Vibration stärker. Wenn das Maximum erreicht ist, vibriert es zweimal an den Seiten. Drücken Sie dann wieder Pause ist man wieder im normalen Modus.

5. Vibrationsabschwächung

Drücken Sie die Pausentaste und dann den Favorit-Knopf, dann wird die Vibration weniger.

6. Kalibrieren: Nehmen Sie den Gürtel in die Hände und schalten ihn ein. Dann halten sie die Kompassstaste 5 Sekunden gedrückt, bis ein wiederkehrendes Vibrationssignal auftritt. Dann bewegen Sie ihr Handgelenk in liegender Achterbewegungen, gerne auch mit ein bisschen Armbewegung. Das Vibrationssignal verschnellert sich und sobald es durchgängig ist, ist die Kalibrierung abgeschlossen.

Es kann eine Störungsvibration an vier Körperseiten geben. Dann ist das Kompasssignal nicht genau. Das kann an Schlüssel oder Handy in der Nähe des Kontrollkastens liegen. Passiert das öfter, muss der Gürtel neu kalibriert werden.

7. Anzeige des Akkustands

Drücken Sie kurz auf die An-Taste, dann wandert ein Vibrationssignal soweit um den Körper, wie der Gürtel geladen ist. Wenn der Gürtel ganz geladen ist, dann wandert es einmal um den ganzen Körper. Wenn es zum Beispiel halb geladen ist, nur bis zum Rücken. Am Schluss gibt es einen doppelten Vibrationsimpuls.

8. Ausschalten

Drücken Sie die An/Aus-Taste für 1 Sekunde, dann vibrieren 4 Einheiten gleichzeitig. Das nimmt ab, bis der Gürtel ganz aus ist.

Aufladen des Akkus

Verwenden Sie den mitgesendeten Micro-USB Stecker. Es befindet sich eine Öffnung in der Bedientasche am oberen Rand des Bedienelements. Das Ganze ist oberhalb der ein/austaste. Die Prägung auf dem Ladekabel muss in Richtung der Knöpfe zeigen.

Der Gürtel kann auch akustisches Feedback geben, wenn er aufgeladen ist. Dafür müssen Sie den Gürtel anlassen und auf Pause drücken. Dann gibt es drei aufsteigende Töne bei fertiger Ladung.

Gibt es weitere Fragen?

A3 Pre-questionnaire

Allgemeine Fragen zu Ihrer Person

Bitte füllen Sie diesen Fragebogen ehrlich aus. Die nachfolgenden Informationen sind für uns wichtig, um nach der Studie Daten zu analysieren und herauszufinden, ob der feelSpace Gürtel ein Hilfsmittel für Blinde ist.

** 1. Welchem Geschlecht fühlen Sie sich zugehörig?*

feminin

maskulin

divers

** 2. Wie alt sind Sie?*

** 3. Welche der folgenden Aussagen trifft zu?*

Ich bin geburtsblind.

Ich bin spät erblindet.

Ich bin sehbehindert.

Bitte geben Sie an, wie lange Sie schon gesetzlich blind bzw. hochgradig sehbehindert sind.

Bitte geben Sie auch den Visus Wert / Sehschärfe für das linke und rechte Auge und das Gesichtsfeld an.

** 4. Bitte geben Sie die Augenerkrankung oder Ursache an, die zu Ihrer Erblindung führte. Geben Sie bitte auch neurologische, psychische, chronische oder sonstige Krankheiten an, falls zutreffend.*

** 5. Welche der folgenden Aussagen treffen auf Sie zu? Sie können auch mehrere Antworten auswählen.*

Ich kann eine Bordsteinkarte erkennen.

Ich sehe hell-dunkel Kontraste.

Ich bin schwarzblind.

Sonstiges (bitte genauer beschreiben)

**6. Welche Mobilitätshilfen/Hilfsmittel verwenden Sie im Alltag. Bitte wählen Sie die folgenden für Sie passenden Aussagen aus.*

Ich verwende einen Blindenstock.

Ich verwende einen Kompass.

Ich greife auf eine Begleitperson zurück.

Ich habe einen Blindenführhund.

Ich verwende weitere Hilfsmittel (bitte näher erläutern).

**7. Welche Orientierungsstrategien verwenden Sie im Alltag. Bitte wählen Sie die folgenden für Sie passenden Aussagen aus.*

Ich orientiere mich am laufenden Verkehr.

Ich nutze mein Smartphone zur Navigation.

Ich nutze Leitlinien zur Orientierung.

Ich verwende weitere Orientierungsstrategien (bitte näher erläutern).

**8. Bitte wählen Sie die folgenden für Sie passenden Aussagen aus.*

Himmelsrichtungen sind mir bekannt.

Gradzahlen und Winkel sind mir bekannt.

Ich habe schon einmal Mobilitätstraining erhalten

Wenn Sie schon einmal Mobilitätstraining erhalten haben, geben Sie bitte an, wie viele Stunden Mobilitätstraining Sie erhalten haben. (0-25 25-50 >50?)

**9. Bitte geben Sie an, welcher Beschäftigung Sie nachgehen und welche Aktivitäten, Hobbys und Interessen Sie haben.*

**10 Bitte wählen Sie aus.*

	<halbe Stunde	halbe - 1 Stunde	1-2 Stunden	2-3 Stunden	>3 Stunden
Wie viele Stunden sind Sie in der Regel täglich draußen unterwegs?					

**11. Bitte geben Sie an, wie sehr Sie den folgenden Aussagen zustimmen.*

	1 – stimmt nicht	2 – stimmt wenig	3 – stimmt mäßig	4 – stimmt ziemlich	5 – stimmt sehr
Ich habe einen guten Orientierungssinn.					
Ich habe eine Abfolge von Anhaltspunkten meiner Umgebung im Kopf.					
Ich habe eine zweidimensionale Karte / innere Karte von meiner Umgebung im Kopf.					
Ich erkunde öfters neue Umgebungen.					
Ich fühle mich in neuen Umgebungen sicher / wohl.					
Ich vermeide neue Umgebungen.					
Es fällt mir manchmal schwer zu erkennen, dass ich eine breite Kurve laufe.					

Ich bin neugierig und gespannt auf meine erste Erfahrung mit dem FeelSpace Gürtel.					
Ich bin motiviert, an der Studie teilzunehmen.					
Der Gedanke an den FeelSpace Gürtel beunruhigt mich.					

**12. Wie oft üben Sie folgende Tätigkeiten aus (mehrere Antworten zulässig)*

	Mache ich nie	Mache ich nur mit Begleitung	Mache ich nur, wenn es nicht anders geht	Mache ich selten	Mache ich ab und zu	Mache ich regelmäßig
Eine große Kreuzung mit mehreren Spuren überqueren						

Eine Straße überqueren						
Einen Bahnsteig entlanglaufen						
Einen großen Platz überqueren						

**13. Bitte geben Sie an, wie Sie die folgenden Emotionen empfinden, wenn Sie eine Kreuzung mit mehreren Spuren überqueren.*

	Empfinde ich nicht	Empfinde ich wenig	Empfinde ich mäßig	Empfinde ich ziemlich	Empfinde ich sehr
Panik					
Angst					
Hilflosigkeit					
Unwohlsein oder Unsicherheit					
Zuversicht					

Sonstige Emotionen, die Sie empfinden (bitte angeben).

**14. Bitte geben Sie an, wie Sie die folgenden Emotionen empfinden, wenn Sie eine Straße überqueren.*

	Empfinde ich nicht	Empfinde ich wenig	Empfinde ich mäßig	Empfinde ich ziemlich	Empfinde ich sehr
Panik					
Angst					
Hilflosigkeit					
Unwohlsein oder Unsicherheit					
Zuversicht					

Sonstige Emotionen, die Sie empfinden (bitte angeben).

**15. Bitte geben Sie an, wie Sie die folgenden Emotionen empfinden, wenn Sie einen Bahnsteig entlanglaufen.*

	Empfinde ich nicht	Empfinde ich wenig	Empfinde ich mäßig	Empfinde ich ziemlich	Empfinde ich sehr
Panik					
Angst					
Hilflosigkeit					
Unwohlsein oder Unsicherheit					
Zuversicht					

Sonstige Emotionen, die Sie empfinden (bitte angeben).

**16. Bitte geben Sie an, wie Sie die folgenden Emotionen empfinden, wenn Sie einen großen Platz ohne Anhaltspunkte überqueren.*

	Empfinde ich nicht	Empfinde ich wenig	Empfinde ich mäßig	Empfinde ich ziemlich	Empfinde ich sehr
Panik					
Angst					
Hilflosigkeit					
Unwohlsein oder Unsicherheit					
Zuversicht					

Sonstige Emotionen, die Sie empfinden (bitte angeben).

(Questions with a star (*) at the beginning are questions that have to be answered, while the other questions are optional questions)

Note: The same questions but in easier language were posed to the two deaf-blind participants.

A4 Weekly questionnaire

*1. Geben Sie Ihre Initialen gefolgt von Ihrem Geburtsjahr an (z.B. MB97)

Art des Benutzens des Gürtels:

2. Gab es technische Probleme mit dem Gürtel? Wenn ja, setzen Sie sich bitte umgehend mit uns in Kontakt.

*3. Wie lange haben Sie den Gürtel letzte Woche jeden Tag in bekannter Umgebung getragen? (Bitte nur die Stundenzahl angeben).

*4. Wie lange haben Sie den Gürtel letzte Woche jeden Tag in unbekannter Umgebung getragen? (Bitte nur die Stundenzahl angeben.)

*5. Ich habe vergangene Woche folgende Aktivitäten mit dem Gürtel absolviert:

*6. Geben Sie an, wie sehr folgende Aussagen auf Sie zutreffen

	Stimmt nicht	Stimmt wenig	Stimmt mäßig	Stimmt ziemlich	Stimmt sehr
Der Gürtel hat mich diese Woche in meinem Alltag eingeschränkt					
Ich nehme den Gürtel während der Tragezeit bewusst wahr					
Ich nehme das Signal als Vibration wahr					
Ich nehme das Signal nicht als Vibration wahr, sondern anders					
Nach dem Ablegen des Gürtels habe ich noch anhaltende Vibrationsgefühle					

Falls Sie das Signal nicht als Vibration wahrnehmen, sondern anders, beschreiben Sie bitte das Gefühl.

Fragenset Emotion und Motivation:

**7. Geben Sie bitte an, wie sehr die folgenden Aussagen auf Sie zutreffen.*

	Stimmt nicht	Stimmt wenig	Stimmt mäßig	Stimmt ziemlich	Stimmt sehr
In der vergangenen Woche war ich motiviert, den Gürtel zu tragen					
Mit dem Gürtel habe ich mich diese Woche sicherer in fremder Umgebung gefühlt als sonst ohne Gürtel					
Mit dem Gürtel habe ich mich diese Woche sicherer im Straßenverkehr gefühlt als sonst ohne Gürtel					
Ich habe in der vergangenen Woche gut geschlafen					
Mir ging es in der vergangenen Woche gesundheitlich gut					

**8. Wenn Sie in der letzten Woche eine große Kreuzung mit mehreren Spuren überquert haben, wie sehr haben Sie dann folgende Emotionen empfunden? Wenn nicht, stellen Sie sich vor, Sie würden dies mit dem Gürtel tun und bewerten Sie die Emotion.*

	Empfinde ich nicht	Empfinde ich wenig	Empfinde ich mäßig	Empfinde ich ziemlich	Empfinde ich sehr
Panik					
Angst					
Hilflosigkeit					
Unwohlsein oder Unsicherheit					

Zuversicht					
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Sonstige Emotionen, die Sie empfinden (bitte angeben).

**9. Wenn Sie in der letzten Woche eine Straße überquert haben, wie sehr haben Sie dann folgende Emotionen empfunden? Wenn nicht, stellen Sie sich vor, Sie würden dies mit dem Gürtel tun und bewerten Sie die Emotion.*

	Empfinde ich nicht	Empfinde ich wenig	Empfinde ich mäßig	Empfinde ich ziemlich	Empfinde ich sehr
Panik					
Angst					
Hilflosigkeit					
Unwohlsein oder Unsicherheit					
Zuversicht					

Sonstige Emotionen, die Sie empfinden (bitte angeben).

**10. Wenn Sie in der letzten Woche einen Bahnsteig entlanggelaufen sind, wie sehr haben Sie dann folgende Emotionen empfunden? Wenn nicht, stellen Sie sich vor, Sie würden dies mit dem Gürtel tun und bewerten Sie die Emotion.*

	Empfinde ich nicht	Empfinde ich wenig	Empfinde ich mäßig	Empfinde ich ziemlich	Empfinde ich sehr
Panik					
Angst					
Hilflosigkeit					
Unwohlsein oder Unsicherheit					
Zuversicht					

Sonstige Emotionen, die Sie empfinden (bitte angeben).

**11. Wenn Sie in der letzten Woche einen großen Platz ohne Anhaltspunkte überquert haben, wie sehr haben Sie dann folgende Emotionen empfunden? Wenn nicht, stellen Sie sich vor, Sie würden dies mit dem Gürtel tun und bewerten Sie die Emotion.*

	Empfinde ich nicht	Empfinde ich wenig	Empfinde ich mäßig	Empfinde ich ziemlich	Empfinde ich sehr
Panik					
Angst					
Hilflosigkeit					
Unwohlsein oder Unsicherheit					
Zuversicht					

Sonstige Emotionen, die Sie empfinden (bitte angeben).

12. Gab es in der letzten Woche eine Situation, in der Ihnen der Gürtel besonders geholfen hat sich sicherer zu fühlen?

13. Gab es Veränderungen in der Art Ihrer Träume? Wenn ja, erläutern Sie sie bitte.

Fragenset Orientierung:

**14. Bitte geben Sie an, wie sehr folgende Aussagen auf Sie zustimmen*

	Stimmt nicht	Stimmt wenig	Stimmt mäßig	Stimmt ziemlich	Stimmt sehr
Ich bin mir mit Gürtel zu jeder Zeit bewusst, wo ich mich im Verhältnis zu meinem Zuhause befinde					
Es fällt mir mit Gürtel leichter als ohne mich in einer fremden Umgebung zurechtzufinden					
Es fällt mir mit Gürtel leichter als ohne, die Lage von verschiedenen Orten zueinander einzuschätzen					
Es fällt mir mit Gürtel leichter als ohne, die Lage von verschiedenen Straßen zueinander einzuschätzen					
Es fällt mir mit Gürtel leichter als ohne zu merken, dass ich eine Kurve laufe					
Seit ich den Gürtel trage, nehme ich Himmelsrichtungen bewusster wahr					
Mein räumliches Orientierungsvermögen hat sich subjektiv verbessert, seit ich den Gürtel trage					
Wenn ich den Gürtel abnehme, verschlechtert sich mein räumliches Orientierungsvermögen					

15. Gab es in der letzten Woche eine Situation in der Ihnen der Gürtel besonders geholfen hat sich zu orientieren? Wenn ja, erläutern Sie diese.

Fragenset Attentional resources:

**16. Bitte geben Sie an, wie sehr folgende Aussage auf Sie zutreffen*

	Stimmt nicht	Stimmt wenig	Stimmt mäßig	Stimmt ziemlich	Stimmt sehr
Ich konzentriere mich bewusst auf den Gürtel, um mich besser zu orientieren					
Mit Gürtel fällt es mir beim Orientieren leichter, andere Eindrücke wahrzunehmen und einzuordnen als ohne Gürtel					

Fragenset Sonstiges:

17. Ist Ihnen diese Woche während des Tragens des Gürtels etwas Besonderes aufgefallen? Wenn ja, beschreiben Sie es bitte so genau wie möglich.

18. Ist Ihnen diese Woche, während Sie den Gürtel nicht getragen haben, etwas Besonderes aufgefallen? Wenn ja, beschreiben Sie es bitte so genau wie möglich.

19. Freie Tagebucheinträge

(Questions with a star (*) at the beginning are questions that have to be answered, while the other questions are optional questions)

Note: The same questions but in easier language were posed to the two deaf-blind participants.

A5 Post-questionnaire

**1. Ich bin*

Rechtshänder

Linkshänder

Beidhändig

**2. Bitte geben Sie Ihre Initialen und Ihr Geburtsjahr an (z.B. RM98).*

**3. Ich habe schon vor dieser Studie Erfahrungen mit dem feelSpace Gürtel gehabt:*

Ja

Nein

Wenn ja, erläutern Sie bitte genauer, wie Sie in Kontakt mit dem Gürtel gekommen sind, und geben Sie die ungefähre Tragedauer an.

**4. Bitte geben Sie an, wie sehr Sie den folgenden Aussagen zustimmen*

	Stimmt nicht	Stimmt wenig	Stimmt mäßig	Stimmt ziemlich	Stimmt sehr
Mein Orientierungsvermögen hat sich durch das Tragen des Gürtels verbessert					
Ich stelle keinen Unterschied in meinem Orientierungsvermögen fest, wenn ich die Zeit vor dem Tragen des Gürtels und jetzt vergleiche					
Mein Orientierungsvermögen hat sich verschlechtert					
Ich habe eine Abfolge von Anhaltspunkten meiner Umgebung im Kopf					
Ich habe eine zweidimensionale bzw. innere Karte meiner Umgebung im Kopf					
Meine innere Karte ist nach Norden ausgerichtet					
Der Gürtel hat mir beim Orientieren geholfen					

Der Gürtel ist eine gute Ergänzung zu meinen Orientierungsstrategien					
Ich muss mich dank des Gürtels weniger auf das Orientieren konzentrieren					
Seit ich den Gürtel trage, helfen mir Himmelsrichtungen mehr beim Orientieren					
Der Gürtel hatte keinen Einfluss auf mein Orientierungsverhalten und meine Orientierungsstrategien					
Der Gürtel hat mir vor allem in bekannter Umgebung geholfen					
Der Gürtel hat mir vor allem in unbekannter Umgebung geholfen					
Mit dem Gürtel fällt es mir leichter zu merken, wenn ich langgestreckte Kurven laufe als ohne Gürtel					
Der Gürtel hat mir ein Gefühl der Sicherheit gegeben					
Ich nehme den Gürtel als eine Entlastung im Alltag wahr					
Der Gürtel stört mich im Alltag					
Der Gürtel hat keine Auswirkung auf mich gehabt					
Das Vibrieren des Gürtels war die ganze Zeit sehr präsent und prominent					
Das Vibrieren des Gürtels habe ich im Laufe der Zeit kaum noch wahrgenommen					
Meine Umgebung (Freunde, Familie etc.) hat positiv auf den Gürtel reagiert					

5. Wenn der Gürtel einen Einfluss auf Ihre Orientierungsstrategien hatte, erläutern Sie bitte genauer, welche Auswirkungen der Gürtel hatte.
6. In diesen Situationen hat der Gürtel mir besonders geholfen.
7. Das hat mir am Gürtel gefallen.
8. Das hat mich am Gürtel gestört.
9. Das würde ich mir für eine zukünftige Version des Gürtels wünschen.
10. Mir ist noch etwas Anderes aufgefallen, was bisher nicht durch die Fragebögen abgefragt wurde, oder ich möchte etwas näher erläutern.
11. Wenn Sie nicht geburtsblind sind, beantworten Sie bitte die folgenden Fragen:
 - Wann hatten Sie die erste Sehschwäche?
 - Wie stark war diese Sehschwäche?
 - Woher resultierte sie?
 - Wie verlief die Zeit zwischen der ersten Sehschwäche und der Erblindung? (In welchen Etappen gab es Verschlechterungen?)

(Questions with a star (*) at the beginning are questions that have to be answered, while the other questions are optional questions)

Note: The same questions but in easier language were posed to the two deaf-blind participants.

A6 Questions concerning the participants' feelings after each condition on the experiment days

1. Geradeaus-Gehen-Experiment

Bitte geben Sie an, wie sehr die Aussagen zum Experiment für Sie zutreffen.

	Sehr viel sicherer	Sicherer	Eher sicherer	Es bestand kein Unterschied	Eher unsicherer	Unsicherer	Sehr viel unsicherer
Wie haben Sie sich gefühlt?							
Wie sicher waren Sie, dass sie wirklich geradeaus gehen?							

2. Grad-Drehung Experiment

Bitte geben Sie an, wie sehr die Aussagen zum Experiment für Sie zutreffen.

	Sehr viel sicherer	Sicherer	Eher sicherer	Es bestand kein Unterschied	Eher unsicherer	Unsicherer	Sehr viel unsicherer
Wie sicher haben Sie sich gefühlt, wirklich die entsprech- ende Drehung durchzufüh- ren?							

3. Dreiecksvervollständigung

Bitte geben Sie an, wie sehr die Aussagen zum Experiment für Sie zutreffen.

	Sehr viel sicherer	Sicherer	Eher sicherer	Es bestand kein Unterschied	Eher unsicherer	Unsicherer	Sehr viel unsicherer
Wie haben Sie sich gefühlt?							
Wie sicher waren Sie, den Ausgangs- punkt richtig zu lokalisieren?							

A7 Guidelines for conducting the experimental part of the study in accordance with the Corona policy in Germany and Lower Saxony of 22nd March 2020

Richtlinien zur Einhaltung der am 22.03.2020 von Bund und Ländern beschlossenen Corona-Maßnahmen bei Experimentdurchführung

1. Vorgabe: „In der Öffentlichkeit ist, wo immer möglich, ein Mindestabstand von 1,5m zu einzuhalten“

Konsequenz: Versuchspersonen und Versuchsleiter halten diesen Mindestabstand ein. Ist eine blinde Versuchsperson zu führen, geschieht dies mit einem vorher desinfizierten Stab.

2. Vorgabe: „Der Aufenthalt im öffentlichen Raum ist nur alleine oder mit einer weiteren nicht im Haushalt lebenden Person erlaubt.“

Konsequenz: Die Versuchsperson hält sich im öffentlichen Raum nur mit EINEM Versuchsleiter auf. Sie haben weder Kontakt mit anderen Versuchspersonen noch anderen Versuchsleitern.

3. Vorgabe: „Der Weg zur Arbeit, zur Notbetreuung, Einkäufe, Arztbesuche, Teilnahme an Sitzungen, erforderliche Termine und Prüfungen, Hilfe für andere oder individueller Sport und Bewegung an der frischen Luft sowie andere notwendige Tätigkeiten bleiben selbstverständlich weiter möglich.“

Konsequenz: Die erforderliche wissenschaftliche Studie wird modifiziert durchgeführt.

4. Vorgabe: „Es [...] ist wichtig, die Hygienevorschriften einzuhalten und wirksame Schutzmaßnahmen für Mitarbeiter und Besucher umzusetzen.“

Konsequenz: Versuchspersonen und Versuchsleiter tragen Mundschutz und Handschuhe. Alle Utensilien werden vor und nach Gebrauch gründlich desinfiziert.

A8 Compass Experiment Application for the experimental tasks