Institute of Cognitive Science
Department of Neuroscience

Bachelor thesis

Evaluating the concepts of weak and sub-cognitive integration
— an experimental study using vibrotactile sensory augmentation for the blind

By
Anna Ricarda Luther
Mat. No: 972347

First Supervisor: Prof. Dr. Peter König
Second Supervisor: M.Sc. Silke Kärcher

Submission date: 25th September Osnabrück, 2020

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.

A handwritten signature in black ink, appearing to read 'R. Ruther', is written over a horizontal line.

Signature

Osnabrück, 25.09.2020

Abstract

Navigating in foreign surroundings necessitates peak concentration for blind travellers. Yet, most navigational aids heavily rely on attentional resources as well as on audition. Audition is a modality of supreme importance for the blind, allowing to react to cues of the immediate environment. Thus, it would be highly beneficial for a navigational aid for the blind to not or only partially rely on attentional resources and be easily interpreted and integrated into behaviour. Following the sensorimotor contingency (SMC) theory, which is embedded in the theoretical framework of embodiment, such endeavour has the potential to succeed by employing sensory augmentation devices. According to SMC theory, statistic regularities termed sensorimotor contingencies coupling action and perception are constitutive of conscious perception. Consequentially, since those regularities differ in between modality, also the qualitative experience of different modalities differ. Following this line of thought, new SMCs can be created through sensory augmentation devices and learned by exploring the SMC. The objective of this study is to further investigate if and to what extent such sensory augmentation device can be integrated into behaviour. Therefore, the weak integration hypothesis and the sub-cognitive processing hypothesis as established by Nagel et al. (2005) will be employed to evaluate the integration according to their criteria.

Eleven congenitally and adventitiously blind adult subjects were provided with vibrotactile directional information of the magnetic north around the waist through a device termed naviBelt for seven weeks. At the beginning and at the middle of the study the integration of the signal of five participants was assessed using a battery of behavioural tests. These tests consisted of a straight-line-walking task, an angular rotation task and a triangle completion task. Furthermore, throughout the period of study all participants completed preliminary, weekly and final questionnaires, inspired by Kärcher et al. (2012). The questionnaires allowed to gain a more holistic picture of the subjective experience and the self-assessed benefits of the belt. In addition, two deaf-blind participants were provided with the belt for three to four weeks and answered questionnaires adjusted to their needs.

The straight-line-walking task showed instant improvements in path stabilization when provided with the belt. In two participants characteristic behaviour of the sub-cognitive processing hypothesis is obtained. An overall improvement independent of whether the belt is worn or not is especially evident after the training period in the angular rotation task. This indicates an enhanced direction estimation accuracy, which is highly related to the understanding of the belt signal. Evidence for enhanced path integration and navigational skills through the belt can be found in the results of the triangle completion task. For two participants the performance improved even with an additional attentional load, hinting towards sub-cognitive processing.

Overall, the data supports the weak integration hypothesis and points towards the sub-cognitive processing hypothesis and thus show that SMCs can be learned, which is in line with the theory of embodiment. Crucially, the study further exemplifies how such integration into behaviour can be of great benefit as assistive device for blind and deaf-blind.

Table of Contents

1. Introduction	1
1.1 Theories of embodiment.....	1
1.2 Sensorimotor contingency theory.....	2
1.3 Sensory substitution.....	4
1.3.1 Sensory substitution for the blind.....	4
1.4 Sensory augmentation	5
1.5 Integration concepts of sensory augmentation devices and experimental findings	5
1.6 Own experimental study.....	6
2. Materials & Methods	8
2.1 The feelSpace belt	8
2.2 Participants	9
2.3 Experimental study design	12
2.3.1 Straight-line-walking task	14
2.3.2 Angular rotation task.....	15
2.3.3 Triangle completion task.....	16
2.4 Subjective methods.....	17
2.4.1 Additional participants	18
2.4.2 Deaf-blind participants.....	19
3. Results	20
3.1 Experiments.....	20
3.1.1 Straight-line-walking task	20
3.1.2 Angular rotation task.....	29
3.1.3 Triangle completion task.....	43
3.2 Subjective methods.....	51
3.2.1 Individual evaluation.....	52
3.2.2 Group evaluation	61
3.2.3 Deaf-blind participants	66
4. Discussion	68
4.1 Reflections on the study design.....	70
4.2 SMC theory and assistive sensory augmentation devices	71
4.3 Future prospects.....	73
5. Conclusion.....	74
6. Literature	75
7. Appendix	78

List of Figures

Figure 1: The feelSpace naviBelt	9
Figure 2: Study Procedure	13
Figure 3: The grid drawn on the ground for the straight-line-walking task	14
Figure 4: The angular rotation and the calculation of the absolute turning error	16
Figure 5: The three triangles for the triangle completion task	17
Figure 6: The triangle completion and the calculation of the absolute turning error	17
Figure 7: Distance to goal - Participant 1	21
Figure 8: Deviation from goal point - Participant 1	21
Figure 9: Time - Participant 1	22
Figure 10: Distance to goal - Participant 2	23
Figure 11: Deviation from goal point - Participant 2	23
Figure 12: Time - Participant 2	23
Figure 13: Distance to goal - Participant 3	24
Figure 14: Deviation from goal point - Participant 3	24
Figure 15: Time - Participant 3	25
Figure 16: Distance to goal - Participant 4	26
Figure 17: Deviation from goal point - Participant 4	26
Figure 18: Time - Participant 4	26
Figure 19: Distance to goal - Participant 5	27
Figure 20: Deviation from goal point - Participant 5	27
Figure 21: Time - Participant 5	28
Figure 22: Distance to goal - Mean	29
Figure 23: Deviation from goal point - Mean	29
Figure 24: Time - Mean	29
Figure 25: Median turning error - Participant 1	30
Figure 26: Mean absolute deviation - Participant 1	31
Figure 27: Maximal absolute turning error - Participant 1	32
Figure 28: Median turning error - Participant 2	33
Figure 29: Mean absolute deviation - Participant 2	34
Figure 30: Maximal absolute turning error Participant 2	35
Figure 31: Median turning error - Participant 3	36
Figure 32: Mean absolute deviation - Participant 3	37
Figure 33: Maximal absolute turning error - Participant 3	38
Figure 34: Median turning error - Participant 4	39
Figure 35: Mean absolute deviation - Participant 4	39
Figure 36: Maximal absolute turning error - Participant 4	40
Figure 37: Median turning error - Participant 5	41
Figure 38: Mean absolute deviation - Participant 5	41
Figure 39: Maximal absolute turning error - Participant 5	42
Figure 40: Average amount of errors exceeding the scope of one module	43
Figure 41: Average amount of errors exceeding the scope of two modules	43
Figure 42: Absolute turning error without belt - Participant 1	45
Figure 43: Absolute turning error with belt - Participant 1	45

Figure 44: Absolute turning error without belt - Participant 2	46
Figure 45: Absolute turning error with belt - Participant 2	46
Figure 46: Absolute turning error without belt - Participant 3	47
Figure 47: Absolute turning error with belt - Participant 3	47
Figure 48: Absolute turning error without belt - Participant 4	49
Figure 49: Absolute turning error with belt - Participant 4	49
Figure 50: Absolute turning error without belt - Participant 5	50
Figure 51: Absolute turning error with belt – Participant 5	50
Figure 52: Absolute turning error without belt – All participants	51
Figure 53: Absolute turning error with belt – All participants	51
Figure 54: Subjective improvement of orientational abilities – Participant 1.....	53
Figure 55: Subjective use of attentional resources – Participant 1.....	54
Figure 56: Subjective improvement of orientational abilities – Participant 2.....	55
Figure 57: Subjective use of attentional resources – Participant 2	56
Figure 58: Subjective improvement of orientational abilities – Participant 3	57
Figure 59: Subjective use of attentional resources – Participant 3.....	57
Figure 60: Subjective improvement of orientational abilities – Participant 4	58
Figure 61: Subjective use of attentional resources – Participant 4.....	59
Figure 62: Subjective improvement of orientational abilities – Participant 5.....	60
Figure 63: Subjective use of attentional resources – Participant 5.....	60
Figure 64: With belt I am always conscious where I am in relation to my home	62
Figure 65: With belt I orient myself better in foreign surroundings	62
Figure 66: With belt it is easier to set different locations into relation	62
Figure 67: With belt it is easier to set different streets into relation	62
Figure 68: I face difficulties to detect an elongated curve	63
Figure 69: With belt it is easier to detect that I walk an elongated curve –	
Final Questionnaire	63
Figure 70: With belt it is easier to detect that I walk an elongated curve –	
Weekly Questionnaire	63
Figure 71: My sense of direction subjectively improved since I wear the belt.....	64
Figure 72: When I remove the belt my sense of direction worsens	64
Figure 73: My sense of direction improved since wearing the belt	65
Figure 74: The belt helped my while orienting	65
Figure 75: The belt is a good complement to my other orientation strategies	65
Figure 76: I consciously concentrate on the belt to navigate better	66
Figure 77: It is easier to process various inputs with belt when navigating.....	66
Figure 78: Thanks to the belt, I have to concentrate less while orienting.....	66

List of Tables

Table 1: Overview of the participants of the experimental study.....	10
--	----

1. Introduction

“In my everyday life, whenever I navigate, I am somewhat distracted.” (“In meinem Alltag bin ich immer irgendwie abgelenkt, wenn ich mich orientieren muss.”) - This quote from one of our subjects speaks the minds of many blind people. When navigating, attentional resources are especially important for blind travellers to react to important cues of the environment e.g. of traffic or possible obstacles. But not only that, large-scale and small-scale navigation requires high concentration and accuracy, since without visual feedback allowing for correction, errors in path integration accumulate easily. Many assisting aids such as speaking compasses, just to name one, draw heavily on the attentional resources at a moment of peak concentration. This creates a huge problem in the usage of many - at heart useful - navigational aids. Hence, solving this problem by designing a device which succeeds to supply directional information without or barely living of attentional resources would be a move towards further independence and thus of great importance for the blind. Following the theoretical framework of embodiment, to put it more precisely its sub-area the sensorimotor contingency (SMC) theory and applying it through sensory substitution, such results are feasible through the integration of the navigational aid into perception and thereby into behaviour.

1.1 Theories of embodiment

Traditional views on cognition suggest an amodal semantic memory system where world knowledge resides separately from the brain's modal systems for perception and action. According to those views, the input of the modal system is transduced into amodal representations which are constitutive for abstract knowledge. Upon this abstract knowledge, cognitive processes are constructed (Barsalou, 2008). Following this approach, action and perception have a unidirectional relationship in the sense that perceptual processing occurs to build an internal representation of the outside world, based upon which humans then plan and execute actions (Marr, 1982). This traditional view was challenged by several points of criticism: First to be mentioned is the little empirical evidence supporting the presence of amodal symbols in cognition. Another lack in explanatory power can be found in the grounding problem (O'Regan and Noë, 2002), which is concerned with the problem of how amodal concepts explain the interfacing of perception and action. And last to be mentioned, these traditional views do not offer potential solutions to reconcile amodal symbols with neural principles of computation (Barsalou, 2008).

Hence, it needed a new theoretical framework aiming to close those explanatory gaps. Theories of embodiment seek to do so. Even though containing divers notions of cognition (Gibbs, 2006; Wilson, 2002; Barsalou, 2008), Theories of Embodiment or Theories of Grounded Cognition unite behind the general rejection of a semantic amodal system separated from modal systems as well as the rejection of a unidirectional relationship between action and perception. In contrast, embodiment suggests a strong interdependence between action and perception. Some accounts focus on bodily states, based upon widespread findings that bodily states can create cognitive states and be effects of them (Barsalou et al., 2003). Others emphasize the roles of simulation in cognition (Decety & Grezes, 2006). Simulation in those accounts is defined as “Reenactment of perceptual, motor and introspective states acquired during experience with the world, body, and mind” (Barsalou, 2008, p. 618). Again other accounts emphasize the purpose of development of the cognitive system as a supporting system for specific goal-directed action

required by the specific situation the person was in (Glenberg, 1997; Prinz, 1997; Rizzolatti & Craighero, 2004; Robbins & Aydede, 2007; Smith & Semin, 2004; Yeh & Barsalou, 2006). These approaches focus on the interaction between action, perception, the body, the environment, and possible other agents, which can be summarized with the umbrella term of situated action.

Here it is crucial to clarify some common misperceptions of embodiment. By focusing on the interaction of the body with its environment and considering the resulting sensorimotor representation of the external world as constitutive for knowledge, embodiment does not claim that those sensorimotor representation are the only source of representing knowledge and that any form of cognition is necessarily depending on bodily states. This would render any abstract concept, which cannot be grounded externally, unrepresentable for the human mind. However, proponents of embodiment do not make this kind of assumption (Barsalou, 2008).

Despite differing focuses of interest and different implementations of the core ideas of embodiment, one can summarize that the overall notion of cognition within this action-oriented paradigm is considered to be deeply rooted in the agent's interaction with the world (Noë, 2004). Hence, embodied cognition can be termed as “active and multisensory probing of the environment” (Kaspar, 2014, p. 47), which crucially rests upon the bidirectional relationship of action and perception.

1.2 Sensorimotor contingency theory

Inside the scope of theories of embodiment O'Regan and Noë developed the theoretical framework of sensorimotor contingencies (O'Regan & Noë, 2001). This scheme suggests that perception and the qualitative difference of the perceptual experience of different modalities is determined by differing statistic regularities of specific motor action and sensory stimulation in between modalities, namely SMCs.

When first introduced, the SMC theory was mainly concerned with the highly discussed explanatory gap between neural activity and the quality of conscious experience (O'Regan & Noë, 2001). This explanatory gap is distinguishable into three “sub-gaps”. First to be mentioned is the absolute gap, which addresses the question why neural processes should be accompanied by conscious experience at all. The second gap is termed intermodal comparative gap and tackles the question why certain neural activity gives rise to visual experience and other neural activity gives rise to for example auditory experience. The third and last gap is occupied with intramodal qualitative differences, i.e. why certain neural activity gives rise to the experience of seeing red rather than green. According to previously mentioned classical theories of cognition, the answer to these questions lies possibly within the intrinsic properties of neural correlates of consciousness, which might reside in higher cortical areas (Crick & Koch, 1998). Another hypothesis answers those questions with the differences between sensory apparati projecting to different sites of sensory processing in the brain. But O'Regan and Noë doubt this explanation, since neural properties are “qualitatively inscrutable” (Hurley & Noë, 2003, p.161) and extend their perspective following the embodiment approach to “dynamic relations between brain, body, and world” (Hurley & Noë, 2003, p. 132). This dynamic sensorimotor account attempts to bridge the comparative gaps as foundation to, eventually, also bridge the absolute explanatory gap.

The suggested solution lies within the framework of SMC theory, proposing that motor actions and associated sensory stimulations are interconnected by lawful relations called SMCs

(O'Regan & Noë, 2001) and that these are constitutive for perception and the quality of perception. Since these rules differ from modality to modality, the qualitative experience also differs from modality to modality, which bridges the intermodal comparative gap.

An instance of a SMC distinct for the visual percept is the expansion of flow pattern on the retina when the body moves forward and the analogue contraction when the body moves backwards (O'Regan & Noë, 2001). Audition in turn receives different feedback when the body moves towards respectively away from a sound source. This movement mainly affects the amplitude but not the frequency of the sensory input (O'Regan & Noë, 2001). These examples show paradigmatically the differences in between laws distinguishing the modalities, which forms the explanatory foundation for intermodal qualitative differences, bridging the intermodal comparative gap.

Ensuing this line of thought, SMCs also differ within modality. Even though they differ in a seemingly more minor manner than in between modalities, the distinction nevertheless elucidates the origin of intramodal qualitative differences, providing a solution approach for the third gap.

SMCs can be further distinguished into modality related SMCs and object related SMCs (O'Regan & Noë, 2001). While the former describes lawful connection of action and perception determined by the sensory apparatus e.g. the eye, the latter apprehend the relation of multimodal sensory patterns caused by interaction with certain objects. An example for a modality-related SMC and an example of an object-related SMC will illustrate this distinction and will further the understanding of this framework.

A modality-related SMC is for example the specific shift of sensory stimulation of the retina when the eye rotates. This shift is determined by the spherical shape of the retina, the nature of the ocular optics and the extent of the eye-movement. For the beholder, this eye-movement results in shifting contours and changing curvature of lines (O'Regan & Noë, 2001). Furthermore, due to the difference of photoreceptor density in the focal and the peripheral area (Gazzaniga et al., 2019, p. 190), the overall distribution of information drastically changes through motion of the eye, but, and this is the crucial core of SMC theory, in a lawful manner. Object-related SMCs of vision in turn are determined by visual attributes, such as size, shape, texture, position in three-dimensional space, to name a subset. Visual exploration of objects for example only provides a front view of the object to be observed. When moving around the object, parts appear while others disappear. Hence, visual exploration will never fully enclose the object in observation, whereas tactile exploration for example allows for some objects to be fully encompassed. However, to fully cover all regularities underlying a modality and hence being constitutive for the qualitative experience, would go beyond the scope of this discussion. Another crucial aspect of this theory is the fact that these SMCs must be learned through acting in the world and exploring this action-perception-interdependence. The enormous plasticity of the brain (Elbert et al., 1995; Kaas, 1991) enables the extraction of the contingencies during this learning process and simultaneously shapes our perception of the world. Conclusively, the indispensable building block for perception following the SMC theory is “the exploration of the environment in a way that is governed by both kinds of SMCs and the actively exercised mastery of them” (Kaspar et al., 2014). Experiments in the sphere of sensory substitution have provided underpinning of the SMC theory.

1.3 Sensory substitution

Sensory substitution applies the SMC approach to the aim of designing a device that substitutes a possibly partly or majorly impaired modality by providing the input via another modality. This allows for information processing without or barely relying on attentional resources through the mastery of the new SMCs. Since normal perception does not necessarily require attention (Borojevic et al., 2013), the sustenance of information sampled by technical sensors in a SMC-like manner should consequentially enable perceptual learning through exploration of this new SMC. In effect, this implies that artificial SMCs, conveyed by human-machine interfaces, can be learned and consequentially permit the emergence of a perceptual experience just like natural sensory perception. Following this line of thought, this newly learned perceptual experience, just like normal perception, would not necessarily depend on attentional resources. As aforementioned, this would be highly beneficial for the further development of navigational aids for blind people.

1.3.1 Sensory substitution for the blind

In the case of blind subjects, visual information can be provided through a non-visual modality for example auditory and tactile cues. A ground-breaking instance for this attempt depicts the tactile-to-visual-substitution-system (TVSS) developed by Bach-y-Rita. This TVSS consists of a camera coupled with a vibrotactile stimulation system on the skin of the back which is aligned to the statistical regularities, or SMCs, of vision. For example, when the subject moved closer to a quadratic object, the active vibrotactile sensors placed on the back shifted to sensors positioned further on the periphery of the back, indicating the larger visual image the camera received. The experiments using this TVSS showed that the brain of adult blind subjects are plastic enough to learn how to use the tactile sensory substitution system already after a short period of training and use it in a goal-directed manner in tasks such as object recognition and localization (Bach-y-Rita et al., 1969). Crucially, the subjects described the perceptual experience of the TVSS as particularly visual, such that objects were perceived as if located in the external space and not on the back or skin. Another crucial insight gained through consecutive studies with the TVSS is that such perceptual changes were only possible when the participants could actively explore their environment with TVSS (Bach-y-Rita, 2004; Bach-y-Rita et al., 2003). If the camera was modulated from outsiders no such perceptual changes or utilization of the TVSS in a goal-directed manner were observed, which further supports the SMC theory. These results have been underpinned by many other studies testing different substitution systems with blind subjects such as vision-to-tactile substitution (Sampaio et al., 2001), vision-to-auditory substitution (Aboud et al., 2014; Levy-Tzedek et al., 2012) and vision-to-vestibular substitution (Tyler et al., 2003). Such results are also reported in sighted subjects, when blindfolded (Schumann & O'Regan, 2017; König et al., 2016).

As shown, to some extent sensory substitution can be implemented successfully. Nevertheless, the experiments with visual sensory substitution face the problem that the information processed by the visual system surpasses those of the somatosensory system. Consequentially, perception fabricated by a substitution system cannot resemble the normal visual modality (Nagel et al., 2005).

This begs the question if humans can learn to perceive sensory information that is not natural in humans, but nevertheless constitutes an aid in situations demanding visual perception. Thus, if SMCs that are not inherent in humans can be implemented in the human brain, when

transmitted through technical sensory “following qualitatively different transformation laws” (Kärcher et al., 2012, p.2) than vision. Conveying SMCs which are new to the carrier of the device is termed sensory augmentation.

1.4 Sensory augmentation

Based upon the assumptions of SMC theory, Nagel et al. (2005) investigated the hypothesis that providing a new set of SMCs not supplied by another sensory apparatus leads to qualitatively new experience.

Therefore, they designed a belt as an artificial means to supply the information of the magnetic north through vibrotactile stimulation around the waist in a continuous fashion. The waist is chosen, since the abdomen plays a crucial role for processing the position relative to the environment while being susceptible to position and detect vibrotactile signals (Cholewiak et al., 2004). To our current scientific knowledge, humans, unlike animals (Ritz et al., 2002; Mora et al., 2004; Mouritsen et al., 2005), have no natural sensory organ providing this kind of directional information (Fildes et al., 1984). Hence, the information provided constitutes a new type of SMC, which is not inherent in humans. Sighted adult subjects were supplied with the belt for 6 weeks during all waking hours. Their navigational skills as well as the integration of the belt signal was evaluated before and after the training period through outdoor navigation tasks, navigation tasks in VR, physiological tests and subjective reports.

To categorize how the new signal is integrated, Nagel constituted four different levels of integration: the weak integration hypothesis, the sub-cognitive processing hypothesis, the strong integration hypothesis, and the new modality hypothesis.

1.5 Integration concepts of sensory augmentation devices and experimental findings

Weak integration hypothesis: The belt signal is considered weakly integrated when the sensory augmentation adds useful information about the environment and the usage of the belt leads to improvement of performance in at least some behavioural tasks if attended to (Nagel et al., 2005; Kärcher et al., 2012). Hence, the signal and its interpretation draw on attentional resources at this stage of integration.

Strong integration hypothesis: The key characteristic for a strong integration is that inconsistency between the belt signal and other sensory inputs produces measurable responses in behavioural tasks. An example of such measurable response can be found in natural perception. If we encounter a mismatch between auditory and visual input, the ventriloquism effect is empirically observable, meaning in such scenario the visual information dominates the auditory input (Templeton et al., 1966). Such observable behavioural results indicate that the signal is fully integrated and the information of the belt signal is processed mandatorily (Nagel et al., 2005).

Sub-cognitive processing hypothesis: When sub-cognitively integrated, the belt delivers useful additional information of the environment to its user and the implementation of the signal also improves performance in at least some behavioural tasks. The crucial difference to weak integration here lies in the requirement of attentional resources. When the signal of the belt or of another sensory augmentation device is considered sub-cognitively integrated, its interpretation relies only partly or not at all on attentional mechanisms. Kärcher further elucidates this stage of integration with an example in vision: The coupling of words to their meaning happens without the requirement of attentional resources after having learned the

interpretation of the letters (Kärcher et al., 2012), as is evident from the Stroop task (Gazzaniga et al., 2019, p.78-79).

New modality hypothesis: To fulfil the requirements of the new modality hypothesis, the new set of SMCs must be fully mastered. This mastery in turn leads to a new quality of sensory perception. In our case this would mean that the belt signal is sensed as something “beyond mere tactile perception” (Kärcher et al., 2012, p. 2).

In the abovementioned study Nagel et al. (2005) investigated these hypotheses and found increased skills in navigational tasks as well as a change in the adaptation time constant of ocular nystagmus through the belt pointing towards sub-cognitive processing. Additionally, two out of the four subjects reported a qualitative change in perception, which might give support for the new modality hypothesis (Nagel et al., 2005).

Seizing on these different concepts, Kärcher further investigated the plausibility of the weak integration hypothesis, the sub-cognitive processing hypothesis and the new modality hypothesis while also evaluating emotional impact of an updated version of the vibrotactile belt used in the Nagel study, termed naviBelt (for further details, see Materials and Methods: “The naviBelt”) for a blind participant. In this case study an adventitiously blind male was supplied with the naviBelt for 6 weeks during which he was instructed to wear the belt throughout all waking hours and to follow an elaborate training schedule to ensure the exploration of the environment with the belt. The subject was tested in several behavioural tasks before and after the training period and daily and weekly questionnaires as well as face-to-face interviews were conducted. The resulting data from the behavioural tasks give evidence for the weak integration hypothesis and the sub-cognitive processing hypothesis, whereas the subjective methods do not point towards the new modality hypothesis.

As shown, experiments using sensory augmentation supports the feasibility of sub-cognitive integration even in an adult age, allowing to bypass the attentional bottleneck. Thus, sub-cognitively integrated sensory augmentation devices for the blind can be of great advantage. Nevertheless, blind people have highly diverse orientation strategies and abilities as well as different space perception, among others due to their differing time scales of impaired vision and complete loss of eyesight ranging from congenitally blind, early-blind to late-blind (Iachini et al., 2014; Postma et al., 2007; Veraart & Wanet-Defalque, 1987). Therefore, aiming to generalize these findings onto the heterogeneous group of blind people, further studies with more participants need to be conducted.

1.6 Own experimental study

Here, we ensue this line of thought and further investigate the integration of the SMCs conveyed by the naviBelt signal into the perception of blind participants. Therefore, the performance of five blind subjects in three behavioural tasks before and after exploring the belt for four weeks while being instructed to wear the belt during all waking hours, will be evaluated. Additionally, weekly questionnaires over a period of seven weeks were conducted and assessed with eleven participants, who also were instructed to wear the belt during all waking hours. The behavioural tasks as well as the questionnaires are highly based on the abovementioned study by Kärcher et al. (2012). Since the main trait of the strong integration tackles the results of possible sensory mismatches between the belt signal and other sensory input, experiments supporting respective disconfirming the strong integration hypothesis would require incongruent information provided by the belt. However, the belt is supposed to be a reliable navigational aid for the

blind. Thus, to ensure trust in the naviBelt, this hypothesis is not directly tested here. Considering that subjective reports can only hint towards the new modality hypothesis, it will not be covered in the framework of this study.

Hence, the core of this work lies in the evaluation of the weak integration hypothesis and the sub-cognitive processing hypothesis of vibrotactile sensory augmentation signals in blind participants.

2. Materials & Methods

2.1 The feelSpace belt

Following the approach to convey a completely new set of SMCs (Nagel et al., 2005), the device for this study, distributed by the company feelSpace (feelSpace, Osnabrück, Lower Saxony, Germany), signals the magnetic north through vibrotactile simulation in a continuous manner (*Figure 1*). This is enabled through 16 vibromotors that are positioned around the waist and an implemented compass that senses the direction of magnetic north. The direction of magnetic north is then allocated by the control unit at the northernmost vibromotor which starts to vibrate whenever the belt is turned on. Since previous studies showed that more than one vibrating element at a time is perceived as distracting (Nagel et al., 2005), only the northernmost module is vibrating, allowing for a range of 22.5° per module.

To ensure usability during the everyday life indoor and outdoor, the belt is using a long-lasting battery of at least 8h and up to 20h, is weatherproof, and is processed with skin friendly fabric (for further technical details see Kärcher et al., 2012).

Furthermore, the belt is equipped with several different functions aside the compass function, for example the strength of the vibrotactile stimulation is manually adjustable to allow a pleasant wearing experience while ensuring perceptibility of the signal. Second to mention, the belt offers the street-crossing mode, a function designed upon request of blind customers. When switched on, the street-crossing mode transmits pulsing vibrotactile stimulation precisely on the bellybutton. The bellybutton is an especially sensitive area, where changes are often sensed more accurately. Given that the blind traveller loses course, the signal wanders in a fashion such that, aiming to return to the right course, the traveller has to turn back in the direction, such that the signal is situated exactly on the belly button again.

Another function is the routing function, which allows navigation to a previously entered destination through the vibrating signal. Since the feelSpace application is required to use the routing function, and the application was out of service for Android systems due to programming work aiming to expand the functions offered, the subjects were only partly able to work with this function. Even though the street-crossing mode was tested in our experimental tasks and the routing function was mentioned by some participants in the framework of the weekly questionnaires, this thesis will solely focus on the compass function and its possible integration. This focus comes about, because the subjects were explicitly encouraged to wear the belt in the compass mode every waking hour. Consequentially, the vast majority of exposure and training with the belt conveyed the SMCs specific to the compass mode.

Each subject received the belt, a charging device to charge the device self-reliant when necessary, and an individual briefing about the belt (Appendix A.1), its functions and technicalities. The subjects of the experiments did not report any malfunction whatsoever.

To summarize, the belt gives continuous directional information through vibrotactile stimulation around the waistline. All subjects, i.e. the subjects for the experimental study and the subjects for the survey, were instructed to wear the belt during all waking hours for seven weeks. Seven weeks as experiment duration period was chosen due to a motivational low at week four found by previous studies (Kärcher, et al., 2012) along with the aim to give each subject the chance to experience as many different key orientation situations with the belt.

Figure 1: The feelSpace naviBelt
(<https://www.feelspace.de/?lang=en> , last access:
25.09.2020).

2.2 Participants

Due to the SARS-CoV-2 pandemic, solely a few people felt comfortable to take place in an experimental study with physical interaction with an experimental supervisor. Consequentially, two different groups were formed, one group of subjects who were willing to take part in experiments, and another group of subjects who preferred to only take part in the survey. Five subjects participated in the experiment (*Table 1*) and answered weekly questionnaires (four males, one female, age: $\mu = 56$, $\sigma \approx 14.01$) and eleven subjects answered only the weekly questionnaires (six males, five females, age: $\mu \approx 54.36$, $\sigma \approx 11.96$). The participants were acquired through contact of the company feelSpace with the “Blinden- und Sehbehindertenverband Niedersachsen” (<https://www.blindenverband.org/>, last access: 25.09.2020). The group of participants who solely participated in the survey will be introduced in the Subjective methods section.

In advance, each subject was asked to fill out the preliminary questionnaire where we asked for personal data, cause of blindness as well as their orientation strategies among others (see Appendix A.2). In addition, before the experiment, the subjects were informed about the general procedure of the experiment (see Appendix A.3) as well as that they can quit without giving reasons at any point in time.

Since blind people are a highly heterogeneous group and we worked with a low number of participants, we regard each participant and his performance during the experiments case-by-case. Thus, each participant and both his key data and his everyday navigation strategies will be introduced separately, and an overview will be given in the following.

Table 1: Overview of the participants of the experimental study.

	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5
Gender	Male	Male	Male	Male	Female
Age	48	34	68	73	57
Eye disease	Infantile glaucoma	Missing optic nerve	Retinitis pigmentosa	Retinitis pigmentosa	Glaucoma
Duration of Blindness in years	34	34	45	60	34
Visual acuity	-	-	0.01 in left eye	-	-
Mobility training (hours)	50	>50	25-50	50	>50

Participant 1

The first participant was an adventitiously blind male at the age of 48. Owing to congenital glaucoma (Mandal & Chakrabarti, 2011), he lost eyesight at the age of 16 leaving him completely blind.

He was able to preserve an active and self-dependent lifestyle. This is apparent for example from his job as a social worker. Performing this job, he regularly travels on official business. In a private context he enjoys traveling as well as taking long walks summing up to approximately between one to two hours daily spent outdoor. Hence, he navigates on a regular basis with assistance and without.

Participant 1 does not consider himself avoidant of new environments even though he neither agrees nor disagrees with the statement “I feel secure in new environments”.

Whenever he navigates, he relies on cane, compass and the application blindsquare (<https://www.blindsquare.com/>, last access 25.09.2020) and an accompanying person when in new environments. His common orientational aids are the sounds of the traffic, his smartphone and guiding lines. He emphasizes that he particularly relies on acoustic cues in every environment and that he weakly relies on olfactory cues in known environments.

Participant 1 is familiar with cardinal directions, angles and degrees and received mobility training. Prior to the study, he strongly agreed to the phrase “I have a good sense of direction”. Moreover, he states that he has a sequence of orientation marks in his head, forming an inner map. He strongly denies that this map is facing north or is anyhow aligned to north. The belt continuously signals the magnetic north and his inner map is not aligned to north. The effect of this mismatch on his integration of the belt signal will be observed in the following.

Previous to the study, Participant 1 tested the belt in the frame of an exhibition for orientational aids but wears the belt the first time over a longer period of time in the scope of this study.

Besides, he showed high curiosity for the belt and high motivation to participate in this study while expressing no possible concerns regarding neither study nor belt.

Participant 2

A congenitally blind male at the age of 34 was the second participant. He was born without the optic nerve rendering him completely blind.

When navigating, he uses a cane and navigational systems on the smartphone and occasionally, he relies on an accompanying person. Within his environment he utilizes the sounds of traffic,

guiding lines and traffic lights for alignment. Additionally, he emphasizes the overall important role of acoustic cues in navigation and mentions infrequent use of olfactory cues.

He is a social worker as which he frequently travels in different cities which forces him to navigate through a new environment on a regular basis. His daily time spent outdoors ranges between a half and one hour.

Participant 2 is familiar with cardinal directions, angles and degrees and received mobility training. According to his self-statement he has a particularly good sense of direction and when navigating he follows an inner map formed by a sequence of orientation marks. This inner map is not north-facing or anyhow aligned to north. The effect of him being congenitally blind and the non-alignment of his inner map on his integration of the belt signal will be evaluated. Prior to the study, he rated his motivation and his curiosity to participate as high and his possible concerns as low.

Participant 3

The third participant was an adventitiously blind male of 68 years of age. He suffered from retinitis pigmentosa (Natarajan, 2011) with first small visual impairments at age seven. Those impairments worsened throughout forty years leading to a visual acuity of 0 in the right eye and 0.1 in the left eye enabling him to perceive only extraordinarily strong light differences.

Nevertheless, he leads an active and self-dependent life, e.g. he takes walks daily, spending approximately one to two hours outside and currently works in an honorary capacity as association functionary. Furthermore, Participant 3 considers himself as not avoidant of new surroundings. When navigating in new environments as well as known ones, he relies on a cane, smartphone apps such as blinksquare, and tactile maps. In his everyday life traffic and guiding lines constitute orientational aids.

In addition, he is familiar with cardinal direction, angles and degrees and received mobility training. Before the study, he agreed to the phrase “I have a good sense of direction”. Moreover, he states that he has a sequence of orientation marks in his head, forming an inner map. Crucially, he additionally states that this inner map is facing north. The north-aligned inner map as well as his firm knowledge of cardinal directions might facilitate the integration of the belt signal since it is continuously indicating the magnetic north. Hypothetical effects of his north-aligned inner map on his integration of the belt signal will be assessed.

Just like the participant in the case study conducted by Kärcher et al. (2012), Participant 3 can be seen as „the other extreme in comparison to a congenitally blind subject [...] who [...] was only able to integrate the belt’s signal after an extensive explanation of cardinal directions and their meaning“ (Kärcher et al., 2012, p. 3).

Furthermore, he strongly agreed to the phrase “I am curious about my first experience with the feelSpace naviBelt” as well as with the phrase “I am motivated to participate at the study”. Hence, he displayed huge motivation to participate in this study as well as enthusiasm for the belt. Besides, he strongly denies any form of concerns in respect to the study and the belt. This is as well evident from the fact that he bought the naviBelt at the beginning of the study.

Participant 4

The fourth participant is an adventitiously blind male at the age of 73. He suffered from retinitis pigmentosa leading to his complete loss of eyesight at the age of 13. Just like the other participants he was able to maintain a highly active and self-dependent life. Participant 4

considers himself as strongly interested in exploring new environments and regularly takes walks, goes hiking and undertakes tandem tours summing up to averagely more than three hours daily spent outdoors. When undertaking such activities, he relies on a cane and apps such as blindsquare. An orientational anchor constitutes for him the traffic, guiding lines and especially acoustic landmarks. He particularly emphasizes the importance of acoustic landmarks for his orientation enabled by his very well-trained hearing. Lastly to be mentioned, he self-stated that he seldomly banks on olfactory cues.

Cardinal directions, angles and degrees values are well-known to him and he received mobility training. Following his self-assessment he considers himself to have a very good sense of direction and a sequence of orientation marks in his head but he neither agrees nor disagrees when asked if he has an inner map of his environment in his mind. However, if he had to choose if this inner map is north-facing, he would agree strongly. Again, this north-alignment of a potential inner map is of interest in this study. Consequentially, the effect of a north-facing inner map of the integration of the belt signal will be evaluated in the following.

Before partaking in this study, he had some previous experience with the belt, but solely of a minor extent. Regarding his motivation, Participant 4 expresses high motivation and curiosity towards the study and the belt and denies any forms of concern.

Participant 5

The fifth participant was an adventitiously blind female of 57 years. She suffers from glaucoma since birth leaving her with 0.1 visual acuity in the right eye and 0.05 visual acuity in the left eye until 18 years of age. At this age she completely lost the ability to see with the right eye due to retinal detachment and at age 24 she also lost eyesight in the left eye completely.

Living in the countryside, she is seldomly forced to navigate through enlivened traffic nor through winding roads. Participant 5 works as a physiotherapist with long shifts leaving her with approximately between 30 minutes and 1 hour daily spent outdoor. During this time, she depends on a cane and a guidance dog. In those occasions confronted with traffic, she tries to integrate the sounds of running traffic as well as the kerbside into her orientation system.

Participant 5 is acquainted with cardinal directions, degrees and angles and received mobility training.

Concerning her self-assessment, she attests herself a good orientation and strongly agrees with the phrase “I have a sequence of orientational marks in my head” and “I have an inner map in my mind”. Participant 5 strongly denies any north-alignment of this inner map. Possible implication of this non-alignment for the eventual integration of the belt signal will be investigated.

She too asserts high motivation to participate in this study and reports high curiosity towards the belt. Lastly, she also strongly denies any potential concerns or insecurities towards the sensory augmentation device.

2.3 Experimental study design

To evaluate the weak integration hypothesis and the sub-cognitive processing hypothesis, three different behavioural tasks were performed by the subjects and a preliminary and final questionnaire as well as weekly questionnaires were answered (*Figure 2*). Both experimental tasks and the questionnaires enveloped different aspects of the everyday challenges blind people face.

Figure 2: The overall study procedure, with * being only performed by the five individually introduced participants.

Before the actual experiments took place, the belt was given to the subjects and briefly explained and tested. Any beforehand questions or misunderstandings regarding the functionality of the belt were answered. Prior to the experiments, general introductions to the experimental tasks were read out to the participants (Appendix A.4). A test trial of each behavioural task was conducted to avoid misunderstandings of the task or general insecurities and to facilitate habituation to the experimental conditions. After each condition in every behavioural task, the subjects were asked about their sense of security (Appendix A.5) to both ensure a positive framework for the experiment and to investigate a possible emotional effect of the belt.

Each experimental task was repeated in the exact same manner with a temporal difference ranging between four and slightly more than six weeks. This unfortunate inaccuracy and variance between the subjects came about due to the SARS-CoV-2 pandemic. We crafted our set-up in a manner such that the guidelines of behaviour given by the government at that time (Appendix A.6) are fulfilled, e.g. such that the subjects and the experiment supervisor had the possibility ensure a distance between each other of 1.5m. Consequentially, the subjects had to come to Osnabrück which was not feasible for all subjects with the same temporal difference between the first and the second experiment and resulting in a training period ranging from 29 days to 47 days. Moreover, masks were worn by both experimenters and the participants, each participant was only in contact with one of the experimenters and hands and the auxiliary cane was disinfected before and after each participant.

After the first experiments, all participants were instructed to wear the belt during all waking hours for the experiment period of seven weeks unless they find themselves at home or in situations with little to no trunk movements, such as working in an office. In those seven weeks the subjects completed weekly questionnaires (Appendix A.7). Moreover, they were encouraged to explore new environments with the belt, given the SARS-CoV-2 pandemic allowed it. At the end of the experimental period the subjects were asked to complete a final questionnaire (Appendix A.8) to evaluate the overall experience and to summarize the effects of the belt (for a time schedule see Figure 2).

All three experiments on both measuring days were conducted on an even space with minimal sources of acoustic disturbances. Nevertheless, it is a public space unable to be entirely

the other side and it additionally serves as an acoustic orientation mark for the goal direction adjustment. The experimental supervisor at the start point follows the subject, stopping the subject as soon as the limits of the experimental field are reached as well as minuting the path of the subject. Therefore, the supervisor relies on the grid on the ground, recording any crossing of the grid every 5m. The time is measured, and each trial is filmed from behind. Two practice trials take place before the measurements to acquaint the subject to the task, one with belt and without distraction and one without belt and without distraction.

Every Participant passes through 12 trials, 2 trials per condition. Possible conditions were: Without belt, with belt in the compass mode and with the belt in the street crossing mode. Each of those conditions were performed either with or without distraction, with the distraction task being to subtract 3 repeatedly from 1000 as a mental calculation task. The participants were instructed to calculate as fast and as precise as possible and say each result out loud. The additional distraction task was always conducted first for each condition to avoid a potential training effect leading to less attention required in any case after having trained twice without distraction.

In consideration of the fact that this study is concerned with the evaluation of different integration concepts regarding the compass signal, the results of the street crossing mode will not be discussed (for further information see Bordasch (2020) und Brandebusemeyer (2020)). The conditions were randomized across participants but remained identical within participants for the first and the second experiment (see Appendix A.9).

The deviation at the goal line from the goal point, the distance travelled, and the time per distance travelled were evaluated.

2.3.2. Angular rotation task

The angular rotation task was employed to evaluate egocentric orientation, meaning orientation based solely on idiothetic cues. Relating to the belt, this task evaluates how the belt signal is understood and implemented in one's behaviour. Improvement in the angular rotation task would support the weak integration hypothesis.

The experimental supervisor aligns the subjects with the starting direction and hands a smartphone to the subject which is coupled with the belt. On the phone an application specifically programmed for this experiment is opened. This application announces the rotation and the direction in which the subject must rotate e.g. "half-turn left". The application in the hand of the participant announces the instruction in a way that no acoustic landmark can be used as aid during this task. Then, the subject tries to rotate with the phone in an as exact angle as possible and touches the screen to indicate his final direction. The application measures the time needed for the turn, the present orientation, the difference to the start orientation and the orientation at the end of the last turn, the turning degree and the turning direction (clockwise or counter clockwise).

Per condition, the subjects had to perform a quarter, a half and a full rotation each twice in left and twice in right direction in a fixed order (see Appendix A.10). Before the actual measurements, four practice turns are performed, two with belt and two without.

Possible conditions were with and without the belt and again the conditions were randomized across participants but stayed the same for the first and the second experiment. The absolute turning error (see *Figure 4*), the median turning error, the mean absolute deviation, and the maximal absolute error were used as error measure.

Figure 4: Angular rotation task and calculation method of the absolute turning error.

2.3.3 Triangle completion task

“One always goes in right angles, looking for fix points... the life of a blind person is oriented in right angles.” (“Man geht immer in rechten Winkeln und sucht nach Fixpunkten...das Leben einer blinden Person ist nach rechten Winkeln ausgerichtet.”) (Kärcher et al., 2012, p.12) – as evident from this quote, blind people rarely to never take cut-offs but rather navigate in right angles, taking the same route back and forth. Hence, the ability to do path integration and orientate based solely on idiothetic cues would be of great help for blind people when navigating and it would further the unfolding of a two-dimensional inner map. Path integration describes the ability to monitor and update the position and orientation during locomotion (Chrastil et al., 2019). This ability is proven in e.g. ants (Wittlinger et al., 2006) as well as in humans (Wiener et al., 2011). Small-scale path integration and navigational skills can be quantified by the homing task (Nagel et al., 2005). Consequentially, the triangle completion task, as a special case of the homing task, does too.

Besides, the triangle completion task examines possible improvements through the belt either directly at first use or after the training period. Such results would support the weak integration hypothesis. In addition, this study investigates if such improvements rely on attentional resources, or if they are also possible without having all attentional resources at one’s disposal, supporting the sub-cognitive processing hypothesis.

In a triangle completion task, the experimenter leads the subjects with a cane along two edges of a triangle, which is drawn on the ground (*Figure 5*). At the end of the second edge of the triangle, the experimenter takes down the cane. This signals the subject to turn to the start point, as if he would want to return and fulfil the triangle. The cane was used to avoid possible cues given by the body language of the experimenter as well as to ensure the required distance of 1.5m. In the normal triangle completion task, the subjects has to return to the start point but since we already evaluate straight-line-walking in the first experimental task, the subjects do not have to return but simply point to the start point by turning the entire body towards the estimated start point. During this task, the naviBelt is connected with an app programmed specifically for this test, measuring the angle of the rotation and the time used.

In total, the subjects were tested on three triangles walked in both directions, resulting in six triangles with a 30°, 90°, and 150° turn left or right. The differences in between angles and

direction of turn will not be discussed here, for further information, see Brandebusemeyer (2020)).

Figure 5: Visualization of the three triangles for the triangle completion task, with the red numbers depicting the six different starting points and the dashed line indicating the correct direction.

Executed conditions were with belt with distraction, with belt without distraction, without belt with distraction and without belt without distraction. The distraction task was identical to the distraction task of the straight-line-walking and was always performed first to avoid a training effect. The participants were instructed to calculate as fast and as precise as possible. Again, the conditions were randomized between subjects (Appendix A.11) but identical within subjects in both experiments.

The absolute turning error (Figure 6), the mean absolute deviation, and the maximal absolute turning error as well as the median turning error are used as error measures.

Figure 6: Calculation method of the absolute turning error.

2.4 Subjective methods

Complementary to the experimental study, we conducted a survey including the preliminary questionnaire, the weekly questionnaires and the final questionnaire.

Since a survey permitted a participation without physical presence, more participants during the SARS-CoV-2 pandemic could be solicited. The participants were acquired through contact of the company feelSpace with the “Blinden- und Sehbehindertenverband Niedersachsen” or the “Deutschen Blinden- und Sehbehindertenverband e.V.” (<https://www.dbsv.org/>, last access: 25.09.2020). Six new participants combined with the five participants of the experiment completed all questionnaires, mounting up to eleven participants (seven males, four females).

Their ages ranged from 34 to 73 ($\mu = 54.36$, $\sigma = 11.96$) with five congenitally blind subjects (two females, three males) and six adventitiously blind subjects (two females four males). The late blind participants vary highly in their in the time and age of onset of blindness with an age of onset ranging from 13 to 53. Furthermore, the degree of blindness differ, since four subjects are completely blind, and two subjects can differentiate between different lighting conditions and one of them can recognize a curb in good light conditions. No participant suffers from any neurologic, psychiatric or chronic disease. Moreover, most participants rate the motivation to participate in this study as high and denied any sense of discomfort when thinking about the belt, with the exception of two participants who reported slight discomfort.

The survey participants were instructed to wear the belt in every waking hour and to explore new environments with the naviBelt. After a preliminary questionnaire acquiring personal data general motivation and orientation strategies, the participants were asked to answer the weekly questionnaire for a total of seven weeks. The weekly questionnaire remained the same throughout the seven weeks aiming to detect the development during the course of the study. At the end of the period of seven weeks a final questionnaire must be filled out.

The weekly questionnaires are strongly inspired by the successfully tested questionnaire drafted by Kärcher et al., (2012) and evaluate the overall usage experience, the belt perception, the emotional and motivational outlooks, and changes induced by the belt. Furthermore, it assessed potential changes in orientation abilities and strategies, potential changes in the usage of attentional resources when navigating with the belt and offered the possibility to write free text in a diary-like manner. The questionnaires are composed of multiple-choice questions, matrix questions with quantitative Likert-scales and open-ended qualitative questions.

For this survey, the platform “SurveyMonkey” was used, which offered barrier free survey formats (<https://www.surveymonkey.de/>, last access: 25.09.2020). If participants struggled with this format, we offered additional Word and PDF forms along with the possibility to be advised by telephone whenever necessary. Furthermore, the content of the questionnaire was further discussed with a rehab teacher for the blind and the accessibility of the questionnaires was tested with a blind subject

All standardized questions used a 5-Likert-scale with 1 labelled as “Not true”, 2 as “Partly true”, 3 as “Moderately true”, 4 as “Rather true” and 5 as “Completely true”. This allowed for quantification of the subjects’ experience on a standardized scale. Addressing the question of whether the signal of the belt can be integrated weakly or sub-cognitively, this study will focus on the set of questions tackling the use of attentional resources and the enhancement of orientational abilities.

2.4.1 Additional participants

Initially, we started the survey with seventeen participants, four of which abandoned the study due to the unexpected amount of time used for the completion of the questionnaires besides the surplus load the SARS-CoV-2 pandemic imposed on them.

One participant quit the study because he faced problems implementing the belt signal in a goal-directed manner, which lead to several situations where he felt significantly more insecure with belt than without. Consequentially, he did not consider himself to be able to further explore the belt and his functions considering the insecurities he experienced. According to his self-statement, the problems in implementing the belt signal resulted from him being blind for just a short period of time and his vision-oriented alignment strategies. Following this line of

thought, it confused him that when turning right for example the belt signals turns left. Furthermore, he stated problems with processing tactile information in general, a problem that makes the processing of tactile maps for example difficult for him.

Another participant had to abort the survey due to serious unrelated health issues. All six participants that quit, quit to different points in time, which makes it difficult to evaluate the completed surveys. Therefore, these six participants will be neglected in the following and only the eleven participants that filled out the questionnaire in all seven weeks will be evaluated.

2.4.2 Deaf-blind participants

Additionally, five deaf-blind participants were supplied with the belt and the weekly questionnaires over the same period. Due to the different levels of language comprehension in deaf-blind people, the questionnaires were formulated in a more simplistic way (see Appendix A.12-A.13) but nevertheless aiming to maintain the same content of the questionnaire for the blind participants. This draft was evaluated and improved in dialogue with the advisor for deaf-blinds from the “Deutscher Blinden- und Sehbehindertenverband e.V.”

Since the completion of the questionnaires imposed serious issues for some of the deaf-blind participants, only the results of two deaf-blind participants until week three and four will be briefly discussed. Both were male, 56 and 63 years old, and the reason for their deaf-blindness is congenital usher syndrome (Fakin et al., 2012). Severe visual impairments occur in both participants since 13 and 14 years, nevertheless differences between light and dark are perceptible. Like most deaf-blinds, both experience slight vestibular problems. When navigating, they rely on a cane, tactile guiding lines and an accompanying person. Both are familiar with cardinal directions, angles and degrees. Besides, they rate their motivation as high and any discomfort in regard to the belt is denied.

3. Results

3.1 Experiments

3.1.1 Straight-line-walking task

Utilizing the straight-line-walking task, it was evaluated if wearing the belt enables path stabilization in blind participants. Additionally, it was assessed if potential path stabilization relies on attentional resources or if path stabilization takes also place without attending to the belt. In the following, the performance of each participant will be evaluated individually, ensued by an overview of the group.

For the assessment of the performance, the results of the two trials per condition are averaged and compared in between condition and in between the first measurement and the second measurement. The criteria to evaluate the straight-line-walking task are the distance to goal, the deviation from the target point and the required time for the task. The distance to goal describes how far the participants were able to travel. When subjects exited the previously drawn grid, the trial was aborted, and the distance to goal was noted. This criterion is of high significance for the blind since it indicates that the subject was able to approximately steer the course. The deviation from the target point further specifies how exact the subject was capable to steer the course. When the trial had to be aborted before reaching the target line, the deviation from the line of the rectangular path was noted. Yet, changes in that deviation of for examples 1m imply a deviation from the course of 1.146° , hence the expressiveness is rather vague. Similarly, the time required for the task is mostly subject to relatively small variations, which does not allow to draw too strong conclusions. Nevertheless, also strong variations are empirically observable, which indicates a sense of security respective insecurity and constitute an important component of the mastery of the task. In cases where the goal line was not reached, the time was extrapolated in relation to the distance travelled, aiming to ensure comparability. The evaluation of these three criteria in combination with one another grant to hint towards changes in path stabilization.

Participant 1

On the first day of experimental measurements Participant 1 was immediately able to utilize the belts signal, as is evident from the distance to goal (*Figure 7*). When Participant 1 was equipped with the belt, he always reached the target line, whereas within the condition with distraction and without the belt, on average 7.5m were missing to the goal line. Directly using the belt in a goal-directed manner hints towards the weak integration hypothesis. On the second day of measurement we observe a deterioration regarding the distance travelled when distracted. A huge difference can be observed between the conditions without belt and with distraction and without belt without distraction. When distracted, Participant 1 lacked on average 22.5m to the goal, whereas without distraction he managed to travel the entire route. Strikingly, the difference induced by the additional distraction is of a significantly smaller extent when the belt was worn. Here, when wearing the belt and with distraction, a mean distance of 5m was missing, whereas without distraction the entire route was covered.

Besides pointing towards the sub-cognitive processing hypothesis, this indicates that the belt improves straight-line walking and simultaneously allows for other environmental cues to be processed.

An improvement through the belt is evident from the deviation from the targeted end point (*Figure 8*). On the first day when distracted, he performed remarkably better with the belt than without, with him arriving on average 0.75m away from the target point. Whereas without the belt his average end point was located at 2.75m distance. Without distraction, the performance with and without belt were almost identical, with either 2.5 m distance without the belt and 2.75m distance with the belt. During the second measurement, Participant 1 performed generally better with belt than without, concerning the deviation from the targeted point. A huge difference is observable between the condition without belt and with distraction and without belt and with distraction. Here, Participant 1 performed worse without belt and with distraction than without distraction. No such difference between with and without distraction can be found when the belt was used. This hints towards the sub-cognitive processing hypothesis, since the additional task did not affect his performance.

Regarding the time used for the task before the training period, solely the condition without belt and without distraction stands out (*Figure 9*). Here the subject was on average five seconds faster than in every other condition. This changed on the second day of experimental measurements, where Participant 1 is remarkably faster with belt than without. Especially in the condition with distraction, he was on average approximately ten seconds faster when supplied with the directional information of the belt. Without distraction he was approximately six seconds faster using the belt.

To sum up, it is evident that Participant 1 is instantly able to integrate the belt signal into his behaviour, delivering support for the weak integration hypothesis. Furthermore, after the training period his performance is indicative of the sub-cognitive processing hypothesis.

Figure 7-9: The results are further subcategorized into belt (left) and no belt (right), before training (left) and after training (right), and whether distracted (red) or not (blue).

Figure 7: Distance to goal of Participant 1: Without distraction the goal is always reached and with distraction the performance without belt is affected negatively.

Figure 8: Deviation from goal point of Participant 1: The deviation is lower with belt and less negatively affected by the distraction task.

Figure 9: Time of Participant 1: A negative impact of the distraction task without belt is obtained but not with belt. Furthermore, the time reduces with belt and without distraction after training.

Participant 2

Participant 2 was also partly able to directly use the belt signal on the first day of experimental measurements. Support is delivered by the difference between the distance to goal (*Figure 10*) in both conditions with belt and in both conditions without belt. When supplied with the belt, Participant 2 always travelled the entire route, whereas without belt and with distraction averagely he lacked 15m and without belt and without distraction on average 25m were missing. Portending to the weak integration, he benefitted from the belt already on the first day. Albeit, after the training with the belt on the second experimental day, a worsening in performance is observable. Participant 2 was not able to cover the entire route in any condition, but a tendency to cover longer distances when not distracted is detectable. The results hint neither towards the weak integration hypothesis, since the belt does not enable better performance, nor towards the sub-cognitive processing hypothesis, since the additional task negatively affects the performance.

Concerning the deviation from the target point before the training, averagely smaller deviations from the targeted points were apparent when Participant 2 utilized the directional information of the belt, hinting towards the weak integration hypothesis (*Figure 11*). Furthermore, on average, the supplementary distraction task affected the performance with the belt less than the performance without the belt. Yet, that difference adjudge in a range of 0.75m – 1m which is neglectable considering that 50m had to be travelled. After the training period, solely the condition with belt and without distraction exhibits noteworthy changes, with a deterioration in performance. On the first day he arrived 1m away from the target point while after being exposed to the belt for the training period, he arrived with a 3m distance. These results point neither towards the weak integration nor towards the sub-cognitive processing hypothesis.

Concerning the time used to complete the straight-line-walking task, Participant 2 needed more time to accomplish the route without belt (*Figure 12*). When equipped with the belt, he was able to accomplish the entire route and use less time. This might indicate that the belt gave him a sense of security leading him to walk faster. Additionally, a huge difference between with belt

and with distraction and with belt and without distraction is evident. Without distraction he is on average approximately 14 seconds faster, portending that the distraction task negatively affects his performance. On the second day of experimental measurements, Participant 2 completed the task faster with the condition with belt and without distraction being an exception. Here, he accomplished the task approximately ten seconds slower, which contradicts the weak integration hypothesis and the sub-cognitive processing hypothesis.

Figure 10-12: The results are further subcategorized into belt (left) and no belt (right), before training (left) and after training (right), and whether distracted (red) or not (blue).

Figure 10: Distance to goal of Participant 2: The distance to goal is shorter with belt in every condition. The distraction task does not impact the performance negatively with belt.

Figure 11: Deviation from goal point of Participant 2: The deviation increased with belt and decreased without belt after training.

Figure 12: Time of Participant 2: The additional distraction task affected both conditions less after training.

All in all, mixed results are observable with the first experimental day delivering weak support for both hypotheses whereas the second measurement slightly contradicts both hypotheses.

Participant 3

A remarkable improvement in performance induced by the belt is perceptible already on the first day of experimental measurements. Participant 3 always finished the route when utilizing the belt, whereas when the distance had to be travelled without the belt, all trials had to be aborted (*Figure 13*). Crucially, the supplementary distraction task affected the performance without the belt but not with the belt. This direct improvement enabled by the belt plus the stable performance with belt whether distracted or not delivers support for both, the weak integration hypothesis and the sub-cognitive processing hypothesis. When evaluated after the training period, Participant 3 still covered the entire route when equipped with the belt and travelled remarkable longer distances without the belt, with 2.5m missing until the goal line whether distracted or not.

Regarding the deviation from the target point, a generally better performance with belt than without is observable before the training (*Figure 14*). Moreover, the distraction task did neither affect the performance with belt nor the performance without the belt. After training, an improvement in all conditions is observable. Nevertheless, Participant 3 performed best when utilizing the belt. Here, the distraction task affects both conditions equally, resulting in an additional deviation of 0.5m when distracted.

On average he performed the task faster, when equipped with the belt on the first day of experimental day measurements (*Figure 15*). Additionally, Participant 3 completed the task faster when he was not distracted, regardless of whether he was equipped with the belt or not. Consequentially, he was able to benefit from the belt signal. Nevertheless, the distraction task posed additional difficulty upon him, hinting towards the weak integration hypothesis. When evaluated after training, he completed the task faster in every condition except without belt and without distraction than before training. The differences in between the other conditions are neglectable, indicating that the belt signal can be evaluated without entirely relying on attentional resources, pointing towards sub-cognitive processing.

Figure 13-15: The results are further subcategorized into belt (left) and no belt (right), before training (left) and after training (right), and whether distracted (red) or not (blue).

Figure 13: Distance to goal of Participant 3: With belt he always reaches the goal, whether distracted or not. Without belt, the distraction task negatively affects his performance before training, and the distance to goal shrinks after the training period.

Figure 14: Deviation from goal point of Participant 3: The deviation is lower with belt in every condition and improves after training when distracted.

Figure 15: Time of Participant 3: The time slightly reduces after training in both conditions, whether distracted or not.

In summary, Participant 3 performed remarkably better when using the directional information of the belt. Furthermore, he improved performance after training and was not negatively affected by the distraction task, which is suggestive of the sub-cognitive processing hypothesis.

Participant 4

At the first day of experimental measurements, Participant 4 covered the entire route in every condition, hence the criterion of distance to goal does not give us further information about the differences in between conditions (Figure 16). After the training period, the entire route is only travelled without the belt. When equipped with the belt, Participant 4 lacks on average 20m with distraction and 12.5m without distraction. During the second measurement of the straight-line-walking task, he faces problems only in the condition with belt and expresses serious doubt about the usefulness of the distraction task. According to his self-statement, he did not perform as well as he did in his everyday life with the belt when he is not in a test setting. Furthermore, he criticises the latitude of 22.5° that each module allows, which he considers not precise enough. Consequentially, he contemplated to cancel the experiment, which he decided not to after a clarifying talk. Nevertheless, this mindset as well as the feeling of being tested negatively affected his performance at the second day of experimental measurement.

Regarding the deviation from the goal point (Figure 17), Participant 4 performed better during the first measurements without the belt independent of if an additional distraction task was posed. On the second day of measurements the deviation is generally larger when distracted, independent of whether he was equipped with the belt or not. On average, he performed better without belt than with the belt, which contradicts the weak integration hypothesis and the sub-cognitive processing hypothesis.

Before the training, Participant 4 completed the task significantly faster when not distracted, regardless of whether he was wearing the belt or not (Figure 18). Crucially, when distracted and equipped with the belt, he completed the task approximately seven seconds slower than when he was distracted and not wearing the belt. A possible explanation might be that the new belt signal in addition to the distraction task are too many new, unfamiliar inputs that need integration into behaviour. After the training, the time worsened in every condition. On average,

he performed better without belt than with belt, which might be ascribed to the mental setting he found himself in during the second measurement.

Figure 16-18: The results are further subcategorized into belt (left) and no belt (right), before training (left) and after training (right), and whether distracted (red) or not (blue).

Figure 16: Distance to goal of Participant 4: Before training, the goal is reached in every condition. After training, he faced problems solely with belt and was negatively affected by the distraction task, due to his state of mind during the measurements.

Figure 17: Deviation from goal point of Participant 4: The deviation decreases after training in both conditions but solely without distraction. The distraction task negatively affects the performance in with belt before and after training.

Figure 18: Time of Participant 4: The time increases after training with belt and without belt. After training, Participant 4 is faster without belt, whether distracted or not.

Overall, Participant 4 exhibits characteristic behaviour for the weak integration hypothesis on the first day of measurements but does not display behaviour indicative of both the weak integration and sub-cognitive processing hypothesis during this task after training. Due to the difficulties he faced during the second measurements, the experimental results strongly contradict his reported experiences as well as the evaluation of the weekly questionnaires, which renders the validity of the results questionable.

Participant 5

During the first measurements, Participant 5 directly benefitted from the usage of the belt as is evident from the distance to goal (*Figure 19*). On average, she travelled a longer distance when using the belt. When not distracted, she lacked a distance of 7.5m, notwithstanding whether she was equipped with the belt or not. Yet, a huge difference is observable when Participant 5 was distracted during the task. She reached the goal when equipped with the belt, whereas when distracted and not wearing the belt, averagely 37.5m still had to be travelled. Thus, the supplementary task did not affect her performance with the belt, but remarkably impeded her execution of the task without the belt, which points toward sub-cognitive processing. After the training, a comparable result is detectable with the performance with the belt still yielding shorter distances to the goal. Without the belt an improvement can be noticed when distracted, but a deterioration when not distracted.

During the first measurements, the deviation from the target point (*Figure 20*) was smaller when Participant 5 was equipped with the belt. Moreover, this was not affected by the additional distraction, whereas without the belt the distraction task affected the performance negatively. Even though the influence was only of minor extent, this might be suggestive of sub-cognitive processing. Throughout the second measurements, the deviation is still on average smaller when equipped with the belt than when not. Strikingly, the additional distraction task affects the performance positively, both with belt and without.

Regarding the time required for the task at hand (*Figure 21*) during the first measurements, uniquely the condition without belt and with distraction stands out, with approximately 12 seconds longer duration. This indicates that the distraction task negatively affects the performance without the belt. But the signal of the belt and its integration into behaviour is not affected by the distraction task, which is indicative of the sub-cognitive processing hypothesis. During the second day of experimental measurements improvements in every condition are perceptible except in the condition with the belt and without distraction. Participant 5 mentioned a sense of pressure, which might have affected here performance and lead to correcting the path more often than average, which might explain the increase in time used.

Figure 19-21: The results are further subcategorized into belt (left) and no belt (right), before training (left) and after training (right), and whether distracted (red) or not (blue).

Figure 19: Distance to goal of Participant 5: The distance to goal is always shorter with belt.

Figure 20: Deviation from goal point of Participant 5: The deviation is always shorter with belt.

Figure 21: Time of Participant 5: The duration for the task is negatively affected by the additional distraction task solely without belt.

In summary, characteristics of the weak integration and the sub-cognitive processing hypothesis are found before the training, whereas after the training, ambiguous results are obtained.

Summary

To conclude, in three out of five subjects evidence for the weak integration and the sub-cognitive processing hypothesis regarding the straight-line-walking task can be found. In one subject mixed results are observed, which leaves a possible assignment to none, one or both hypotheses vague. The mean performance concerning distance to goal (Figure 22), deviation from goal point (Figure 23) and time (Figure 24) show that the belt is especially helpful when distracted, which points towards subcognitive processing.

The state of mind in which Participant 4 was in during the second day of experimental measurements renders the validity of his results convertible. Thus, the results of the straight-line-walking task yield support for both hypotheses but for a conclusion of stronger expressiveness more trials with more participants need to be conducted.

Figure 22-24: The results are further subcategorized into belt (left) and no belt (right), before training (left) and after training (right), and whether distracted (red) or not (blue).

Figure 22: Mean distance to goal: The distance with belt is shorter already before training. Furthermore, the distance to goal is lower with belt in every condition and the performance with belt is not negatively affected by the distraction task, whereas without belt it is.

Figure 23: Mean deviation from goal: The deviation is lower with belt in every condition except after training without distraction. The distraction task is never of negative influence with belt but without belt it negatively affects the performance after training.

Figure 24: Mean time: Before training, the time was negatively impacted by the distraction task whether supplied with the belt or not. After training, only the time without belt is negatively impacted by the distraction task.

3.1.2 Angular rotation task

The angular rotation task was used to evaluate direction estimation accuracy, which is closely intertwined with the understanding of the belt signal as well as its implementation in one's behaviour. Since the set-up of the angular rotation task does not allow for an additional distraction task, potential improvements in the angular rotation task can only grant support for the weak integration hypothesis. Hereafter, each participants performance will be evaluated separately followed by an overview of the group.

The median turning error, the mean absolute deviation, and the maximal absolute turning error with and without the belt will be used to assess the performance of the subjects. Even though

the latter is prone to outliers, it still shows maximal misjudgement, which has huge implications on the everyday life of a blind person. Choosing the median instead of the mean ensures for more resilience towards outliers. The uncertainty of the subject when performing the rotation are hinted towards via the mean absolute deviation, which enables a robust measurement of statistical dispersion. To further evaluate the turning error with and without the belt and to further evaluate the changes after the training period, the Wilcoxon signed-rank test will be performed on the absolute turning errors. Additionally, the performance with the belt is evaluated alongside the criterion, if the error is within the range of a module of the belt or if the error extends beyond the range of one or two modules of the belt. This indicates whether the error is still in the tolerance range of the belt, or if the signal was not implemented as exact as possible. Furthermore, the expressiveness of the turning error with belt in a range below the latitude of a module accounting for 22.5° can be considered vague. To further illustrate the results, a graph displays the extent of the median turning error, respective mean absolute deviation or maximal absolute turning error. It must be noted that the error angle is always depicted as an error on the left side from the black line depicting the correct direction. The direction of the error is not representative of the measurements, but the figures solely aim to exemplify the extent of the error.

Participant 1

During the first day of experimental measurement, Participant 1 was not able to directly benefit from the vibrotactile directional information of the belt. This is evident from the median turning error (*Figure 25*), which is on average 8° smaller when he was not equipped with the belt. On the second day of measurements, the absolute turning error with belt is significantly higher ($p=0.0442$) than without belt. Yet, when comparing before the training and after the training, the absolute turning error with belt reduces significantly ($p=0.0269$) over time as well as the absolute turning error without the belt ($p=0.0081$). The median turning error without belt diminished by 9.5° and the median turning error with belt was reduced by 12.5° (*Figure 25*). This sums up to a reduction of the median total turning error of 22° after the training period. Hence, this indicates that the participant generally improved in egocentric orientation through the training with the belt.

Figure 25: Median turning error of Participant 1: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training period, the median turning error reduces for both conditions, but is lower without the belt before and after the training. After the training, the median error is always in the scope of one vibromotor.

During the first measurement, the mean absolute deviation (*Figure 26*) is 15.50° lower for the condition without belt. This difference shrunk on the second day of measurement to 3.08° , which is neglectable considering the range per module of 22.5° . Furthermore, the mean absolute deviation without belt shrinks by 2.00° and with belt by 14.42° , further underpinning the positive long-term effect of the belt on the angular rotation task.

Figure 26: Mean absolute deviation of the turning error of Participant 1: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training period, the mean absolute deviation reduces for both conditions. The reduction is of a larger extent with belt.

On the first day of experimental measurement, Participant 1 performed six angular rotations during which the error extended beyond the range of one module and three trials during which the error extended beyond the range of two modules. An improvement is apparent after the training, where only two trials yield an error beyond the range of one module and no trials where the error expands beyond the scope of two modules. This improvement indicates that the belt is better understood and implemented into behaviour after the training phase.

The last criteria to be mentioned is the maximal absolute error (*Figure 27*). Before the training, the maximal absolute error of Participant 1 is 31° smaller when not equipped with the belt. Again, a huge change after the training is observable. Even though Participant 1 is still more precise without the belt, the difference diminishes to 6° . Anew, the general performance independent of the condition improved remarkably. The maximal absolute error without belt decreases by 25° and the maximal absolute error with belt decreases by 50° .

To conclude, even though Participant 1 performed more precise without belt than with belt on the first and second day of experimental measurement, this difference shrinks to a neglectable degree on the second day. Simultaneously, he generally improved on the second day, independent of the condition, which indicates that the training period with the belt supported him in further specify his notion of angular rotations.

Condition	Without belt	With belt
Before training	44°	75°
After training	19°	25°

Figure 27: Maximal absolute error of Participant 1: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training period, the maximal absolute error reduces for both conditions. The error with belt only slightly exceeds the range of one module.

Participant 2

Before the training, Participant 2 did not benefit from the information of the belt during the angular rotation task, as is apparent from the median turning error (Figure 28). When supplied with the belt, he performed on average 43.5° less precise. Furthermore, the absolute turning error is significantly lower without belt ($p=0.0034$). After the training period, the median is on average 14.5° more precise with the belt than without. A deterioration is observable in the condition without the belt. During the second measurements, the median error without belt increases by 17.5°. The median error with belt in turn decreases by 40.5°. Thus, after being acquainted with the belt signal, Participant 2 can benefit from the belt signal.

Figure 28: Median turning error of Participant 2: The conditions are further categorized into before training (solid line) and after training weeks (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training period, the median turning error reduces when supplied with the belt, indicating that the interpretation of the signal is more thoroughly understood after the training. The median error with belt after the training is in the scope of a module.

The mean absolute deviation (Figure 29) during the first measurement is 37.42° lower for the condition without belt than for the condition with belt. On the second day of experimental measurements this tendency remains but diminishes 11.09°. Nevertheless, the improvement for the condition with belt indicates that the SMCs conveyed the belt are learned and yield a higher certainty in performance.

Figure 29: Mean absolute deviation of Participant 2: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training period, the mean absolute deviation reduces with belt, hinting towards an enhanced certainty with the belt. Without belt, the mean absolute deviation increases.

When measured before the training, nine trials with belt yielded an error beyond the span of one module and during seven trials the error extended the range of two modules. Whereas after the training, this reduces to five trials with an error beyond the span of one module and three trials where the scope two modules were exceeded.

A comparable improvement is observable regarding the maximal absolute error (Figure 30). During the first measurements, the maximal absolute error is 187° larger with belt than without. This extreme difference is attributable to a possible misinterpretation of the announced turn. When asked to turn 360°, the Participant 2 performed a half rotation. For congenitally blind people the concepts of different angular rotations are often more abstract and difficult to implement, which might lead to this misinterpretation. However, an improvement is observable after the training period. The maximal absolute error with belt reduces by 89°.

Condition	Without belt	With belt
Before training	21°	208°
After training	112°	119°

Figure 30: Maximal absolute error of Participant 2: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training, the maximal absolute turning error decreases with belt. Nevertheless, the error is still high and always occurs at the whole turn, indicating uncertainties with the concept of a whole turn.

In summary, Participant 2 performed significantly worse with the belt before the training period. Solely after a familiarization phase, he was able to benefit from the usage of the belt and perform on average better with the belt than without. Nevertheless, the highest absolute error occurred on both days when conducting a whole turn, indicating that either the signal of the belt or the concept of a whole turn was not entirely clear to him. A possible explanation for the difficulties he faced to implement the belt signal during this task might be that he neither experienced space through vision at any given time nor was cognitively grounded through for example a north-aligned inner map.

Participant 3

From the first day on, Participant 3 was able to benefit from the directional information of the belt. The median turning error (Figure 31) was on average 11.5° lower when equipped with the belt. Besides, the absolute turning error belt was significantly lower with belt ($p = 0.0122$). After training, he significantly reduces the absolute turning error in both conditions (with belt: $p = 0.0337$, without belt $p = 0.0012$). Furthermore, the median turning error reduces to 9° in both conditions. The direct improvement as well as the effect of the training on the performance supports the weak integration hypothesis.

Figure 31: Median turning error of Participant 3: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). First, the median turning error is lower without belt. After the training, the median turning error reduces in both conditions to the same level.

When supplied with the belt signal, the mean absolute deviation (Figure 32) is 7.91° lower than when asked to perform the turn without belt. After the training period, the mean absolute deviation shrinks in both conditions. Yet, the condition with belt still yields a mean absolute deviation of 3.33° smaller than the condition without belt.

Figure 32: Mean absolute deviation of Participant 3: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training, the mean deviation reduces in both conditions. Without belt, a lower mean absolute deviation at both points in time is obtained.

Moreover, Participant 3 performed five angular rotations with an error exceeding the range of one module and one turn with and error larger than the range of two modules. After the training period, the errors of Participant 3 never exceed the range of a module, hinting towards a deeper understanding of the belt and a further implementation of the signal into behaviour.

The maximal absolute error (Figure 33) during the first measurement is 36° smaller when equipped with the belt. Additionally, also after the training, the absolute maximal error is lower when Participant 3 wore the belt than when he did not. Furthermore, independent of the condition, the maximal absolute error shrinks on the second day of experimental measurements. With belt, the error reduces by 62° and without the belt the error diminishes by 45°.

Figure 33: Maximal absolute error of Participant 3: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training, the maximal absolute error reduces in both conditions. With belt, a lower maximal absolute error at both points in time is obtained.

Consequently, Participant 3 is directly able to integrate the belt signal into his behaviour while further improving after the training period. Thus, these results support the weak integration hypothesis. A possible explanation for the direct utility that the belt signal depicts for Participant 3 in the angular rotation task might be found in his north-aligned inner map. Due to this north-alignment, the signal of the magnetic north might be easier to integrate since he can cognitively ground the signal.

Participant 4

Participant 4 is directly able to integrate the belt signal into his behaviour during the angular rotation task. The median turning error (Figure 34) is on average 14.5° more precise when equipped with the belt. During the second measurement an average deterioration of 9.5° with belt is observable, whereas the condition without belt improved, resulting in a median turning error of 9.5°. This improvement is also apparent in the absolute turning error without belt, which is highly significant ($p=0.0073$). Yet, the absolute turning error is higher with belt than without belt after the training.

Figure 34: Median turning error of Participant 4: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). Before training, the median turning error is lower with belt, whereas the opposite is obtained after the training.

Before the training, the mean absolute deviation (Figure 35) is 21.32° lower when equipped with the belt. After the training, the performance without belt is better than the performance with belt, resulting from an improvement without belt and a deterioration with belt. This indicates that the certainty with belt is lower after training, which might be attributable to his state of motivation.

Figure 35: Mean absolute deviation of Participant 4: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). Without belt, the mean absolute deviation strongly decreases after training, whereas with belt it remains rather constant. After the training, the mean absolute deviation differs only slightly between with and without belt.

Besides, on the first day of experimental measurements already, Participant 4 only conducts one rotation with an error exceeding the scope of one module, which is also the one rotation with an error larger than the span of two modules. Nevertheless, on the second day of

measurements, a deterioration is detectable, with four turns yielding an error larger than 22.5° and one error exceeding two modules.

The maximal absolute turning error (*Figure 36*) with the belt before the training period is 106° smaller when Participant 4 wore the belt. After the training period, we observe a general reduction of the maximal absolute turning error. With the belt, the maximal turning error is 42° smaller than before the training and without the belt, the turning error reduces by 166° . Yet, the maximal absolute turning error is 12° smaller without the belt on the second day of experimental measurement.

Figure 36: Maximal absolute error of Participant 4: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). After the training, the maximal absolute error decreases for both conditions.

Two crucial limitations to the validity of these results need mentioning. Firstly, before the training, Participant 4 noted a continuous rustling of the heating system of nearby buildings. Since he insistently emphasized the huge role acoustic landmarks play for his orientation strategies, this might have influenced his performance. Additionally, he stated that he primarily used the noise source for orientation and not the belt. Secondly, the previously mentioned problems Participant 4 faced on the second day of measurements and the resulting low motivation result in vague expressiveness of the results on both days of experimental measurements. In summary, Participant 4 initially benefitted from the belt, pointing towards the weak integration hypothesis and after training, the results support none of the hypotheses due to the abovementioned reasons.

Participant 5

On the first day of experimental measurements, the absolute turning error of Participant 5 (Figure 37) is significantly lower with belt than without ($p=0.0029$). Furthermore, the median turning error is 5.5° smaller when equipped with the belt. During the second measurements, a slight deterioration in the performance with belt is noticeable with an increase of the median turning error by 8.5° . The increase of the absolute turning error with belt is of significance ($p=0.0161$). Simultaneously, the error decreased by 7.5° for the condition without the belt, resulting in a significant higher absolute turning error with belt ($p=0.0408$). She performed on average 10° less precise with belt than without belt.

Figure 37: Median turning error of Participant 5: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). The median error is always within the scope of one module.

Before the training, the mean absolute deviation (Figure 38) is approximately 6.20° smaller when performing with belt. After the training, a negligible deterioration with belt is empirically observable, whereas the condition with belt slightly improves. Though, the overall mean absolute deviation of errors changed anew by approximately 1° .

Figure 38: Mean absolute deviation of Participant 5: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). Before the training, the condition with belt yields a lower mean absolute deviation, whereas after the training both are alike.

Moreover, before the training, Participant 5 conducted no turns with an error larger than the range of one module. Albeit, after the training she performed 4 trials with the error exceeding the range of one module and one rotation with an error larger than two modules.

The maximal absolute error (*Figure 39*) on the first day is lowest for the condition without belt, with the difference mounting up to 23° . But during the second measurement, a clear worsening is observable: The maximal absolute error without belt increases by 15° and the maximal absolute error with the belt increases by 34° .

Figure 39: Maximal absolute error of Participant 5: The conditions are further categorized into before training (solid line) and after training (dashed line) and whether the participants were supplied with the belt (green) or not (orange). With belt, the maximal absolute is lower on both days of experimental measurements.

Additionally, it must be mentioned, that Participant 5 repeatedly brought up exhaustion caused by her increased workload due to the SARS-CoV-2 pandemic. Consequentially, she took more breaks than previously.

To sum up, Participant 5 was directly able to benefit from the belt, even though in a minor manner. Yet, after the training no improvement is apparent and a slight shift towards a better performance without belt is observable.

Summary

Since the results of one participant lacks expressiveness due to the abovementioned circumstances, altogether in one out of four participants no significant changes are detectable and in three out of four improvements induced by the belt occur either directly or after the

training period. The three participants that benefitted from the belt also performed more precise without belt after the training period.

Furthermore, the two participants who directly profited from the belt to a larger extent are the two participants who self-stated to navigate along a north-aligned inner map. This might underpin that, if cognitively grounded, the belt signal is easier and faster to implement.

As the weak integration hypothesis as interpreted by Kärcher et al. (2012) implies direct improvement in some behavioural tasks when attended to, the contribution of these results to support the weak integration hypothesis are debateable. Since two participants improved performance solely after the training, it is not known, at what point exactly the improvement took place. Considering that it is possible that this increase in precision took place at the same day of the first experiment or the day of the second experiment, the support for the weak integration hypothesis regarding those cases remains vague. Furthermore, the weak integration hypothesis presupposes improvements in some behavioural tasks when attended to. Thus, the absence of improvement in some task for some participants is not necessarily contradictory to weak integration hypothesis. Yet, improvements in egocentric orientation skills with belt (Figure 40 & Figure 41) and without belt (Figure 41) and an enhanced understanding of the belt signal are apparent, yielding empirical underpinning for the weak integration hypothesis.

Figure 40

Figure 41

Since the results of Participant 4 lack expressiveness on both days of measurement, the average amount of errors exceeding one module (Figure 40) or two modules (Figure 41) are displayed without his data. It is evident, that before training more errors exceeding one module occur with belt (green) than without (orange). Nevertheless, errors exceeding two modules are slightly reduced from begin on, when supplied with the belt. After the training period, a distinct reduction of errors exceeding one module is obtained with belt, but not without. Remarkably, the errors exceeding two modules strongly reduce in both conditions after the training period.

3.1.3 Triangle completion task

The precision of the subjects in a triangle completion task was measured to determine if the naviBelt has a positive impact on path integration and navigational skills, which would support the weak integration hypothesis. Furthermore, it was evaluated if a potential impact on path integration and navigational skills relies on attentional resources to provide evidence for or

against the sub-cognitive processing hypothesis. Five different factors influence the results: the inner angle of the triangles, the length of the edges, the angle at the end point, if the angle is located on the left or the right and the turning direction of the participant. Thus, a two-way statistical analysis of variance (ANOVA) to take possible inter-subject variations into account did not seem like a useful option and the data will be descriptively discussed along three criteria: the median error, the mean absolute deviation and the maximal absolute error. All three criteria were chosen for the same reasons as in the angular rotation task. Moreover, the Wilcoxon signed-rank test will be conducted on the absolute turning error.

Participant 1

During the first day of experimental measurements, Participant 1 did not profit from wearing the belt in the triangle completion task, as is apparent in the median turning error (*Figure 42 & 43*). When performing the triangle completion task without the belt, the error is distinctly lower, whether distracted or not. Furthermore, the additional distraction task affects the performance when not supplied with the belt. The median error is 15.5° larger when having to simultaneously calculate, as when the full concentration is dedicated to the triangle completion. Such effect is not observable when supplied with the belt, since the median error with belt and without distraction is on average 6° larger than with belt and with distraction. After the training period, an enhancement in performance is perceptible since the median error lowered for all conditions except for the condition without belt and without distraction which negligibly worsened by 3.0° . Generally, the condition with belt yields a slightly lower median error on the second experimental day. Furthermore, no negative impact of the distraction task is apparent whether equipped with the belt or not, hinting towards sub-cognitive processing. This is further underpinned with a significant improvement of the absolute turning error in both distraction conditions (with belt: $p = 0.0469$, without belt $p = 0.0313$)

Similar results are evident concerning the mean absolute deviation of Participant 1. Before the training, the mean absolute deviation is lower when completing the triangle without the belt. Anew, the distraction only affects the condition without belt in a negative manner, leading to an increase of the mean absolute deviation of approximately 8.16° , whereas the mean absolute deviation in the belt condition only increases by 1.00° . Furthermore, the mean absolute deviation decreases for all conditions after the training. The distraction task is not of negative influence whether supplied with the belt or not, but further decreases the mean absolute deviation in both conditions, leading to the lowest mean absolute deviation of 5.33 in the condition with belt and with distraction.

A resembling pattern is discernible in respect to the maximal absolute error. During the first experimental measurement the maximal absolute error adjudges in a similar range for all conditions except for the condition without belt and without distraction. This indicates that both, the belt and the distraction task, are of negative impact on the performance. After the training period, the maximal absolute error decreases for all condition, with the condition with belt yielding an averagely lower maximal absolute error. Moreover, the distraction task did not affect the performance without belt and positively affected the performance with belt, resulting in a 17° lower maximal absolute error.

Figure 42

Figure 43

Absolute turning without belt (Figure 42) and with belt (Figure 43): The conditions are further categorized into before training (left) and after training (right) and whether the participants had to perform the task distracted (red) or not (blue). The centered line indicates the median, the bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross. As is evident, after the training, the median error and the deviation is remarkably lower with belt and without belt, pointing towards an improvement in navigational skills independent of the belt. Furthermore, the additional distraction did not affect the performance negatively after the training. When supplied with the belt, the additional distraction task lead to an even lower deviation (orange).

To conclude, the performance of Participant 1 in the triangle completion task is negatively influenced by the belt before the training. Solely after the practice time, the belt is of distinct benefit. Furthermore, both conditions with and without belt improved, which might be partly attributable to the self-stated recognition of some triangles by Participant 1. Moreover, the distraction task is not of negative impact on the performance with belt, pointing towards sub-cognitive processing.

Participant 2

When first measured, Participant 2 experienced direct benefits from wearing the belt, as it is substantiated by the median error (Figure 44 & 45). When not distracted, the median error is 42.5° lower when provided with the vibrotactile signal of the belt. But when Participant 2 had to simultaneously calculate, the median turn with belt becomes 44.0° less precise, whereas the median error without belt reduces by 12.0°. During the second experimental measurement, an improvement in all conditions except with belt and without distraction is apparent. On average, the condition with belt yields a lower median error than the condition without belt (Figure 44 & 45). Moreover, both conditions are positively influenced by the additional distraction task after the training.

The mean absolute deviation before the training period is on average lower when not wearing a belt. Independent of whether Participant 2 was supplied with the belt or not, the mean absolute deviation is higher when additionally having to calculate. This changes after the training period. When supplied with the belt, the mean absolute deviation of Participant 2 is not affected by the additional distraction task. Furthermore, when completing the triangle without the belt, the

mean absolute deviation is on average higher. The additional distraction task results in a decline of the mean absolute deviation of approximately 17.17° when not equipped with the belt.

A similar pattern is detectable in the maximal absolute error. The mean maximal absolute error for both conditions with belt is slightly higher than the mean maximal absolute error for both conditions without belt during the first measurement. Besides, when not equipped with belt, the performance is influenced by the additional task in a negative manner. Whereas when equipped with the belt, the maximal absolute error decreases when the additional distraction task must be conducted. After the training period, the maximal absolute error generally shrinks with the exceptional case of without belt and without distraction. Here, the maximal absolute error increases by 108° . After the training, the maximal absolute error is lower with the belt and the additional distraction task is not of negative influence.

Figure 44

Figure 45

Absolute turning error without belt (Figure 44) and with belt (Figure 45): The conditions are further categorized into before training (left) and after training (right) and whether the participants had to perform the task distracted (red) or not (blue). The centered line indicates the median, the bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross. Before training, the performance with belt is negatively affected by the additional distraction task (45.2). After the training, the median error with belt and with distraction (45.4, orange) and without belt and with distraction (44.4, orange) reduces.

In summary, Participant 2 benefitted only in a minor manner from the belt at the beginning of the study. After the training period, a slight improvement is detectable, most prominent in the median error with belt and with distraction, only vaguely pointing towards sub-cognitive processing.

Participant 3

The median turning error (Figure 46 & Figure 47) is on average lower with belt than without, regardless of whether a supplementary arithmetic problem needed to be solved simultaneously or not. Besides, the additional attentional load only affects the performance without the belt in a slight negative manner, increasing the median error by 7.0° . After the training period, the performance without belt improved, with a reduction of median error of 13.5° without distraction and 18.5° with distraction. This improvement without belt is further substantiated

with a significantly more precise estimation without belt and with distraction than with belt and with distraction ($p = 0.0313$). Whereas the median error with belt remains approximately the same when distracted and increased by 11.0° when not distracted.

The mean absolute deviation during the first day of experimental measurement is approximately of the same extent in all conditions, except for without belt and with distraction which is approximately 11° larger. A reduction of approximately 16° of mean absolute deviation on the second day of measurements is observable in that condition. Yet, the other conditions remain in a comparable extent to the first measurement, indicating a similar certainty of estimation independent from training or conditions.

The maximal absolute turning error of Participant 3 before the training is 22° higher for the condition without belt and with distraction in comparison to the condition without belt and without distraction. Thus, the additional distraction task negatively affects the performance without belt. The maximal absolute error with belt only increases by 1° when distracted. After the training period, the maximal absolute error slightly increases with belt. Without belt, mixed results are obtained. When distracted, the maximal absolute error shrunk by 40° , whereas the maximal absolute error in the condition without distraction increased. The maximal absolute error in the latter condition can be clearly considered an outlier (Figure 46.3) since the median error in that condition is the lowest of all.

Figure 46

Figure 47

Absolute turning error without belt (Figure 46) and with belt (Figure 47): The conditions are further categorized into before training (left) and after training (right) and whether the participants had to perform the task distracted (red) or not (blue). The centered line indicates the median, the bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross. Before the training, the median error with belt and distraction (47.2, orange) is lower than without belt and with distraction (46.2, orange). After the training period, both the median error and the deviation is higher with belt, irrespective of the additional distraction task.

In summary, Participant 3 initially benefitted from the belt in the triangle completion task also when distracted, even though in a minor manner. After the training period, when supplied with the belt, a deterioration in performance with belt is apparent while simultaneously an

improvement without belt is obtained. These results do not support the sub-cognitive processing hypothesis.

Participant 4

The median error (*Figure 48 & Figure 49*) on the first day of experimental measurements is on average slightly better with belt than without. Furthermore, the additional arithmetic task negatively affects the median error with belt, whereas without belt no such effects are perceptible. During this measurement, Participant 5 repeatedly mentioned, that he has not yet implemented the signal enough to benefit from it. After the training period, the median error decreases in all conditions. Yet, when completing the triangle without belt, the estimation is more precise than with belt, whether distracted or not. Without the distraction, this disparity is of solely 3.5° , while with distraction the difference mounts up to 11.0° . During the experiment, Participant 4 mentioned that the belt in combination the distraction task is “one input too much”. On the first day of experimental measurements the mean absolute deviation (*Figure 48 & Figure 49*) is remarkably lower when completing the triangle without the belt than when supplied with the belt. This tendency is independent from the additional distraction task. After the training period, the mean absolute deviation decreases for every condition except for the condition without belt and with distraction. This is partly ascribable to a large outlier in that condition, as is the high mean absolute deviation in the condition with belt and without distraction.

Before the training, the maximal absolute error is remarkable lower without the belt, regardless of the additional distraction task. After the training period, mixed results are obtained. The maximal absolute error decreased in three out of four conditions in different extents, except for when Participant 4 was not equipped with the belt and additionally distracted. Besides, we see a lower maximal absolute error with belt when distracted than when not distracted, whereas a higher maximal absolute error without belt occurred when distracted than when not distracted. The maximal absolute errors without belt and with distraction and with belt without distraction can be considered outliers (*Figure 48.4 & Figure 49.3*).

Figure 48

Figure 49

Absolute turning without belt (Figure 48) and with belt (Figure 49): The conditions are further categorized into before training (left) and after training (right) and whether the participants had to perform the task distracted (red) or not (blue). The centered line indicates the median, the bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross. Before training, the absolute turning error without distraction of similar extent in the condition with belt (49.1) and without belt (48.1). With distraction, Participant 4 benefits from the belt (48.2 in comparison to 49.2, both marked orange). After the training period, the median is slightly lower without belt and the deviation is lower without belt.

To sum up, Participant 4 did not benefit from the belt during the first measurements and on the second day of experimental measurements mixed results are observed. The expressiveness is vague due to the aforementioned low motivation of Participant 4. Nevertheless, the overall performance improves over the period of the study.

Participant 5

When first measured, Participant 5 only partly benefitted from the belt, as is evident from the median error (Figure 50 & Figure 51). Without the additional distraction task, the median error is 11.5° higher when provided with the belt. With the additional distraction task, the median error is 6.0° lower with the belt. This pattern is inverted on the second day of experimental measurements. Furthermore, the median error increased in every condition except with belt and without distraction, which decreased by 21.5°. These results contradict her subjective experience on the second day of experimental measurements, since she stated that she is constantly preoccupied with converting the belt signal to benefit from it. The self-stated use of attentional resources during the task is congruent with the median error for the condition with belt and with distraction, which yields the highest median error of all conditions of 42.5°.

Before the training, the mean absolute deviation overall is lower without belt than with belt. Nevertheless, the mean absolute deviation is lower for the condition with belt and without distraction than without belt and without distraction. But when instructed to simultaneously calculate, a converse relation is obtained. After the training period, the mean absolute deviation is higher with the belt, regardless of the additional distraction task. The highest mean absolute deviation occurs with belt and without distraction, which is ascribable to an outlier of the maximal absolute error (Figure 51.3).

The maximal absolute error during the first measurement is approximately of the same extent with belt, whether distracted or not. Without the belt, the maximal absolute error is lower with distraction than without. After the training period, the maximal absolute error increases for all conditions except without belt and without distraction, which slightly decreases. Especially the maximal absolute error with belt and without distraction of 173° stands out, which can be considered an outlier (Figure 51.3) due to the low median error in that condition during the second measurements. Participant 5 repeatedly mentioned her exhaustion, which might account for the outlier.

Figure 50

Figure 51

Absolute turning without belt (Figure 50) and with belt (Figure 51): The conditions are further categorized into before training (left) and after training (right) and whether the participants had to perform the task distracted (red) or not (blue). The centered line indicates the median, the bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross. Before training, no clear benefit from the belt is evident. After the training, Participant 5 performed more precise with the belt, when not distracted (50.3 in comparison to 51.3, both marked orange).

Overall, Participant 5 benefitted from the belt in a triangle completion task exclusively after the training and without distraction, which supports the weak integration hypothesis but is not indicative of sub-cognitive processing.

Summary

Since the results of one participant are short of expressiveness due to the abovementioned circumstances, altogether four out of four participants benefit either from begin on or in the course of the study from the belt in a triangle completion task, supporting the weak integration hypothesis. Concerning the sub-cognitive processing hypothesis, two participants exhibit no characteristics of the sub-cognitive processing hypothesis, while the results of one Participant is vaguely supporting the sub-cognitive processing hypothesis and the results of another participant are strongly indicative of sub-cognitive processing. Evidence for the sub-cognitive processing theory can be found in the absolute turning error of all participants (Figure 52 & Figure 53), since the distraction task did not negatively influence the median.

The congenitally blind participant does not display significantly different behaviour than the adventitiously blind participants. North-alignment of the inner map does not positively impact

the integration of the signal in the triangle completion task, as the results of both participants stating to have a north-aligned inner map are not suggestive of sub-cognitive processing. The median turning error and the high mean absolute deviation in the first day of experimental measurement in all participants except Participant 3 shows that the triangle completion task is difficult to resolve.

Figure 52

Figure 53

Absolute turning without belt (Figure 52) and with belt (Figure 53) for all participants: The conditions are further categorized into before training (left) and after training (right) and whether the participants had to perform the task distracted (red) or not (blue). The centered line indicates the median, the bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross. Before training, the performances with belt deviate more when distracted (53.2). After the training period, the absolute error reduces and the distraction task does not negatively affect the absolute error for both conditions.

3.2 Subjective methods

The questionnaires were employed to evaluate the perception of the belt, the emotional and motivational outlooks and changes induced by the belt. For investigating the weak integration hypothesis and the sub-cognitive processing hypothesis, it furthermore assessed potential changes in orientational abilities and strategies and if potential changes in the usage of attentional resources when navigating with the belt occurred. Even though subjective experience and objective observation might diverge, the self-assessment of a larger group could hint towards none, one or both hypotheses. Nevertheless, especially assessing if one's own attentional resources are used and if to what extent, is highly subjective and thus rather vague in its expressiveness.

The results of each participant that took part in the experimental measurements will be assessed individually, followed by an evaluation of the entire group that partook in the survey and brief assessment of the results of the deaf-blind participants. Both individuals and the group are assessed in the same manner. First, possible restrictions of logistic, health or sleep related nature induced by the belt will be mentioned. To examine self-stated benefits from the usage of the belt, the set of questions employing a 5-point Likert-scale (1- Not true, 2 – Partly true, 3 – Moderately true, 4- Rather true, 5- Completely true), and which are concerned with orientational abilities and possible changes of such will be evaluated. Seven statements in the

weekly questionnaire (14.1-14.5, 14.7-14.8, see Appendix A.7) addressed the self-assessment of orientational abilities when provided with the belt. All statements were formulated in a manner such that high values correspond to an enhancement of one's orientational abilities when supplied with the belt. Therefore, the rating for every question of one week will be summed up and averaged to evaluate the enhancement of orientational abilities. Furthermore, statement 11.7 of the preliminary questionnaire and statement 3.1, 3.7-8, 3.14, 3.16 of the final questionnaire will be evaluated regarding the weak integration hypothesis. For further investigation of the sub-cognitive processing hypothesis, the set of questions using a Likert-scale in the weekly and final questionnaire concerned with the usage of attentional resources during navigation are examined. This set consists of the questions 16.1 & 16.2 of the weekly questionnaires (see Appendix A.7) and statement 3.9 of the final questionnaire. Since one question formulated in a manner that high values support the sub-cognitive processing hypothesis and the other question is formulated in a manner that high values contradict the sub-cognitive processing hypothesis, they will be plotted individually. For the participants of the experimental measurements, the findings will be set into relation with the experimental results. For the group, the differences from one week to another as well as the difference from the first to the fourth and from the first to the last week will be tested for significance using the Wilcoxon signed-rank test. It is probable that the participants that partook in the behavioural tasks evaluated their experience different than those that did not. However, these differences will not be discussed here, for further information see Bordasch (2020).

Other aspects that are not discussed here such as emotion, motivation and the amount of time during which the belt signal was explored are also of influence. For further information see Brandebusemeyer (2020) and Bordasch (2020). Another aspect of the questionnaires which is not tackled for the individual or the group evaluation here are the open-ended questions since none of them directly addressed the weak integration hypothesis or the sub-cognitive processing hypothesis. Nevertheless, due to the high heterogeneity of blind people and the lack of direct personal contact to some of the members of the group, the open-ended questions are more extensive and allow a more comprising understanding for the individual and their development. For further information see Brandebusemeyer (2020) and Bordasch (2020).

3.2.1 Individual evaluation

Participant 1

Possible restrictions induced by the belt are subcategorized into constraints of the everyday life, impacts on the quality of sleep and changes of the health status. Participant 1 reported a good to particularly good health status throughout the seven weeks of the study with a value on the Likert-scale ranging from 4 to 5. Moreover, the quality of sleep remained on a constant good level with an average rating of 3.8. Regarding the restrictions of the belt in everyday life, Participant 1 averagely rated the belt as slightly restricting with a decrease in the second half of the study and final assessment of "Partly true". Thus, neither the health nor the sleep was negatively impacted by the belt. Nevertheless, he considered the usage experience as slightly restricting.

In week one, three out of seven statements concerning enhanced orientational abilities when wearing the belt (*Figure 54*) are rated as "Rather true" or higher, indicating that Participant 1 directly benefitted from the belt. For example, in the preliminary questionnaire he assessed

problems with detecting to walk an elongated curve as “Moderately true”, whereas in week one of the weekly questionnaire, he noted improvements in detecting a curve with the belt. Another example that further elucidates the advantage that the belt constituted for Participant 1 is evident in his exploration behaviour of foreign environment. While only moderately agreeing to explore new environment in the preliminary questionnaire, in the final questionnaire he explicitly emphasizes that the belt enabled him to further explore new surroundings. Yet, a motivational dip is observable around week 3, which is congruent with his statement during the second measurements (*Figure 54*). Participant 1 stated that he did not realize the real added value of the belt until just before the experiment. A complicated crossing and a forest path posed serious difficulties upon him when not supplied with the belt. When he tried the path with the belt, he felt more secure and this key moment led to a further increase in the self-assessed enhancement of orientational abilities induced by the belt. This is also evident in the final questionnaire where all statements concerned with orientational abilities are rated 3 or higher. Thus, the assessment of the improvement through the belt are rather high from begin on and after the key moment until the end of the training period the rating of three statements increased and the ratings of the other statements remained as high as in the first week, pointing towards weak integration.

Figure 54: Averaged Likert-scale rating and the linear trend line during the study for all questions concerned with subjective improvement of orientational abilities due to the belt of Participant 1: The rating increased throughout the study.

Participant 1 rated the statement “I consciously concentrate on the belt to navigate better” as “Moderately true” at week one (*Figure 55*). This remains until week seven except for week five, where the rating increased to “Rather true”. The statement No. 16.2 constantly varies between “Partly true” or “Not true” throughout the study (*Figure 55*). Nonetheless, in the final questionnaire he rates the statement “Due to the belt I have to concentrate less while orienting” as “Moderately true”. Hence, the overall results of the questionnaires do not deliver support for the sub-cognitive processing hypothesis.

Figure 55: Likert-scale rating of the statements concerned with the use of attentional resources when navigating with the belt throughout the study of Participant 1: The rating remains rather constant.

To conclude, his self-assessment supports the weak integration hypothesis but does not yield underpinning for the sub-cognitive integration hypothesis. This is only partly congruent with the experimental findings of Participant 1, since his results of the straight-line-walking task supports the sub-cognitive processing hypothesis.

Participant 2

Participant 2 stated a particularly good health status throughout the seven weeks of the study. Besides, the rating of the quality of sleep constantly varied between a good and a particularly good level with an average rating of 4.57. Furthermore Participant 2 denied any restriction of the belt in the everyday life throughout the study. Hence, neither the health nor the sleep or his everyday life was negatively impacted by the belt.

Four out of seven statements addressing the self-assessment of the improvement of orientational abilities (Figure 56) are rated four or higher during week one, pointing towards a direct benefit obtained through the belt. Particularly, Participant 2 strongly denied any problems with detecting to walk an elongated curve in the preliminary questionnaire. Yet, in the first weekly questionnaire he strongly agreed that the belt helps him to detect an elongated curve, indicating that he was previously not as aware of walking an elongated curve as the belt allowed him to be. In the process of familiarization with the belt, minor variations in the ratings are observable. Moreover, a particularity in week 4 is apparent (Figure 56), where Participant 2 labelled three statements as “Not true”, even though ranking them previously and afterwards significantly higher. These outliers are neither explained in the diary section nor in direct communication, where he emphasized the support that the belt yields. Nonetheless, at the end of the study, the ratings improved in comparison to the first week in four out of the seven questions and three ratings remained as high as in the beginning. Additionally, in the final questionnaire he strongly agreed with every statement concerning improved orientational abilities due to the belt.

Figure 56: Averaged Likert-scale rating and the linear trend line during the study for all questions concerned with subjective improvement of orientational abilities due to the belt of Participant 2: The rating is high from begin on and a slight increase during the study is obtained, with a dip in week four (orange circle).

Throughout the study, he ranked the statement No 16.1 as three or higher (*Figure 57*). When asked to assess statement 16.2, Participant 2 labelled it as “Rather true”, with an increase to “Completely true” in the last week of the study. The self-assessment of increased ability to process various input when navigating with the belt delivers support for the sub-cognitive processing hypothesis (*Figure 57*) and is further underpinned in the final questionnaire, where he agreed that due to the belt he needed to concentrate less when orienting.

Figure 57: Likert-scale rating of the statements concerned with the use of attentional resources when navigating with the belt throughout the study of Participant 2: The rating varies slightly throughout the study, but the first and last rating do not differ remarkably (orange circles).

To conclude, the questionnaires of Participant 2 deliver support for the weak integration hypothesis and contradicting results regarding sub-cognitive processing. This is congruent with the experimental findings, where the weak integration hypothesis finds substantiation and mixed results regarding the sub-cognitive processing hypothesis were obtained.

Participant 3

The health status as well the quality of sleep of Participant 3 ranks on the constant particularly good level with an average rating of five. During week one, the statement “The belt restricted me in my everyday life” was estimated as “Partly true”, yet from week two on until the end of the study, the statement was labelled “Not true”. These ratings indicate that the belt did not affect Participant 3 negatively.

During the first week, two out of seven statements concerning the orientational skills (Figure 58) when provided with the belt are rated four or higher. Even though in a minor manner, Participant 3 directly benefitted from the belt. E.g. in the preliminary study, he mentioned problems with detecting an elongated curve and in the first weekly questionnaire he strongly agrees that the belt helps him with that task. Constant low ratings are notable, when asked about improvement in his sense of direction and his knowledge of his position in relation to his home. In contrast, improvements are observable in the questions concerned with setting streets into relation to one another or navigating in foreign surroundings. Nonetheless, the overall changes during the studies remain minor (see Figure 58). Moreover, he rated all statements concerning improved orientational abilities through the belt in the final questionnaires four or higher, except the statement “My sense of direction improved due to the belt”, with which he only partly agrees. Thus, the self-stated direct improvement in orientational tasks caused by the belt underpin the weak integration hypothesis.

Figure 58: Averaged Likert-scale rating and the linear trend line during the study for all questions concerned with subjective improvement of orientational abilities through the belt of Participant 3: The rating is slightly below average and remains constant throughout the study.

Concerning the attentional resources used during navigation (Figure 59), Participant 3 constantly rated it as “Rather true”, that he consciously concentrated on the belt during navigation. Furthermore, he evaluated his ability to process various inputs when navigating and provided with the belt as “Partly true”. These findings do not support the sub-cognitive processing hypothesis, as is also evident in the final questionnaire, where Participant 3 rated the statement “Due to the belt I have to concentrate less while orienting” as only “Partly true”.

Figure 59: Likert-scale rating of the statements concerned with the use of attentional resources when navigating with the belt throughout the study of Participant 3: The rating remains constant throughout the study.

In summary, the self-assessment of Participant 3 is only partly compatible with the experimental results, since the results of the experiments with Participant 3 support the weak integration and the sub-cognitive processing hypothesis, while the questionnaires do not support the latter.

Participant 4

Restrictions of health or sleep related nature caused by the belt are not observable in Participant 4. He constantly rated both, his health and his quality of sleep as particularly good. Furthermore, he strongly denied any limitations in his everyday life induced by the belt during the entire study.

As is evident in the set of questions concerned with orientation (*Figure 60*), Participant 4 directly profited from the belt. All statements are rated “Moderately true” or better, and four out of the seven statements are rated “Rather true” or better. One of them is the statement “It is difficult to detect that I walk an elongated curve”. While strongly agreeing that this poses difficulties upon him in the preliminary questionnaire, he strongly agrees already in the first week that the belt helps him in the situation. Besides, in four statements an increase in ratings is observable and in two statements, the highest rating remained throughout the study. A minor decrease in assessment is apparent in the agreement with the statement “With belt, I am always conscious about where I am in relation to my home”. Furthermore, the final questionnaire shows strong agreement with every statement concerned with enhancement in orientation caused by the belt, supporting the weak integration hypothesis.

Figure 60: Averaged Likert-scale rating and the trend line during the study for all questions concerned with subjective improvement of orientational abilities through the belt of Participant 4: The rating is high from begin on and slightly increase during the study.

Participant 4 states it as only “Partly true” at the beginning of the study that he needs conscious concentration to benefit from the belt. In week three, four and five this drops to “Not true”. In the last week this is evaluated as “Partly true”, pointing towards sub-cognitive processing (*Figure 61*). In the beginning, he congruently strongly agrees that with belt, various inputs are easier to process when navigating with the belt. From week four on, the agreement decreases with a sudden major reduction to strong disagreement in the last week of study (*Figure 61*). This is contradictory to his final evaluation where he strongly agrees with the statement “Due to the belt I have to concentrate less while orienting”.

Figure 61: Likert-scale rating of the statements concerned with the use of attentional resources when navigating with the belt throughout the study of Participant 4: While the assessment of conscious concentration on the belt varies only slightly, the evaluation of facilitated processing of various input when navigating heavily decreases during the course of the study (see first and last rating, circled orange).

Hence, Participant 4 assessed the advantages of the belt compatibly with his experimental results: He instantly benefitted from the belt during the experiments, as well directly evaluating the belt as helpful, which supports the weak integration hypothesis. Additionally, he shows mixed results regarding the sub-cognitive processing hypothesis in both experiments and questionnaires.

Participant 5

No negative impact of the belt on health or sleep is evident in Participant 5, as both is constantly rated 4 or higher. The restriction that the belt posed upon her everyday life is assessed as rather minor, since the evaluation constantly varies between “Partly true” and “Not true”.

Participant 5 immediately benefitted from the belt, since all statements concerned with enhanced orientational abilities (Figure 62) are considered “Moderately true” or higher and five statements are rated “Rather true” or higher. Like Participant 4, she stated that she faced problems with detecting an elongated curve before the study. In the first weekly questionnaire, she agreed that the belt helped to detect curves, exemplifying the immediate benefit that the belt represents to her. During the study only minor variations in the ratings occur, nevertheless an ascending tendency is evident. In the final week, one ranking slightly decreases, whereas two assessments remained the same and three slightly increased. The ascending tendency with increased exposure time is also apparent in the final questionnaire. One out of five statements concerned with improved orientational abilities is rated as “Rather true” and the other four statements are rated “Completely true”. Overall, Participant 5 self-stated that she benefitted both directly and in the long run from the belt when performing orientational tasks.

Figure 62: Averaged Likert-scale rating and the trend line during the study for all questions concerned with subjective improvement of orientational abilities through the belt of Participant 5: The rating is high from begin on and remain rather constant during the seven weeks.

Concerning the substantiation of the sub-cognitive processing hypothesis, the self-assessment of Participant 5 is rather vague (Figure 63). On the one hand, an increase of agreement with the statement that with belt other inputs are processed more easily when navigating with the belt with a peak rating in week six as “Completely true” and a final rating as “Rather true” is obtained. Moreover, she agreed that the belt enabled her to concentrate less while orienting. On the other hand, she strongly agrees throughout the study that she must consciously concentrate on the belt to benefit from the directional information in an orientational task.

Figure 63: Likert-scale rating of the statements concerned with the use of attentional resources when navigating with the belt throughout the study of Participant 5: The rating of both statements are rather high from begin on and after some variations slightly increase at the end of the study. Since both statements are formulated such that high values correlate to either support or opposition of the sub-cognitive processing hypothesis, the results are contradictive.

Thus, the results of the survey further back the findings from the experiment: Strong support for the weak integration hypothesis and vague results concerning the sub-cognitive processing hypothesis.

3.2.2 Group evaluation

When filtered by the self-rated north-alignment of the inner map or by congenital or adventitious blindness, no remarkable differences in the evaluation are detectable. Hence, the group is evaluated altogether. This indicates that the subjective perception of improvement in orientational abilities as well as the subjective use of attentional resources is neither affected by a north-aligned map nor the moment of blindness.

The health status is assessed as high throughout the study with a rather constant Likert-scale mean value of 4.72 during the seven weeks. Similarly, the quality of sleep is evaluated as good in the course of the entire study. The average rating throughout the study is 4.45 or higher. Furthermore, the restrictions on the everyday life induced by wearing the belt is rated low from week one on with an average Likert-scale value of 1.81. After minor variation from week two to week five, the evaluation stabilizes at an average rating of 1.36 at week six and week seven. Besides, no significant changes are observable in the assessment of possible restrictions of logistic, health or sleep related nature induced by the belt. Consequentially, the belt affected neither the health status, nor the quality of sleep nor the everyday life negatively at no point in time.

During the first week the statement “With belt I am always conscious where I am in relation to my home” (*Figure 64*) is averagely rated 3.54, indicating that the group directly benefits from the belt in performing this task. Throughout the study, minor variations are observable, none of which reach significance. Thus, in regard to one’s allocation in respect to home, the group reports a direct improvement but do not exhibit characteristics of long-term enhancement.

When asked to evaluate if it is easier to orient in foreign surroundings when supplied with the belt (*Figure 65*), moderate agreement is apparent in week one. The average rating of 3.18 from week one increases as the survey goes along and peaks at the final week with 3.81. The difference between week one and week seven is close to significance ($p = 0.0625$). An instant benefit from wearing the belt in foreign surroundings is evident together with an improvement induced by further familiarization with the belt. Potential reasons for the enhancement through time, is that in order to explore foreign surroundings with the belt requires trust in the belt signal which tasks time to build. Another aspect playing a part is the SARS-CoV-2 pandemic, which might have reduced the possibilities in which the subjects found time, as well as comfort to explore new environments.

Improvement in setting different locations into relation (*Figure 66*) with one another when wearing the belt is detectable from week one on. The average rating at the begin of the study mounts up to 3.72 and increases over the course of the study to 4.09. Hence, wearing the belt yields instant subjective support when setting different locations into relation.

A similar, yet not identical task, yields comparable results. When asked to assess if the belt supports the ability to estimate the relation of two streets to one another (*Figure 67*), the average rating in week one amounts to 3.9. This rating slightly increases from week four on and stabilizes from week five on at the average Likert-scale value 4.27. None of the weekly changes reach significance. Thus, the participants experience immediate improvement as well as minor long-term improvement.

Figure 64-67: The mean rating is depicted with the red dotted line and the median with the red solid line. The bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross.

Figure 64: The ratings are high from begin on and slightly decrease in the course of the study.

Figure 65: The ratings are moderate at begin but increase during the study.

Figure 66: The ratings are rather high from begin on and slightly increase. A dip in week four is obtained (orange).

Figure 67: The ratings are high from begin on and slightly increase during the seven weeks.

The statement “With belt it is easier to detect that I walk an elongated curve” (Figure 69) is the only statement that is evaluated not only in the preliminary questionnaire, but also in the final questionnaire and registered the strongest agreement among statements concerned with subjective enhancement of orientational abilities through the belt (Figure 70). The average rating in week one amounts to 4.63 and after various minor changes during the survey that do not reach significance, the final rating is 4.54. Thus, strong immediate subjective improvement through the belt is observable when asked to note an elongated curve. Strikingly, the statement “I face difficulties to detect that I walk an elongated curve” (Figure 68) from the preliminary questionnaire registered an average of 3.63, only slightly above moderate agreement. Potentially the awareness of walking an elongated curve was previously not as present and the experience with the belt furthered the perception of it.

Figure 68 – 69: The mean rating is depicted with a red cross and the median rating with a red solid line. The bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross.

Figure 68: The rating of the preliminary questionnaire is moderately high.

Figure 69: The rating in the final questionnaire is high, indicating that the belt helps to solve the problem of detecting an elongated curve.

Figure 70: The mean rating is depicted with a red dotted line and the median rating with a red solid line. The ratings slightly vary throughout the study but are overall very high.

The group average moderately agrees that the sense of direction improved subjectively (Figure 71) since wearing the belt in the first weekly questionnaire. This slightly varies during the study and peaks in the final week at 3.45.

Lastly, the group was asked to evaluate if their sense of direction worsens when removing the belt (Figure 72). Here, the rating is rather low from begin on. The average rating in week one is 2.18 and only gradually increases with the final rating being 2.45, which ranks between “Partly true” and “Moderately true”. Hence, the results possibly indicate that the slight improvement in the sense of direction is not necessarily bound by the belt but allows for improvement also without the belt.

Figure 71-72: The mean rating is depicted with the red dotted line and the median with the red solid line. The bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross.

Figure 71: The ratings improve especially in the last two weeks. The deviation within the group decreases in those last weeks (orange).

Figure 72: The ratings slightly improve throughout the study, while the deviation within the group remains rather constant.

Since the prerequisite for weak integration consists of improvement in some behavioural tasks, the positive self-assessment in the weekly questionnaire regarding possible orientational enhancement due to the belt, supports the weak integration hypothesis.

Further support for the weak integration hypothesis is apparent in the final questionnaire. With a mean rating of 3.25 the participants agree on average moderately with an improvement in their sense of direction (Figure 73). Clearer agreement is evident with the statement “The belt helped me while orienting” (Figure 74), which is averagely estimated as 4.17. More support is apparent in the agreement to the statement “The belt is a good complement to my other orientation strategies” (Figure 75), which is averagely rated as “Rather true”. Thus, the subjective reports of improved orientational abilities yields support for the weak integration hypothesis.

Figure 73-75: The mean rating is depicted with the red cross and the median with the red solid line. The bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross.

Figure 73: The mean ratings are moderately high. The ratings highly vary within the group.

Figure 74: The mean ratings are high and the variation within the group is moderate.

Figure 75: The mean ratings are high and the variation within the group is moderate.

The statement concerning the sub-cognitive processing hypothesis yields comparably vague results. The statement that conscious concentration on the belt is necessary to benefit from the belt (Figure 76) in the first weekly questionnaire is averagely rated with 3.55 in the first week. After a small increase in agreement from week one to week two, the agreement decreases significantly ($p = 0.00313$) to week three. During the study, further variations are apparent, nevertheless a descending tendency is evident, resulting in a final mean rating of 3, corresponding to moderate agreement. Stronger agreement is evident in the final questionnaire. When asked to evaluate in the final questionnaire if one has to concentrate less while orienting (Figure 78) when supplied with the belt, the mean rating mounts up to 3.66. Furthermore, the ability to process various inputs when navigating and provided with the belt (Figure 77) was assessed as slightly above as "Partly true" in the first week of the study. This varies throughout the study with an increase up to 3.1 and the final rating of 2.63.

Thus, the support of the self-assessment for the sub-cognitive processing hypothesis remains comparatively vague. It must be emphasized that estimating the usage of attentional resources is first to be mentioned difficult and second highly subjective.

Figure 76-77: The mean rating is depicted with the red dotted line and the median with the red solid line. The bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross.

Figure 76: The mean rating from week two on decrease (compare week two and seven, marked orange).

Figure 77: The mean rating varies between 2 and 3 throughout the study.

Figure 78: The mean rating is depicted with the red cross and the median with the red solid line. The bottom edge of the box marks the 25th percentile and the top edge marks the 75th percentile. The whiskers extend to the more extreme data points not regarded outliers and the outliers are plotted through the red cross. The mean rating is moderately high and the variations within the group is high.

3.2.3 Deaf-blind participants

Both participants rated their health status as well as their quality of sleep as high throughout the study. Furthermore, the belt did not restrict them in their everyday whatsoever.

Concerning the self-assessment of the orientational abilities, both experience an improvement. Especially strong agreement in both participants is evident in the statement “With belt I am always conscious where I am in relation to my home”. When asked to evaluate the improvement induced by the belt when setting places or streets into relation, only one of the two participants confirms such improvement, while the other only slightly agrees. The assessment of detecting an elongated curve shows strong parallels to the results of the blind participants. Even though only moderately agreeing that they had problems to detect an elongated curve in the preliminary questionnaire, later in the study they strongly agreed that the belt helps to realize a deviation of a straight course.

Concerning the sub-cognitive processing hypothesis, no support is evident in the answers of the deaf-blind participants. Neither easier processing of other inputs while navigating with the belt nor less conscious concentration on the belt is reported throughout the study. This might be attributable to the fact that when orienting it is always a moment of peak concentration. With understanding and further implementing the signal into behaviour, even more focus is needed. Another possibility is that the belt was worn for a too short period of time in order for the underlying SMCs to be learned.

Yet, the communication with the participants and especially the open-ended questions show the immediate subjective great improvement in mobility and orientation for deaf-blind, as is evident from this quote from one deaf-blind participant : “The naviBelt is really a great thing. A few years ago, it was unthinkable like science fiction and now it is reality. A great aid for the deaf-blind! Incredibly very important orientation and mobility device for deaf-blind people – indispensable.” („Der Navigürtel ist wirklich eine tolle Sache. Noch vor ein paar Jahren ist das unvorstellbar gewesen, wie Science fiction und jetzt ist es Realität. Tolle Unterstützung für die Taubblinden! Unheimlich sehr wichtiges Orientierungs- und Mobilitätssystem für Taubblinde – unverzichtbar!“). Furthermore, the same participant states increased orientation in his own home and a building inner map of his surroundings. The other deaf-blind participant states a huge extension of his hiking tracks and the further independence from the signposts of his accompanying person. Another scenario in which he experiences improvement is in rectilinearly aligned shops, which were a “huge labyrinth” to him beforehand. The enthusiasm for the belt led him to weekly also delivering a protocol of the different routes he used the belt with and how the belt helped him in this specific route.

To sum up, even though no objective data with the deaf-blind participants were obtained, the subjective data highly supports the weak integration hypothesis and does not yield underpinning for the sub-cognitive processing hypothesis. The open-ended questions show the personal value the belt depicted for the participants and the need for further objective investigation in the scope of a more comprising study with respect to deaf-blind participants.

4. Discussion

Ensuing the theoretical framework of SMC, this study investigated the weak integration hypothesis and the sub-cognitive processing hypothesis. A group of eleven blind participants was provided with a vibrotactile directional signal of the magnetic north for seven weeks. Behavioural changes in a subgroup of five participants were assessed through behavioural tasks and the self-assessment of all participants of their subjective changes in orientational abilities and usage of attentional mechanisms when navigating with the belt was evaluated with questionnaires. Additionally, two deaf-blind participants took part in the survey and were supplied with the belt for a period of four weeks.

With regard to the behavioural task: The performance in the straight-line-walking task improved already on the first day for all five participants, when fully attending to the belts signal. After the training period, three out of the five participants exhibit characteristic behaviour of the sub-cognitive processing hypothesis and the benefit of the belt is not reduced by an additional distraction task. In an angular rotation task, only two participants directly experience benefits induced by the belt. Remarkably, four participants estimate the angular rotation increasingly precise after the training period, whether supplied with the belt or not. Particularly the extent of the improvement of the congenital blind participant needs highlighting. The setting of a triangle completion task poses difficulties upon all participants. Yet, two participants instantly benefitted from the belt in the modified homing task, one of them benefitted from the belt even when distracted. Furthermore, after the training four participants show increased precision in the location estimation and two of them also with an additional cognitive load. Yet, in one participant the precision increases only slightly. The improved performances in those behavioural tasks point towards improved spatial learning, path integration, path stabilization, and the successful implementation of the belt signal.

The concomitantly conducted preliminary, weekly, and final questionnaires further underpin the observation in the behavioural tasks. The group overall agrees that through the belt their orientational abilities improved in various areas, comprising egocentric and allocentric reference frames. For a more detailed analysis of the changes in the respective reference frame, see Brandebusemeyer (2020). Concerning the sub-cognitive processing hypothesis, rather vague results are obtained, hinting towards high interindividual differences. This is similar to the experimental findings of the behavioural tasks.

Can the obtained results account for the weak integration hypothesis or the sub-cognitive processing hypothesis? And if so, to what extent? In the following, the experimental findings will be related to the hypotheses.

Weak integration hypothesis: Various results support the hypothesis that the vibrotactile directional information supplied by the belt signal could be integrated in a goal-directed manner and improved performance in “some behavioural tasks” (Nagel et al., 2005). Following the general formulation of the weak integration hypothesis when first developed by Nagel et al. (2005), every behavioural test fulfils those prerequisites. In the straight-line-walking task direct improvement is evident and in the triangle completion task as well as in the angular rotation task improved performance with belt is obtained, even though the majority of participants solely benefitted from the belt after the training. This is especially evident in Participant 2, the only congenital participants among those participating in the behavioural tests. Since he never

visually explored angular rotations and small-scale navigation and was not cognitively grounded, extensive training and exposition to the belt was necessary to ensure the implementation of the belt signal in behaviour. Yet, Kärcher et al. (2012) deploys a more time-bound interpretation of the weak integration hypothesis, presupposing a more immediate improvement in performance when using the belt. Since only two measurements with a temporal difference of four to six weeks were conducted, it is not known when in the course of the study the belt improved performance in those tasks and if this instant in time can be considered immediate or direct. Thus, depending on the definition, the support of the weak integration hypothesis through the experimental findings is either strongly given in every behavioural task or in varying degrees in every behavioural task. Following the time-bound definition, the straight-line-walking task would yield strong support whereas the angular rotation task and the triangle completion task only yields weak support. Furthermore, the subjective assessment of orientational abilities are indicative of the weak integration, since from begin on an enhancement in abilities due to the belt is reported. Additionally, during the study those ratings further improve, pointing towards enhanced spatial learning.

Sub-cognitive processing hypothesis: The results in both the behavioural tasks as well as in the subjective methods remain rather vague. In the two behavioural tasks addressing the sub-cognitive processing hypothesis, only two participants of the five participants showed characteristics of sub-cognitive processing after the training period. Additionally, Participant 4 faced serious issues during the second experiment leading to discontent and low motivation rendering the expressiveness of his results after the training vague. A potential explanation for the lack of support for the sub-cognitive processing hypothesis in the triangle completion task of Participant 3 can be found in the final questionnaire. There, he elaborates on his integration of the belt into his orientation strategies. During the study period he developed a clear hierarchy of orientational aids, and the belt ranks third after the cane in combination with acoustic cues and the condition of the floor. Furthermore, in demanding situations he disregards the signal because according to his self-statement, the cane and acoustic cues are neglected when focusing on the belt. This integration into perception and the clear assignment of a specific priority in his orientational system might have affected the performance in the triangle completion task, which can be categorized as a demanding task. Since in demanding tasks he habituated to rely on different strategies than the directional information of the belt, the performance in a triangle completion task with belt deteriorated after the training period.

When the entire group of 11 participants asked to self-assess the usage of attentional resources - a difficult and highly subjective endeavour - the results vary between slight support and slight opposition.

In regards of the effect of cognitive grounding onto the implementation of the belt signal into behaviour, only a vague tendency is obtained. In the angular rotation task, the participants claiming to have a north-aligned inner map profited more than the other participants from the directional information of the belt. Since this study did not conduct comprising individual interviews assessing the orientational strategies of the participant like Kärcher et al. (2012), the reliability of the self-assessed north-alignment inner map is questionable. This is also evident in the present study. Participant 2 ascribed himself an inner two-dimensional map of his surrounding in the beginning of the study. After being trained with the belt, he denies having such inner map, exemplifying the difficulties to self-assess ones orientational frameworks.

Furthermore, it has to be asked, if the inner map has to be necessarily north-aligned to facilitate implementation or if a two dimensional inner map suffices for such facilitation.

Concerning the differences between congenital and adventitiously blinds, the results of the current study only reveal significant differences in the angular rotation task. A potential explanation is the lack of visual exploration and cognitive grounding in respect to angular rotations. To further solidify this evidence and to further investigate the potential differences, behavioural test with a larger group of both congenital and adventitiously blind people need to be conducted.

To ensure further clarity between agreement and disagreement with the sub-cognitive processing hypothesis, as well as to further specify the extent of support for the weak integration hypothesis, possible alterations of the study design need to be reflected.

4.1 Reflections on the study design

The weak integration hypothesis is currently formulated in a general manner, such that it is not specified, if the improvement in behavioural tasks require a particular time frame. To resolve the issue, a more precise definition would need to be formed, best in dialogue with Kärcher and Nagel. Such precise definition would thus allow for more precise testing, with e.g. a battery of tests in a fixed interval further pinpointing the momentum of enhanced performance. Through EEG recordings as conducted by König et al. (2016), evidence for procedural learning can be found and set into relation with the results of the behavioural tests. Nevertheless, it should not be underestimated that the experimental setting is a stressful situation for the blind participants. As reported by Kärcher et al. (2012), the participant perceived the experiment as a test of his orientational and navigational abilities and not a test of the belt, which affected the performance as well as the framework of the experiment. Comparable patterns could be observed in the current study with Participant 4 and Participant 5. Another possible way to further elucidate the benefit of the belt in behavioural tasks would be to modify the set-up of the straight-line-walking task. A shorter route as well as a wider grid would be beneficial, since numerous trials needed to be aborted because the participant crossed the most exterior line of the grid. We hypothesize that with this modification the reported improvement in performance would be even more pronounced. Furthermore, it would be of interest to change the alignment of the grid. In our experiments the grid was aligned to the north-south direction. Thus, the belt signal was always placed directly on the back. Yet another modification in the study design which might be favourable is a fixed training plan for the participants based on the approach of Kärcher et al. (2012). Here, specific tasks were repeatedly trained to ensure a continuous and diverse involvement with the belt in tasks addressing allocentric as well as egocentric reference frames. This ensures active exploration of the signal, which is a prerequisite for the integration of the signal according to SMC theory. In the current study no such training schedule was feasible due to the SARS-CoV-2 pandemic. This might account for interindividual differences in both, questionnaires and experiments and for the lack of improvement in some participants. To further substantiate the already existing support (Bach-y-Rita, 2004; Bach-y-Rita et al., 2003) for the hypothesis that active exploration is needed for the integration of the signal, it would be of great importance to replicate this study with a control group, which does not actively explore the belt, as prompted by König et al. (2016).

In order to give further and more expressive evidence for the sub-cognitive processing hypothesis, physiological tests need to be employed, such as posturography and

nystagmography, as conducted by Nagel et al (2005). Both physiological tests were designed to “minimize the effect of attention and high-level cognitive reasoning” (Nagel et al., 2005, p. 24) and yielded support for the sub-cognitive processing hypothesis. By replicating this set-up with a larger group of participants, the possible substantiation of the sub-cognitive processing hypothesis would be of stronger expressiveness than the current experimental results and the evaluation of the subjective methods.

Nevertheless, also the subjective methods are of importance and expressiveness, allowing a more comprising understanding and a more holistic picture of the participants and their experience. A method allowing to objectively analyse and generalize the open-ended questions is employed by Kaspar et al. (2014). Through a newly developed category system the qualitative data could be quantitatively captured, grouped and subsequently frequency statistics could be applied. This approach would also be beneficial for the current study.

The last parameter of the study which could be subject to modification is the length of the study. Even though the currently used study period of seven weeks has been successfully tested (Kaspar et al., 2014, König et al., 2016), other studies yielded evidence for changes in perception and benefits of a sensory substitution device even after six months of wearing time. Wade et al. (2005) observed a deeper integration and fully automated processing of the sensory substitution device for colour blindness. Furthermore, even after several years of usage, perceptual changes can be observed as shown by Ward and Meijer (2010), when investigating an auditory-to-vision substitution device with late-blind participants. With a longer period of study, the possible extent of enhanced performance as well as the level of integration could be further investigated.

Again, the previously mentioned aspect of demand on the participants require consideration here. Implementing all suggested modifications to the study design would probably depict a too large demand for the participants. Additionally, the feasibility with a larger group is questionable. But since a larger and diverse group of blind people is desirable to ensure generalizability, one arrives at a trade-off between additional experimental load and strain on the participants. A trade-off, whose bliss point is yet to be found.

In summary, the current study strongly points towards weak integration and weakly supports the sub-cognitive processing hypothesis. By adjusting the study design in the proposed manner, a largescale study could further explore the hypotheses in detail and yield further evidence for the SMC theory.

4.2 SMC theory and assistive sensory augmentation devices

This study was inspired by the four hypotheses of integration of a sensory augmentation device by Nagel et al. (2005), based upon the SMC theory. As distinguished from the current study, Nagel investigated all four hypotheses and found strong support for the weak integration hypothesis, the sub-cognitive integration hypothesis, and weak support for the new modality theory. The foundation for the new modality hypothesis resulted from the line of thought that completely new SMCs can be learned and, if mastered, form a new modality resulting in changes in perception. Even though changes in perception were reported in two out of four participants, Nagel et al. (2005) discussed some limitations to the success of implementing a new modality. The obtained changes in perception can be considered rather an alteration of the meta-modality of spatial perception than a new modality. Since the participants were able to infer spatial information from the belt, then combine it with the pre-existing modalities crucial

for spatial information such as vision, audition and the somatosensory system, they rather modified the meta-modality spatial perception than formed a new modality.

It is possible that for the endeavour to implement a new modality through sensory augmentation a critical period in development exists. The theory of the critical period suggests that brain plasticity is confined to a specific time frame in development early in life (Hensch, 2005). A specific time frame for compensatory brain plasticity was found for blind subjects before adolescence, with a differing time frame for congenitally blind, early-blind, and late-blind participants (Sadato et al., 2002, Röder et al., 2004). As suggested by König et al. (2016), training participants who are currently in the critical period for brain plasticity with a sensory augmentation device could yield more pronounced results. Considering that the participant in this study as well as in the study from Nagel et al. (2005) are all adults, it is even more remarkable that nevertheless perceptual changes and evidence of sub-cognitive processing can be observed.

Yet, for sensory augmentation devices, in our case the naviBelt, it would be beneficial if it would permit fast integration, regardless whether the participant finds himself in the critical period of brain plasticity or not. This problem is addressed by Schumann & O'Regan (2012). They developed a sensory augmentation device named hearSpace, consistent of headphones with integrated compass. The headphones are coupled to the hearSpace app, which samples the current direction and transforms the alignment into distal sounds of a waterfall based on generic head-related transfer function. Just like with the naviBelt, the sound source of hearSpace signals the magnetic north. Schumann and O'Regan argue that many sensory augmentation devices rely on “comparatively low-level tactile signal coding [...] which do not provide the haptic profiles of natural tactile stimulation” (Schumann & O'Regan, 2012, p. 9). HearSpace in turn follows a turning scheme which imitates already existing SMCs of audition, which allows for fast integration even in adult age. They further argue that the signal of hearSpace finds an “entry point to interface with sensory processes that are already in place” (Schumann & O'Regan, 2012, p. 1). This is in line with the SMC theory, since hearSpace does not rely on building new SMCs but piggybacks on already manifested SMCs, circumventing the potential problem of critical phases of brain plasticity. Furthermore, using audition allows for a very continuous signal which is closer to genuine sensory perception. The naviBelt in turn allows for a latitude of 22.5° per module, somewhat lacking the continuity of a genuine perceptual experience.

Yet, it must be noted that the naviBelt in its applied form as an aiding device for the blind does not necessarily intend to form a new modality but provides support in orientational and navigational tasks for visually deprived and blind people. Therefore, the size of a module is designed, aiming to balance the trade-off between precision and cognitive demand (Cholewiak et al., 2004). This study further underpins that feelSpace succeeds in that objective by showing path stabilization and enhanced orientational abilities in allocentric and egocentric reference frames due to the belt. Another huge advantage of the naviBelt compared to hearSpace is that audition is not affected by the belt, which is of huge importance for the navigational strategies of blind people. This shows that even though fast integration is desirable, devices with the fastest integration or the strongest perceptual change induced are not necessarily the most helpful when it comes to application. Also, examining existing strategies to cope with the lack or deprivation of a sensory modality as well as the reality of life of the recipient is of indispensable importance for assistive devices. In summary, the present study supports the SMC theory and further elucidates the trade-off between the aim of firm integration of sensory

augmentation devices and the practicability and feasibility of such as assistive device for the blind.

4.3 Future prospects

As distinguished from other studies, the current study investigates the changes induced by the naviBelt on a larger group of blind people with highly varying medical histories and orientational strategies. A further novelty is the investigation of the effect of the belt on deaf-blind participants. The feedback highly encourages a further, more comprising and systematic investigation of benefits of the belt for deaf-blind participants, as well as the continuation of this line of study with blind participants. In that manner, the questions that remain open for debate after this study could be further investigated, e.g. the differences between congenital and adventitiously blind people and the effect of cognitive grounding onto integration of the belt. Moreover, this study shows the value of incorporating both, quantitative data of behavioural tasks and first-person qualitative data, by proposing an extended version of a successfully tested experimental set-up (Kärcher et al., 2012). This set-up allowed to give a more holistic picture of the experience with the belt and the implementation into behaviour. Furthermore, it exemplified the potential of sensory augmentation as an assistive device for the handicapped allowing to provide information without entirely relying on attentional mechanism. Those advantages are not only objectively measured but also subjectively reported in this study: “The belt is really an indispensable device for blind people!” (“Der Gürtel ist für Blinde wirklich unverzichtbar!”). These words of our participants show the enormous potential of continuous scientific work and application going hand in hand.

5. Conclusion

To conclude, the current study yields evidence that when provided with vibrotactile directional information around the waist for a period of seven weeks, enhanced orientational abilities in congenitally and adventitiously blind participants are obtained. This enhancement is evident in various tasks and only partly relies on attentional mechanisms. The combination of both, qualitative and quantitative data, revealed itself to be particularly valuable. By examining the experience and the performance with the sensory augmentation device, two crucial criteria for assistive technologies could be evaluated.

The results support the weak integration hypothesis and point towards the sub-cognitive processing hypothesis, which is coherent with the SMC theory. With a modified set-up in the suggested fashion (4.1 Reflections on the study design), the predictions of the SMC theory, e.g. that sensorimotor contingencies can be learned and mastered enabling a new modality to be established, could be further explored. Furthermore, the study bears support that despite not being in the critical period of brain plasticity, subjects can to a certain extent implement signals of sensory augmentation devices into behaviour. Thus, the findings of the current study are compossible with concepts of embodiment, emphasizing the bidirectional nature of action and perception. Nevertheless, scrutinizing the effects of the belt with participants in the critical period of brain plasticity would be of interest. Yet, ethical considerations would be necessary. Finally, the study at hand motivates ongoing research on the concepts of SMCs being constitutive of conscious perception as well as to further probe the numerous prospects of sensory augmentation to bear more advanced assistive technology for the handicapped. Particularly the positive feedback from the deaf-blind participants presents a promising starting point to investigate the potentialities of sensory augmentation.

6. Literature

- Abboud, S., Hanassy, S., Levy-Tzedek, S., Maidenbaum, S., Amedi, A. (2014). *EyeMusic: Introducing a visual colorful experience for the blind using auditory sensory substitution*. Restor Neurol Neurosci. 32, 247-257.
- Bach-y-Rita, P. (2004). *Tactile sensory substitution studies*. Annals of New York Academic Sciences. 1013, 83–91.
- Bach-y-Rita, P., Collins, C. C., Saunders, F. A., White, B., Scadden, L. (1969). *Vision substitution by tactile image projection*. Nature. 221, 963–964.
- Bach-y-Rita, P., Kercel S.W. (2003). *Sensory substitution and the human-machine interface*. Trends in cognitive sciences. 7(12), 541-546.
- Barsalou, L.W. (2008). *Grounded cognition*. Annu Rev Psychology 59, 617-645.
- Barsalou, L.W., Simmons, W.K., Barbey, A.K., Wilson, C.D. (2003). *Grounding conceptual knowledge in modality-specific systems*. TRENDS in cognitive Sciences 7(2), 84-91.
- Bordasch, M. (2020). *Experienced Benefits of Vibro-Tactile Navigation for the Blind*.
- Borojevic, S., Gvosdenovic, V. (2013). *Is attention necessary in perception?* Suvremena psihologija. 16 (2013), 2, 171-184.
- Brandebusemeyer, C. (2020). *The impact of the vibro-tactile sensory augmentation device “feelSpace belt” on spatial orientation and navigation of blind people*.
- Cholewiak, R., Brill, J., Schwab, A. (2004). *Vibrotactile localization on the abdomen: Effects of place and space*. Perception & psychophysics. 66, 970–987.
- Chrastil, E. R., Nicora, G. L., Huang, A. (2019). *Vision and proprioception make equal contributions to path integration in a novel homing task*. Cognition. 192, 103998.
- Crick, F., Koch, C. (1998). *Consciousness and neuroscience*. Cereb. Cortex. 8, 97–107.
- Decety, J., Grezes, J. (2006). *The power of simulation: imagining one’s own and other’s behavior*. Brain Res. 1079, 4–14.
- Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., Taub, E. (1995). *Increased cortical representation of the fingers of the left hand in string players*. Science. 270. 305–307.
- Fakin, A., Glavac, D., Hawlina, M. (2012). *Usher Syndrome* Zdravniški Vestnik 81, 133-139.
- Fildes, B. N., O’Loughlin, B. J., Bradshaw, J. L., & Ewens, W. J. (1984). *Human Orientation with Restricted Sensory Information: No Evidence for Magnetic Sensitivity*. Perception, 13(3), 229–248.
- Gazzaniga, M., Ivry, R. B., Mangun, G.R., (2019). *Cognitive Neuroscience – The biology of the mind*. Fifth Edition, New York: W.W. Norton & Company.
- Gibbs, R. W. Jr. (2006). *Embodiment and Cognitive Science*. New York: Cambridge Univ. Press.
- Glenberg, A.M. (1997). *What memory is for*. Behav. Brain Sci. 20, 1–55.
- Hensch, T. (2005). *Critical period plasticity in local cortical circuits*. Nat Rev Neurosci 6, 877–888.
- Hurley, S., Noë, A. (2003). *Neural plasticity and consciousness* Biol. Philos. 18, 131–168.
- Iachini, T., Ruggiero, G., Ruotolo, F. (2014). *Does blindness affect egocentric and allocentric frames of reference in small and large scale spaces?* Behavioral Brain Research, Volume 273.
- Kaas, J. H. (1991) *Plasticity of sensory and motor maps in adult mammals*. Annu. Rev. Neurosci. 14, 137–167.

- Kaspar, K., König, S., Schwandt, J., König, P. (2014). *The experience of new sensorimotor contingencies by sensory augmentation*. Consciousness and Cognition. 28, 47–63.
- Kärcher, S. M., Fenzlaff, S., Hartmann, D., Nagel, S.K., König, P. (2012). *Sensory augmentation for the blind*. Frontiers in Human Neuroscience. Volume 6. Artikel 37.
- König S.U., Schumann, F., Keyser, J., Goeke, C., Krause, C., Wache, S. et al. (2016). *Learning New Sensorimotor Contingencies: Effects of Long-Term Use of Sensory Augmentation on the Brain and Conscious Perception*. PLoS ONE 11(12): e0166647. doi:10.1371/journal.pone.0166647.
- Levy-Tzedek, S., Hanassy, S., Abboud, S., Maidenbaum, S., Amedi, A. (2012). *Fast, accurate reaching movements with a visual-to-auditory sensory substitution device*. Restor Neurol Neurosci. 30, 313-323.
- Mandal, A.K., Chakrabarti, D. (2011). *Update on congenital glaucoma*. Indian Journal of Ophthalmology. 59 (Suppl1), 148-157.
- Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. New York: Freeman.
- Mora, C. V., Davison, M., Wild, J.M., Walker, M.M. (2004). *Magnetoreception and its trigeminal mediation in the homing pigeon*. Nat Neurosci. 432, 508±11.
- Mouritsen, H., Ritz, T. (2005). *Magnetoreception and its use in bird navigation*. Curr Opin Neurobiol. 15,406±14.
- Nagel, S.K., Carl, C., Kringe, T., Martin, R., König, P. (2005). *Beyond sensory substitution--learning the sixth sense*. J Neural Eng. 2(4): R13-26.
- Natarajan, S. (2011). *Retinitis pigmentosa: A brief overview*. Indian Journal of Ophthalmology, 59(5), 343-346, doi: 10.4103/0301-4738.83608.
- Noë, A. (2004). *Representation and mind. Action in perception*. MIT Press.
- O'Regan J.K., Noë, A. (2001): A sensory account of vision and visual consciousness Behavioural and brain sciences 27:939-1031.
- Postma, A., Zuidhoek, S., Noordzij, M.L., Kappers, A.M.L. (2007) *Differences between Early-Blind, Late-Blind, and Blindfolded-Sighted People in Haptic Spatial-Configuration Learning and Resulting Memory Traces*. Perception. 36(8),1253-1265.
- Prinz, W. (1997). Perception and action planning. *Eur. J. Cogn. Psychol.* 9,129–154.
- Ritz, T., Dommer, D.H., Phillips, J.B. (2002) *Shedding light on vertebrate magnetoreception*. Neuron. 34, 503±6.
- Rizzolatti, G., Craighero, L. (2004) *The mirror-neuron system* Annu Rev Neurosci. 27,169-192.
- Robbins, P., Aydede, M. (2009) *A Short Primer on Situated Cognition*, The Cambridge Handbook of Situated Cognition.
- Röder, B., Rösler, F., Spence, C. (2004) *Early Vision Impairs Tactile Perception in the Blind*. Curr Biol. 14:121±4.
- Sampaio, E., Maris, S., Bach-y-Rita, P. (2001). *Brain plasticity: "Visual" acuity of blind persons via the tongue*. Brain Research. 908(2), 204–207.
- Sadato, N., Okada, T., Honda, M., Yonekura, Y. (2002). *Critical period for cross-modal plasticity in blind humans: a functional MRI study*. Neuroimage. 2002; 16:389±400.

- Schumann, F., O'Regan, K. (2017). *Sensory augmentation: integration of an auditory compass signal into human perception of space*. Scientific reports. 7:42197.
- Smith, E. R., Semin, G. R. (2004). *Socially Situated Cognition: Cognition in its Social Context*. In M. P. Zanna (Ed.), *Advances in experimental social psychology*, Vol. 36. 53–117. Elsevier Academic Press.
- Templeton, W. B., Howard, I. P., Lowman, A. E. (1966). *Passively Generated Adaptation to Prismatic Distortion*. *Perceptual and Motor Skills*, 22(1), 140–142.
- Tyler, M., Danilov, Y., Bach-Y-Rita, P. (2003). *Closing an open-loop control system: vestibular substitution through the tongue*. *Journal of integrative neuroscience*. 2(2), 159–164.
- Veraart, C., Wanet-Defalque, M. (1987). *Representation of locomotor space by the blind*. *Perception & Psychophysics*. 42, 132-139.
- Wade, G. (2005). *Seeing things in a different light*. BBC: http://www.bbc.co.uk/devon/news_features/2005/eyeborg.shtml.
- Ward, J., Meijer, P. (2010). *Visual experiences in the blind induced by an auditory sensory substitution device*. *Conscious Cogn.*, 19:492±500.
- Wiener, J. M., Berthoz, A., Wolbers, T. (2011). *Dissociable cognitive mechanisms underlying human path integration*. *Experimental brain research*, 208(1), 61-71.
- Wilson, M. (2002). *Six views of embodied cognition*. *Psychon. Bull. Rev.* 9, 625–36.
- Wittlinger, M., Wehner, R., Wolf, H. (2006). *The ant odometer: stepping on stilts and stumps*. *science*, 312(5782), 1965-1967.
- Yeh, W., Barsalou, L. (2006). *The Situated Nature of Concepts*. *The American Journal of Psychology*, 119(3), 349-384.

7. Appendix

A.1 Briefing for the naviBelt

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, indem Sie eine 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 es immer im Norden. Drehen sie sich doch mal, dann merken Sie, wie das Signal wandert.

2. Pausetaste

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 Kompass-Taste. 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 Pausetaste und die Kompass-Taste 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 Pausetaste 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 Kompass-Taste fünf Sekunden lang gedrückt, bis ein wiederkehrendes Vibrationssignal auftritt. Dann bewegen Sie ihr Handgelenk in liegender Achterbewegungen, gerne auch mit ein bisschen Armbewegung. Das Vibrationssignal beschleunigt 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 eine Sekunde lang, dann vibrieren vier Einheiten gleichzeitig. Das Signal nimmt ab, bis der Gürtel ganz ausgeschaltet 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?

A.2 Preliminary questionnaire

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 Visuswert / 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 sehe Schatten oder Lichtunterschiede.

Ich habe keine Lichteindrücke.

Ich kann eine Bordsteinkante sehen.

Sonstiges (bitte genauer beschreiben)

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

Ich verwende einen Blindenstock.

Ich verwende einen Kompass.

Ich habe eine Hilfsperson.

Ich habe einen Blindenhund.

Ich verwende weitere Hilfsmittel (bitte näher erläutern).

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

Ich orientiere mich am laufenden Verkehr.

Ich nutze Leitlinien zur Orientierung.

Ich verwende weitere Orientierungsstrategien (bitte näher erläutern).

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

*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 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 sehr 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 sehr 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 sehr 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 sehr 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).

A.3 Declaration of consent and protection of privacy

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 des FeelSpace Gürtels 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) Nach dem ersten Treffen werden Sie einige Tage auf unseren Bescheid warten und dann für sieben 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.
- 3) 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.

- (X) Ja, ich bin mit der Teilnahme an der FeelSpace Studie einverstanden.
- (X) Nein, ich bin nicht mit der Teilnahme an der FeelSpace Studie einverstanden.

Datum 17.04.2020

Unterschrift

A.4 Experimental briefing

1. Geradeaus-Gehen

Im folgenden Experiment geht es um das Geradeaus-Gehen. Ihre Aufgabe wird es sein, 50m geradeaus zu gehen. Dies werden Sie mehrfach durchführen, ohne Gürtel und mit Gürtel mit

verschiedenen Signalen. Hierbei geht es darum herauszufinden, ob der naviGürtel dazu führt, dass man besser und sicherer eine gerade Linie läuft. Wir werden uns notieren, wo Sie zu welchem Zeitpunkt sind und es von hinten filmen. Nach jedem Durchgang werden wir Ihnen kurze Fragen zu Ihrem Sicherheitsbefinden und Ihrer Wahrnehmung gegenüber der Aufgabe stellen.

Haben Sie noch Fragen? Sie können diese gerne jederzeit stellen und uns auch jederzeit Bescheid geben, wenn Sie sich nicht wohl fühlen und das Experiment abbrechen wollen.

2. Grad-Drehung

Im folgenden Experiment geht es um das Drehen auf einer Stelle. Ihre Aufgabe wird es sein, eine angesagte Drehung durchzuführen – zum Beispiel so etwas wie eine halbe Drehung nach links. Sie werden mehrere Drehungen durchführen müssen, einen Durchgang mit Gürtel und einen ohne Gürtel. Wenn Sie eine Drehung durchgeführt haben, müssen Sie auf einem Handy, welches Sie fest vor Ihrem Bauch halten werden, auf das Display drücken. So können wir die genaue Richtung und somit den genauen Winkel überprüfen. Bei dem Experiment geht es darum herauszufinden, ob der naviGürtel dabei hilft, eine Drehung präziser durchzuführen. Danach werden wir Ihnen eine kurze Frage zum Sicherheitsbefinden stellen.

Haben Sie noch Fragen? Sie können diese gerne jederzeit stellen und uns auch jederzeit Bescheid geben, wenn Sie sich nicht wohl fühlen und das Experiment abbrechen wollen.

3. Dreiecksvervollständigung

Im folgenden Experiment werden wir Sie einen kleinen Weg entlangführen, welcher aus zwei Geraden und einer Abbiegung besteht. Ihre Aufgabe wird es sein, sich nach dem Weg in die Richtung zu drehen, aus der Sie kamen, also Richtung Startpunkt. Dies werden Sie mit und ohne Gürtel machen. Sobald Sie sich für eine Richtung entschieden haben, in der der Startpunkt liegt, müssen Sie auf einem Handy, welches Sie fest vor Ihrem Bauch halten, auf das Display drücken. Es dient uns als Kompass um genau überprüfen zu können, in welchem Winkel Sie zum Startpunkt stehen. Bei diesem Experiment geht es darum herauszufinden, ob so eine räumliche

Orientierungsaufgabe mit dem unterstützenden naviGürtel besser zu lösen ist. Haben Sie noch Fragen? Sie können diese gerne jederzeit stellen und uns auch jederzeit Bescheid geben, wenn Sie sich nicht wohl fühlen und das Experiment abbrechen wollen.

A.5 Questionnaire sense of security

Tätigen Sie bitte alle Sicherheitseinschätzungen im Vergleich zu ihrem durchschnittlichem Sicherheitsgefühl bei einer entsprechenden Aufgabe im Alltag

1. Geradeaus-Gehen-Experiment

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

	Sehr viel sicherer	Sicherer	Eher sicherer	Kein Unterschied	Eher unsicherer	Unsicherer	Sehr viel unsicherer
--	-----------------------	----------	------------------	---------------------	--------------------	------------	-------------------------

Wie sicher haben sie sich gefühlt?							
Wie sicher waren Sie sich, 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	Kein Unterschied	Eher unsicherer	Unsicherer	Sehr viel unsicherer
Wie sicher haben Sie sich gefühlt, wirklich die entsprechende Drehung durchzuführen?							

3. Dreiecksvervollständigung

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

	Sehr viel sicherer	Sicherer	Eher sicherer	Kein Unterschied	Eher unsicherer	Unsicherer	Sehr viel unsicherer
Wie sicher haben Sie sich gefühlt?							
Wie sicher waren Sie, den							

Ausgangs- punkt richtig zu lokalisieren ?							
---	--	--	--	--	--	--	--

A.6 SARS-CoV-2 guidelines

1. Maßnahme: „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 desinfiziertem Stab.

2. Maßnahme: „Der Aufenthalt in 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 oder anderen Versuchsleitern. Dies gilt auch für die Anreise der Versuchspersonen.

3. Maßnahme: „Der Weg zur Arbeit, zur Notbetreuung, Einkäufe, Arztbesuche, Teilnahme an Sitzungen, erforderlichen Terminen 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. Maßnahme: „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.

A.7 Weekly questionnaire for the blind participants

Geben Sie hier bitte Ihre Erfahrungen der letzten Woche mit dem naviGürtel an.

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

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

3. Wie viele Stunden haben Sie den Gürtel letzte Woche jeden Tag in bekannter Umgebung genutzt?

Samstag

Sonntag

Montag

Dienstag

Mittwoch

Donnerstag
Freitag

4. Wie viele Stunden haben Sie den Gürtel letzte Woche jeden Tag in unbekannter Umgebung genutzt?

Samstag
Sonntag
Montag
Dienstag
Mittwoch
Donnerstag
Freitag

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

6. Bitte geben Sie an, wie sehr Sie den nachfolgenden Aussagen zustimmen. Zur Auswahl stehen stimmt nicht, stimmt wenig, stimmt mäßig, stimmt ziemlich und stimmt sehr.

6.1 Der Gürtel hat mich diese Woche in meinem Alltag eingeschränkt.

6.2 Ich nehme den Gürtel während der Tragezeit bewusst wahr.

6.3 Ich nehme das Signal als Vibration wahr.

6.4 Nach dem Ablegen des Gürtels habe ich noch anhaltende Vibrationsgefühle.

6.5 Ich nehme das Signal nicht als Vibration wahr, sondern anders.

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

7. Bitte geben Sie an, wie sehr Sie den nachfolgenden Aussagen zustimmen. Zur Auswahl stehen stimmt nicht, stimmt wenig, stimmt mäßig, stimmt ziemlich und stimmt sehr.

7.1 In der vergangenen Woche war ich motiviert den Gürtel zu tragen.

7.2 Mit dem Gürtel habe ich mich diese Woche sicherer in fremden Umgebungen gefühlt als sonst ohne Gürtel.

7.3 Mit dem Gürtel habe ich mich diese Woche sicherer im Straßenverkehr gefühlt als sonst ohne Gürtel.

7.4 Ich habe in der vergangenen Woche gut geschlafen.

7.5 Mir ging es in der vergangenen Woche gesundheitlich gut.

8. Wenn Sie in der letzten Woche eine Kreuzung mit mehreren Spuren überquert haben, wie sehr haben Sie dann folgende Emotionen empfunden (empfinde ich nicht, empfinde ich wenig,

empfinde ich mäßig, empfinde ich ziemlich, empfinde ich sehr). Wenn sie letzte Woche keine Kreuzung überquert haben stellen Sie sich vor Sie würden dies nun mit dem Gürtel tun.

Panik

Angst

Hilflosigkeit

Unwohlsein oder Unsicherheit

Zuversicht

Bitte geben Sie sonstige Emotionen an, die Sie in dieser Situation empfinden.

9. Wenn Sie in der letzten Woche eine Straße überquert haben, wie sehr haben Sie dann folgende Emotionen empfunden (empfinde ich nicht, empfinde ich wenig, empfinde ich mäßig, empfinde ich ziemlich, empfinde ich sehr). Wenn sie letzte Woche keine Kreuzung überquert haben, stellen Sie sich vor Sie würden dies nun mit dem Gürtel tun.

Panik

Angst

Hilflosigkeit.

Unwohlsein oder Unsicherheit

Zuversicht

Bitte geben Sie sonstige Emotionen an, die Sie in dieser Situation empfinden.

10. Wenn Sie in der letzten Woche einen Bahnsteig entlanggelaufen sind, wie sehr haben Sie dann folgende Emotionen empfunden (empfinde ich nicht, empfinde ich wenig, empfinde ich mäßig, empfinde ich ziemlich, empfinde ich sehr). Wenn sie letzte Woche keine Kreuzung überquert haben, stellen Sie sich vor Sie würden dies nun mit dem Gürtel tun.

Panik

Angst

Hilflosigkeit

Unwohlsein oder Unsicherheit

Zuversicht

Bitte geben Sie sonstige Emotionen an die Sie in dieser Situation empfinden.

11. Wenn Sie in der letzten Woche einen großen Platz ohne Anhaltspunkte überquert haben, wie sehr haben Sie dann folgende Emotionen empfunden (empfinde ich nicht, empfinde ich wenig, empfinde ich mäßig, empfinde ich ziemlich, empfinde ich sehr). Wenn Sie letzte Woche keine Kreuzung überquert haben, stellen Sie sich vor Sie würden dies nun mit dem Gürtel tun.

Panik

Angst

Hilflosigkeit

Unwohlsein oder Unsicherheit

Zuversicht

Bitte geben Sie sonstige Emotionen an, die Sie in dieser Situation empfinden.

12. Gab es in der letzten Woche Situationen, in der Ihnen der Gürtel besonders geholfen hat, sich sicherer zu fühlen? Wenn ja, erläutern Sie diese.

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

14. Bitte geben Sie an, wie sehr Sie den nachfolgenden Aussagen zustimmen. Zur Auswahl stehen stimmt nicht, stimmt wenig, stimmt mäßig, stimmt ziemlich und stimmt sehr.

14.1 Ich bin mir mit Gürtel zu jeder Zeit bewusst, wo ich mich im Verhältnis zu meinem Zuhause befinde.

14.2 Es fällt mir mit Gürtel leichter als ohne, mich in einer fremden Umgebung zurechtzufinden.

14.3 Es fällt mir mit Gürtel leichter als ohne, die Lage von verschiedenen Orten zueinander einzuschätzen.

14.4 Es fällt mir mit Gürtel leichter als ohne, die Lage von verschiedenen Straßen zueinander einzuschätzen.

14.5 Es fällt mir mit Gürtel leichter als ohne zu merken, dass ich eine Kurve laufe.

14.6 Seit ich den Gürtel trage, nehme ich Himmelsrichtungen bewusster wahr.

14.7 Mein räumliches Orientierungsvermögen hat sich subjektiv verbessert, seit ich den Gürtel trage.

14.8 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.

16. Bitte geben Sie an, wie sehr folgende Aussagen auf Sie zutreffen (stimmt nicht, stimmt wenig, stimmt mäßig, stimmt ziemlich, stimmt sehr)

16.1 Ich konzentriere mich bewusst auf den Gürtel, um mich besser zu orientieren.

16.2 Mit Gürtel fällt es mir beim Orientieren leichter andere Eindrücke wahrzunehmen und einzuordnen als ohne den Gürtel.

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

A.8 Final questionnaire

1.

Ich bin:

- a. rechtshändig
- b. linkshändig
- c. beidhändig

2.

Ich habe schon vor dieser Studie Erfahrungen mit dem FeelSpace Gürtel gehabt:

a.Ja

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

b.Nein

3. 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
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 Karte / innere Karte von 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 breite 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 Auswirkungen auf mich gehabt.					
Das Vibrieren des Gürtels war die ganze Zeit sehr präsent und prominent.					
Das Vibrieren des Gürtels habe ich im Lauf der Zeit kaum noch wahrgenommen.					
Meine Umgebung (Freunde, Familie etc.) hat positiv auf den Gürtel reagiert.					

4. Wenn der Gürtel einen Einfluss auf Ihre Orientierungsstrategien hatte, erläutern Sie bitte genauer, welche Auswirkungen der Gürtel hatte.
5. In diesen Situationen hat der Gürtel mir besonders geholfen:
6. Das hat mir am Gürtel gefallen.
7. Das hat mich am Gürtel gestört.
8. Das würde ich mir für eine zukünftigen Version des Gürtels wünschen.
9. Mir ist noch etwas Anderes aufgefallen, was bisher nicht durch die Fragebögen abgefragt wurde oder ich möchte etwas näher erläutern.
10. Diese Vorerfahrung mit dem Gürtel hatte ich schon vor der Studie (mit Dauer und Zeitpunkt des Tragens):

Wenn Sie nicht geburtsblind sind, beantworten sie bitte die folgenden Fragen

11. Wann hatten Sie die erste Sehschwäche?
12. Wie stark war diese Sehschwäche?
13. Woher resultierte Sie?
14. Wie verlief die Zeit zwischen der ersten Sehschwäche und der Erblindung? (In welchen Etappen gab es welche Verschlechterung?)

A.9 Conditions and randomization: Straight-line-walking

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

A.10 Conditions and randomization: Angular rotation task

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

A.11 Conditions and randomization: Triangle completion

Triangle completion	
Conditions	Trials
(1) Without belt with distraction	1) 90° internal angle, right
(2) Without belt without distraction	2) 150° internal angle, left
(3) With belt, compass mode with distraction	3) 30° internal angle, right
(4) With belt, compass mode without distraction	4) 90° internal angle, left
(5) With belt, road-crossing mode with distraction	5) 150° internal angle, right
(6) With belt, road-crossing mode without distraction	6) 30° internal angle, left
<p>* two conditions are kept together while the order of the three groups are randomized</p>	

A.12 Weekly questionnaire for deaf-blind

- Wie viele Stunden haben Sie den Gürtel an diesen Tagen genutzt?
 - Montag:
 - Dienstag:
 - Mittwoch:
 - Donnerstag:
 - Freitag:
 - Samstag:
 - Sonntag:
- Wie viele Stunden waren Sie davon an Orten, die Sie gut kennen?
 - Montag:
 - Dienstag:

- Mittwoch:
- Donnerstag:
- Freitag:
- Samstag:
- Sonntag:

3. Wie viel Stunden waren Sie an Orten, die Sie nicht so gut kennen?

- Montag:
- Dienstag:
- Mittwoch:
- Donnerstag:
- Freitag:
- Samstag:
- Sonntag:

4. Gab es Probleme mit dem Gürtel? Wenn ja kontaktieren Sie uns bitte.

5. Das habe ich letzte Woche mit dem Gürtel gemacht:

6. Jetzt kommen einige Aussagen. Bitte schreiben Sie zu jeder Aussage eine Zahl zwischen 1 und 5:

1 = stimmt nicht

2 = stimmt wenig

3 = stimmt mäßig

4 = stimmt ziemlich

5 = stimmt sehr

- Der Gürtel hat mich letzte Woche aufgehalten.
- Wenn ich den Gürtel trage, merke ich das immer.
- Das Signal merke ich als Vibration
- Das Signal merke ich NICHT als Vibration. Ich merke es anders.
- Wenn ich den Gürtel ausziehe, spüre ich noch die Vibration.
- Letzte Woche hatte ich Lust den Gürtel zu tragen.
- Mit dem Gürtel fühle ich mich sicherer in neuen Orten.
- Mit dem Gürtel fühle ich mich sicherer im Straßenverkehr.
- Ich habe letzte Woche gut geschlafen.
- Mir ging es letzte Woche gesundheitlich gut.

7. Jetzt kommen einige Situationen. Wie haben Sie sich letzte Woche mit dem Gürtel dabei gefühlt? Wenn die Situation letzte Woche nicht passiert ist stellen Sie es sich vor. Wenn Sie etwas nie tun, lassen Sie es einfach leer. Bitte schreiben Sie zu jeder Aussage eine Zahl zwischen 1 und 5:

1 = gar nicht

2 = ein wenig

3 = mäßig

4 = ziemlich

5 = sehr

Wenn Sie eine große Kreuzung mit mehreren Spuren überqueren, wie sehr fühlen Sie sich:

- Panisch
- Ängstlich
- Hilflos
- Unwohl oder unsicher
- Zuversichtlich oder normal

Wenn Sie eine normale Straße überqueren, wie sehr fühlen Sie sich:

- Panisch
- Ängstlich
- Hilflos
- Unwohl oder unsicher
- Zuversichtlich oder normal

Wenn Sie einen Bahnsteig entlang gehen, wie sehr fühlen Sie sich:

- Panisch
- Ängstlich
- Hilflos
- Unwohl oder unsicher
- Zuversichtlich oder normal

Wenn Sie einen großen Platz ohne Anhaltspunkte überqueren, wie sehr fühlen Sie sich

- Panisch
- Ängstlich
- Hilflos
- Unwohl oder unsicher
- Zuversichtlich/normal

8. Der Gürtel kann helfen, sich sicherer zu fühlen. Ist das Ihnen letzte Woche aufgefallen?
In welchen Situationen?

9. Haben Ihre Träume sich verändert? Wenn ja, wie?

10. Jetzt kommen wieder einige Aussagen. Bitte schreiben Sie zu jeder Aussage eine Zahl zwischen 1 und 5:

1 = stimmt nicht

2 = stimmt wenig

3 = stimmt mäßig

4 = stimmt ziemlich

5 = stimmt sehr

- Ich weiß mit Gürtel immer, in welcher Richtung mein Zuhause ist.
- Mit Gürtel fühle ich mich an neuen Orten besser.
- Mit Gürtel weiß ich eher, wo verschiedene Orte sind. Ich weiß auch eher, wie ich von einem Ort zum anderen Ort komme.

- Mit Gürtel weiß ich eher, wo verschiedene Straßen sind und wie ich von einer Straße zur anderen komme.
- Mit Gürtel merke ich, dass ich eine breite Kurve laufe.
- Seit ich den Gürtel trage, merke ich die Himmelsrichtungen besser.
- Ich finde, seit ich den Gürtel trage, ist meine Orientierung besser.
- Wenn ich den Gürtel abnehme, ist meine Orientierung schlechter.
- Ich konzentriere mich auf den Gürtel, um mich besser zu orientieren.
- Mit Gürtel fällt es mir beim Orientieren leichter, andere Eindrücke zu merken und einzuordnen als ohne den Gürtel.

11. Der Gürtel kann helfen sich besser zu orientieren. Ist das Ihnen letzte Woche aufgefallen? In welchen Situationen?

12. Ist Ihnen letzte Woche mit dem Gürtel etwas Besonderes aufgefallen? Wenn ja, beschreiben Sie es bitte:

13. Ist Ihnen letzte Woche ohne den Gürtel etwas Besonderes aufgefallen? Wenn ja, beschreiben Sie es bitte:

14. Hier können Sie alles andere reinschreiben, was Sie noch sagen wollen.

A.13 Preliminary questionnaire for deaf-blind

Allgemeine Fragen über Sie.

Bitte füllen Sie die Fragen ehrlich aus. Die Daten werden uns helfen den Gürtel besser zu machen. Dabei wird niemand erfahren was Sie geantwortet haben.

Bitte geben Sie Ihre Initialen und Ihr Geburtsjahr an (z.B. MB97)

1. Welches Geschlecht haben Sie?

2. Wie alt sind Sie?

3. Was stimmt für Sie? Schreiben Sie „Ja“ hinter die Aussagen, die stimmen.

Ich bin geburtsblind.

Ich bin spät erblindet.

Ich bin sehbehindert.

4. Wie lange sind Sie schon blind oder sehbehindert?

5. Geben sie Ihre Sehschärfe an.

Linkes Auge:

Rechtes Auge:

Gesichtsfeld:

6. Warum sind Sie blind oder sehbehindert?

7. Haben Sie chronische, neurologische oder psychische Krankheiten. Geben Sie diese bitte an.

8. Haben Sie andere zusätzliche Einschränkung wie Gehbehinderung oder Gleichgewichtsstörungen
Geben Sie diese bitte an.

9. Was stimmt für Sie? Schreiben Sie „Ja“ hinter die Aussagen, die stimmen. Sie können auch mehrere Antworten auswählen.

Ich kann eine Bordsteinkarte erkennen.
Ich sehe hell dunkel Kontraste.
Ich bin schwarzblind.
Sonstiges (bitte genauer beschreiben)

10. Welche Hilfsmittel benutzen Sie oft im Alltag? Schreiben Sie „Ja“ hinter die Aussagen, die stimmen.

Ich verwende einen Blindenstock.
Ich verwende einen Kompass.
Ich habe eine Begleitperson.
Ich habe einen Blindenführhund.
Ich verwende andere Dinge (bitte erkläre Sie).

11. Welche Orientierungsstrategien benutzen Sie häufig im Alltag. Bitte wählen Sie aus. Schreiben Sie „Ja“ hinter die Aussagen, die stimmen.

Ich orientiere mich mit meinem Smartphone.
Ich orientiere mich an Leitlinien.
Ich benutze weitere Orientierungsstrategien (bitte genauer erklären).

12. Bitte wählen Sie passenden Aussagen für Sie aus. Schreiben Sie „Ja“ hinter die, die für Sie stimmen.

Ich kenne Himmelsrichtungen.
Ich kenne Gradzahlen und Winkel.
Ich habe schon Mobilitätstraining gemacht.
Wenn Sie schon einmal Mobilitätstraining gemacht haben, geben sie an wie viele Stunden.

13. Was arbeiten Sie?

14. Was sind Ihre Hobbies?

15. Wie lange sind Sie normalerweise jeden Tag draußen unterwegs?

16. Jetzt kommen einige Aussagen. Bitte schreiben Sie zu jeder Aussage wie sehr sie stimmt. Zur Auswahl sind „stimmt nicht“ = 1, „stimmt wenig“ = 2, „stimmt mäßig“ = 3, „stimmt ziemlich“ = 4, „stimmt sehr“ = 5. Schreiben Sie die entsprechende Zahl dahinter.

Ich habe einen guten Orientierungssinn.
Ich habe eine Abfolge von Anhaltspunkten meiner Umgebung im Kopf.
Ich habe eine innere Karte von meiner Umgebung im Kopf.
Meine innere Karte hat Himmelsrichtungen.
Ich erkunde öfter neue Umgebungen.
Ich fühle mich in neuen Umgebungen wohl.
Ich vermeide neue Umgebungen.
Manchmal erkenne ich nicht, dass ich eine breite Kurve laufe.

Ich bin neugierig auf den FeelSpace Gürtel.
Ich bin motiviert den Gürtel zu tragen.
Der Gürtel beunruhigt mich.

17. Wie oft machen Sie folgende Dinge? Die Auswahlmöglichkeiten sind „nie“ = 0, „nicht alleine“ = 1, „wenn es sein muss“ = 2, „selten“ = 3, „ab und zu“ = 4 und „regelmäßig“ = 5. Schreiben Sie die entsprechende Zahl dahinter.
Eine große Kreuzung mit mehreren Spuren überqueren.
Eine Straße überqueren.
Einen Bahnsteig entlanglaufen.
Einen großen Platz überqueren.

18. Jetzt wollen wir wissen wie Sie sich in jeder Situation fühlen. Wenn Sie etwas nicht tun, lassen Sie es einfach leer. Zu jeder Situation haben wir 5 Gefühle aufgeschrieben. Schreiben Sie dahinter wie sehr sie jedes Gefühl empfinden. Zur Auswahl sind „nicht“ = 1, „wenig“ = 2, „mäßig“ = 3, „ziemlich“ = 4 und „sehr“ = 5. Schreiben Sie die entsprechende Zahl dahinter.
Wenn Sie eine große Kreuzung mit mehreren Spuren überqueren, wie sehr fühlen Sie sich:
Panisch?
Ängstlich?
Hilflos?
Unwohl oder unsicher?
Zuversichtlich oder normal?

Wenn Sie eine normale Straße überqueren, wie sehr fühlen Sie sich
Panisch?
Ängstlich?
Hilflos?
Unwohl oder unsicher?
Zuversichtlich oder normal?

Wenn Sie einen Bahnsteig entlang gehen, wie sehr fühlen Sie sich
Panisch?
Ängstlich?
Hilflos?
Unwohl oder unsicher?
Zuversichtlich oder normal?

Wenn Sie einen großen Platz ohne Anhaltspunkte überqueren, wie sehr fühlen Sie sich
Panisch?
Ängstlich?
Hilflos?
Unwohl oder unsicher?
Zuversichtlich oder normal?