INTUITIVE

INnovative Network for **T**raining in To**U**ch **I**nterac**TIVE** Interfaces

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Description:
Integration of tactile stimulators in a sensory augmentation device. Design and test mapping of sensory information (orientation, distance of obstacles, dynamics of approach and recess) to degrees of freedom of sensory augmentation device (frequency domain, AM-modulation, selection of simultaneously active tactors (UOS). Usability study and validation of behavioural benefits.

Deliverable 3.2:
Next Generation Sensory Augmentation Device

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Important note: *The contents of this report are to be treated confidentially as the majority of contents are currently in publishing, or yet to be submitted/accepted for publication.*

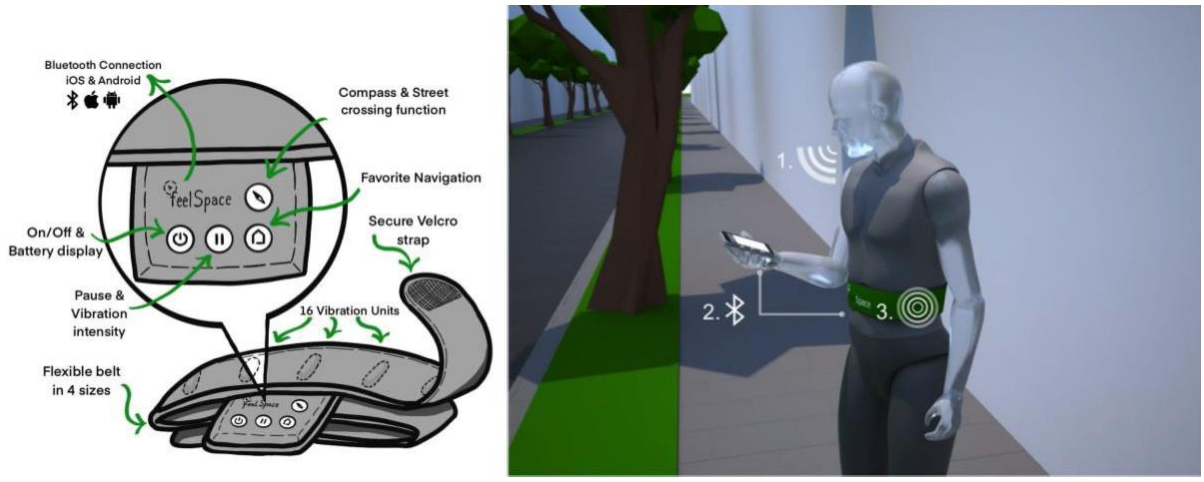
Next Generation Sensory Augmentation Device

Sensory augmentation (SA) refers to the delivery of sensory cues that cannot be perceived naturally through sensory modalities inherent to the body. SA devices enable humans to perceive an incoming signal by ‘translating’ it to a different sensory modality that humans can perceive naturally. The signal is usually recorded with one or multiple sensors before it gets processed to produce the corresponding augmented sensory output. Within the INTUITIVE project our aim is to contribute to the general development of such devices by providing novel scientific insights in the way humans are able to learn and apply these sensens. At the same time, we are collaborating with Actronika and Inventivio (two INTUITIVE project beneficiaries) on the improvement of individual SA devices, such as the feelSpace belt (Tactile Sensory Augmentation for Navigation) and the Tactonom (Audio-tactile Augmentation of two-dimensional data for the blind). This report summarizes the current scientific and technological improvements and provides an outlook towards the future of these projects.

Tactile Sensory Augmentation for Navigation

The feelSpace belt

The feelSpace belt uses tactile SA to provide blind and visually impaired (BVI) users with an enhanced perception of space. Visual information is translated to tactile stimulation around the user’s waist (i.e. ‘pinpointing’ into direction of the user’s target destination), thereby supporting the user to navigate through space. It consists of 16 vibration motors. Only one vibration motor is activated at a time can be controlled manually through an interface that is integrated in the belt, or the feelSpace Navigation app. It features different modes, such as a ‘beeline mode’ that can be used to monitor the direction of the user’s desired destination, or a ‘street crossing’ function that aids blind users to cross the street in a straight line.



Figures A & B [left to right]. A) Working mechanism and components of the feelSpace belt. The controls of the belt are explained in the speech balloon. B) Illustration of a user using voice control (1) and the feelSpace Navigation app (2) to control the feelSpace belt (3).

The feelSpace belt as an augmented sense for cardinal directions

Next to guiding blind users, the feelSpace belt can be used by sighted users in ‘compass’ mode as an augmented sense for cardinal directions. The feelSpace belt provides the user with an artificial sense of cardinal directions through tactile stimulation around the waist. In the compass mode, only the vibration motor facing cardinal North is activated. When the user is rotating, the signal is adjusted in real-time, still facing cardinal North. Thereby, the belt provides tactile stimulation that serves as a stable reference point. If it is possible to learn and effectively apply the augmented sense, this would likely result in an improved ability to navigate through and to orientate in space.

In previous studies feelSpace belt users reported an altered perception of space after wearing and training with the belt for an extended duration of six weeks (König et al., 2016; Kaspar et al, 2014). Participants also reported a subjectively improved spatial navigation ability. While these subjective reports show promising results for the use of the feelSpace belt, it remains to be investigated whether the presence of an augmented sense for cardinal North affects spatial navigation performance on a behavioral level.

Assessing the behavioral effect of the augmented sense for cardinal directions

At the start of the project we were faced with several challenges regarding the development of a naturalistic but controlled environment to investigate potential behavioral changes in spatial cognition caused by the augmented sense. Virtual reality (VR) offers a potential solution to the dichotomy between experimental control and realism by allowing for a visually realistic, nevertheless controllable environment (i.e. König et al., 2019; König et al., 2021). To this end, we analyzed the data from previous studies that used VR to study spatial navigation (i.e. Clay et al., 2019; König et al., 2021) to create an improved urban VR environment that is specifically tailored to this purpose. The VR environment ‘Wesbtrook’ is about 1km^2 in size and contains more than 230 buildings, including four global landmarks and a wide variety of paths, parks and streets (Schmidt, König, S.U., & König, P., *Unpublished Manuscript*).

Participants and Procedure

In order to answer the research question whether SA with the feelSpace belt, by providing a sense of North, affects spatial navigation strategies and performance, a total of fifty-four participants were recruited and divided across two groups. The belt group consisted of twenty-eight participants that were provided with an augmented sense of cardinal North in the form of the feelSpace belt. The control group consisting of twenty-six participants was not provided with the augmented sense and therefore limited to using their native senses. Due to unforeseen time-constraints and other unknown reasons, three participants did not complete the study and were excluded, resulting in a total sample of fifty-one participants (twenty-six belt group; twenty-five control group).

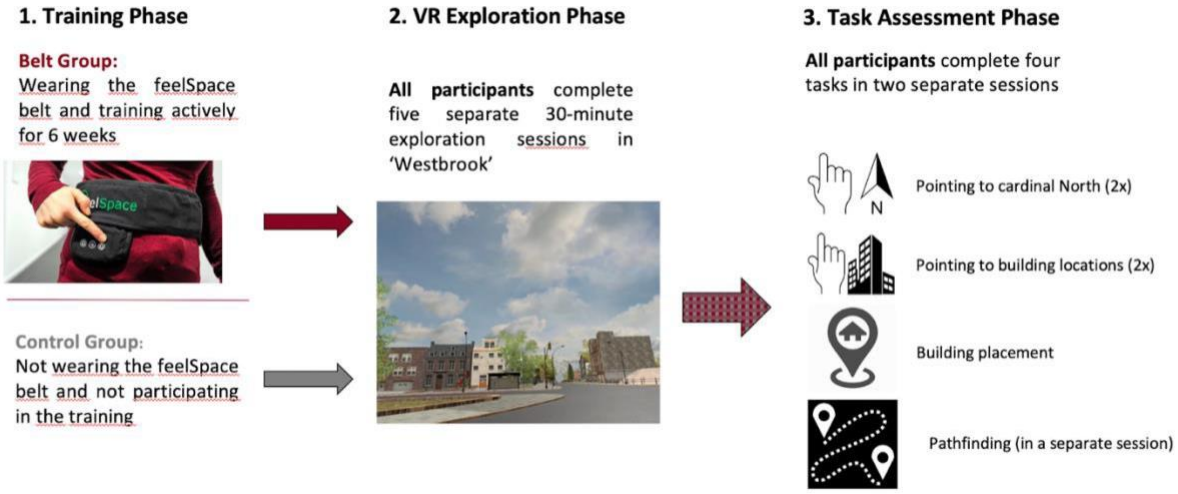


Figure C. Overview of the experimental procedure. The belt group wore the augmented sense of cardinal North for six weeks during their everyday life, before the VR exploration phase started. All participants engaged in five thirty-minute exploration sessions and finally, two test sessions in the urban VR environment 'Westbrook'.

Results: Qualitative Data

We assessed the Questionnaire of spatial strategies ('Fragebogen Räumlicher Strategien'; Münzer & Hölscher, 2011) to ensure there were no pre-existing differences between the two groups in their preferred use of spatial navigation strategies. The Questionnaire of spatial strategies consists of three scales. The 'egocentric/global orientation' scale aims to assess the use of strategies based on an egocentric perspective which are related to a person's ability to orient themselves in space. The 'survey' scale aims to measure the use of allocentric strategies to shape a mental map-like representation of the environment. Finally, the 'cardinal directions' scale aims to measure the use of cardinal directions as spatial cues in the context of navigation (Münzer & Hölscher, 2011; Münzer et al., 2016). Participants in both groups completed this questionnaire once at the beginning of the experiment. We performed a Wilcoxon rank sum test for independent samples on the groups' scores on the FRS scales to examine whether the two groups were comparable in terms of their preferential use of egocentric/global, survey, or cardinal directions navigation strategies at baseline. The results show that there was no significant difference between the two groups at baseline across all three scales, Ws (NBelt ≤ 270, NControl ≤ 270) ≤ 36004, ps > .05 (see *Figure D*). This indicates that two groups were comparable in terms of their reported use of spatial navigation strategies at baseline.

Training Phase. During the six-week training phase in a natural environment, only the participants in the belt group trained to use the augmented sense of cardinal North in the context of spatial navigation. They were instructed to wear the belt during all wake hours and to engage in at least 1.5 hours of active training on a daily basis. Active training was defined as engaging in physical activities that require active movement and rotation such as exploring, running, or cycling. To monitor their training progress and in line with previous research (i.e. Kaspar et al., 2014; König et al., 2016), participants were asked to fill in a daily and a weekly questionnaire (s. Appendices X & Y) that monitored, for instance, their belt wearing and active training times.

Results of the training times show that participants, on average, wore the belt for 9 hours and 11 minutes (SD = 2.775) per day. The self-reported active training time was on average 2 hours and 16 minutes per day (SD = 1.739).

We assessed the FRS questionnaire (Münzer & Hölscher, 2011) a second time after the training phase to investigate whether the training with the augmented sense affected the use of spatial navigation strategies. To compare the results of the FRS questionnaire at baseline with the results after training, we performed an ordinal logistic regression for paired samples. Participants in the belt group scored themselves significantly higher after training than at baseline regarding their use of egocentric / global orientation strategies, W ($N_{\text{Trained}} = 270$, $N_{\text{Baseline}} = 270$) = 3492, $p < .001$; survey strategies, W ($N_{\text{Trained}} = 189$, $N_{\text{Baseline}} = 189$) = 1232, $p < .001$; and cardinal directions, W($N_{\text{Trained}} = 54$, $N_{\text{Baseline}} = 54$) = 21, $p < .001$. Taken altogether, the reported use of egocentric/global, survey, and cardinal spatial navigation strategies was significantly higher in the belt group after they had engaged in the six weeks of active training with the augmented sense of cardinal North (see *Figure D*).

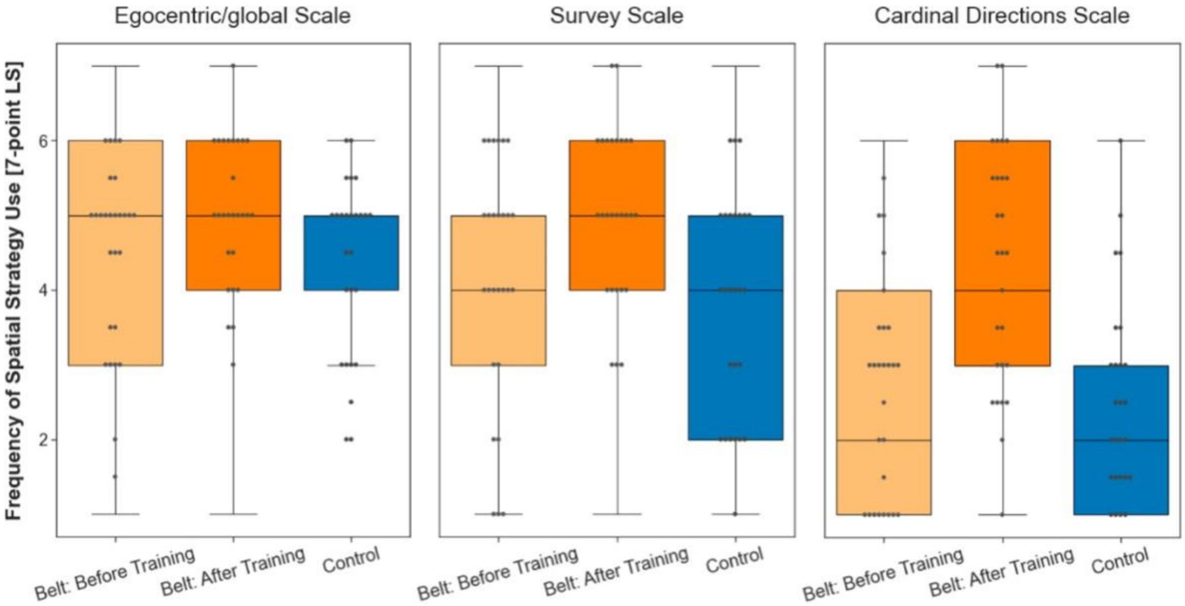


Figure D. Reported use of egocentric/global, survey, and cardinal spatial navigation strategies of belt participants before (baseline), and after training, as well as in the control group. While the reported use of spatial strategies is similar between the control group and the belt group before they engaged in the training, reported use of spatial strategies after training with the augmented sense for six weeks in real life increased across all three scales.

Exploration Phase. All participants performed five thirty-minute long exploration sessions in the virtual environment with the aim of becoming familiar with the buildings and the layout of the city. To this end, participants were instructed to freely explore the city. ‘Westbrook’ has a size of about 1km2 and consists of 284 unique buildings. Fifty-six buildings had street art on their walls. Participants were instructed that whenever they came across a building with street art on its walls, they should take a photo of it. The photos served the purpose of facilitating the participants’ familiarity with the buildings that would later be used as target stimuli in the tasks during the assessment phase. Moreover, finding and photographing all buildings with street art provided a goal for the exploration, potentially increasing participants’ motivation to explore. Only participants in the belt group wore the augmented sense in the form of the feelSpace belt, indicating cardinal North in the VR city during all exploration sessions. The control group did not wear the belt and received no information about cardinal directions in the virtual environment at any point during the experiment.

Results: Task Assessments

To assess spatial navigation performance, we conducted four spatial tasks: ‘pointing to cardinal North’, ‘pointing to building locations’, ‘building placement’, and a ‘pathfinding task’. The first three tasks all aim to measure different aspects of survey knowledge. In contrast, the pathfinding task relies on left- and right- turn combinations, commonly referred to as route knowledge. Moreover, the belt group wore the augmented sense during all tasks but ‘pointing to cardinal North’. All tasks were conducted from a first-person perspective in the VR environment ‘Westbrook’.

Pointing to cardinal North. In order to assess participants’ knowledge of cardinal directions they were placed in front of one of the fifty-six buildings that had street art on their walls and were asked to point into the direction of cardinal North from this location. This procedure was repeated fifty-six times in a randomized order which resulted in fifty-six unique trials, each repeated once (for a detailed description, see Methods). During each trial, the pointing accuracy was measured in terms of the pointing error from the true beeline direction of cardinal North in the virtual environment.

The belt group, as expected, performed better than the control group in pointing towards cardinal North (s. *Figure E*). A Wilcoxon rank sum test indicated that this difference was statistically significant, W ($N_{\text{Belt}} = 3019$, $N_{\text{Control}} = 2912$) = 1727085, $p < .001$. The results demonstrate that participants in the belt group pointed more accurately towards cardinal North than controls, even when the augmented sense of cardinal North was not anymore present.

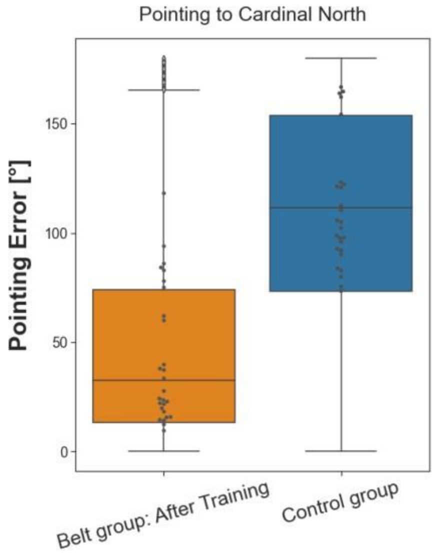


Figure E. Boxplot of pointing error in the 'pointing to cardinal North' task. The grey dots inside the boxplot represent the median pointing error of each participant in the respective group. The dots above the upper bound of the boxplot for the belt group represent outliers. Overall, participants from the belt group had a lower median pointing error (32.37°) than participants from the control group (111.31°). Interestingly, four participants in the control group pointed relatively consistently into the opposite direction of cardinal North.

Pointing to building locations. The pointing to building locations task aims to assess participants' ability to point in a beeline from their current location towards a given building location in the city. Therefore, participants were placed in front of eight building locations. From each location they pointed towards the remaining seven locations before being teleported to the next building location (for a detailed description, see Methods). In total, the task consisted of fifty-six trials, each repeated once. The belt group performed better than the control group in pointing towards given building locations (see *Figure F*). A Wilcoxon rank sum test indicated that this difference was statistically significant, W (N_{Belt} = 3013, N_{Control} = 2912) = 3873130, $p <$ .001. The results indicate that the augmented sense leads to an improved performance in pointing towards building locations.

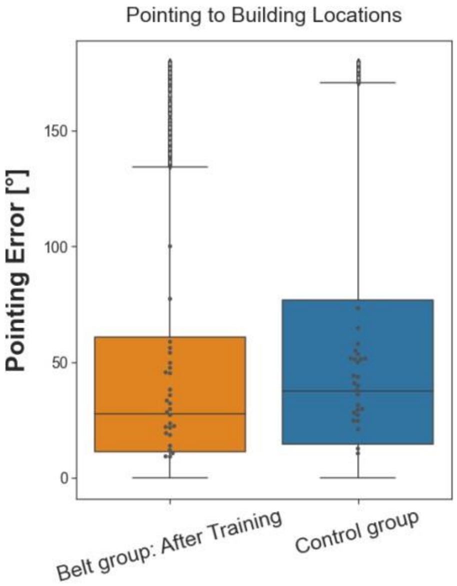


Figure F. Boxplot of pointing error in the 'pointing to building locations' task. The dots represent the median pointing error of each participant in the respective group. Although two participants in the belt group had the highest median pointing errors in the sample, participants from the belt group, overall, demonstrated a lower median pointing error (27.58°) than participants from the control group (37.41°).

Building placement task. In the building placement task participants were instructed to place back twenty-eight buildings to their original location in the city. To this end, participants were placed at one location in the city from which they had to position a building that was mapped to their controller in the correct direction, distance, and orientation (for a detailed description, see Methods). While the placement direction of the building is conceptually similar to the pointing direction in the pointing to building locations task, the placement distance and building orientation relative to one's current location have not been assessed before. As the three outcome variables might rely on different aspects related to spatial navigation, they were considered separately for the analysis. To this end, three Mann-Whitney-U tests were performed, each analyzing the performance differences between the belt and the control group.

The results reveal that placement direction accuracy was higher in the belt group than in the control group, W ($N_{\text{Belt}} = 744$, $N_{\text{Control}} = 724$) = 246938, $p < .001$. Moreover, the belt group was significantly more accurate than the control group in placing the building at the correct distance, W ($N_{\text{Belt}} = 744$, $N_{\text{Control}} = 724$) = 224776, $p < .001$. Finally, participants in the belt group were more accurate than controls in reproducing the initial building orientation, W ($N_{\text{Belt}} = 744$, $N_{\text{Control}} = 724$) = 220824, $p < .001$. In conclusion, the belt group placed the buildings more accurately than the control group with regards to the buildings' direction, distance, and orientation (s. *Figure G*).

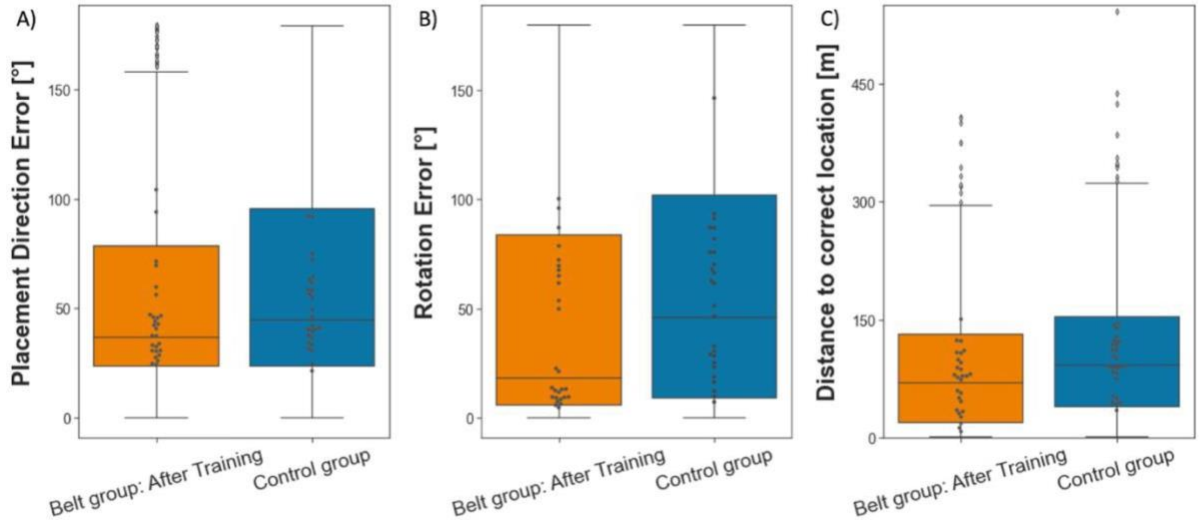


Figure G. Performance in the building placement task divided by group. *A)* illustrates that the belt group (*MED* = 36.60°) placed the buildings more accurately into the correct direction than the control group (*MED* = 44.69°). *B)* displays that participants from the belt group performed more accurately (*MED* = 18.35) in rotating the house to its correct facing direction than control participants (*MED* = 45.98°). *C)* shows that belt participants (*MED* = 69.97 m) placed the houses closer to their original location than controls (*MED* = 91.67m).

Pathfinding Task. Pathfinding was assessed by placing participants at a designated location in the city and asking them to find the most efficient path to a given building location (for a detailed description, see Methods). In order to complete the task, each participant navigated towards nine different locations in regular or reversed order. To determine whether the augmented sense of cardinal North would lead to improved pathfinding, path completion times (in seconds) were recorded and compared between the two groups. Each trial had a maximum duration and trials where the target location was not reached within this time were set to the maximum duration of the longest path. The task aims to provide a close-to-real life application of spatial navigation strategies.

A Wilcoxon rank sum test revealed a significant difference between the groups, W ($N_{\text{Belt}} = 243$, $N_{\text{Control}} = 234$) = 24735, $p < .05$. The results show that participants in the belt group were more efficient in finding the path to a given location in the surrounding environment (s. *Figure H*).

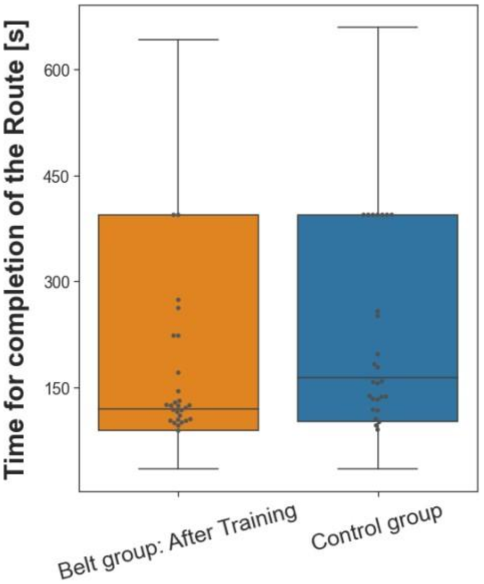


Figure H. Performance in the Pathfinding task separated by group. The belt group (*MED* = 119.50s), overall, performed better and reached their target destination quicker than the control group (*MED* = 163.39s).

Discussion/Conclusion

Participants trained with the feelSpace belt for a duration of six weeks show improved navigation performance in a variety of first-person virtual reality tasks measuring different aspects of spatial navigation. Moreover, the subjective improvements reported by previous studies (i.e. König et al., 2016; Brandebusemeyer et al., 2021) could be reproduced. This indicates that augmented senses, when implemented in a meaningful way and trained for a sufficient duration, can be learned and applied effectively, resulting in behavioral and perceptual changes.

First, results from the Pointing to cardinal North task indicate that the augmented sense was learned and the signal was associated with the environment during the repeated exploration sessions. The control group did not receive information about the virtual cardinal North at any point during the study and therefore pointed into random directions, resulting in a performance slightly worse than the chance level of 90°. Nevertheless, closer inspection of the data revealed that some control participants were able to point consistently into one (incorrect) direction. This raised the question whether the results could be transferred to other aspects of spatial navigation.

During the Pointing to Building task, we found that the effect of the augmented sense on spatial navigation transferred to estimating spatial building-to-building (allocentric) or self-to-building (egocentric) relationships. This indicates that the augmented sense that was associated with the environment could be effectively used as a reference point (similar to how landmarks are used for navigation).

The Building Placement task required participants to place a house back to its original location in the city in terms of its direction, distance, and orientation respective to the participant's location or to other buildings in the city. It therefore tested a more advanced spatial knowledge of the environment, including the distance and orientation/facing direction of the building that needed to be placed. Belt participants showed significant improvements in all three aspects of building placement (direction, distance, orientation). We suggest that this effect might be related to the formation of a mental map, allowing participants to retrieve spatial information regarding the building's direction, distance, and orientation respective to the position of the participant and of surrounding buildings in the VR environment.

The pathfinding task was assessed to investigate whether the effects of the augmented sense would be transferable to a task resembling spatial navigation that humans use on a daily basis. The results suggest that the augmented sense leads to a significant improvement in finding the most efficient path from the participants' location towards a different location in the VR environment. We suggest that this finding supports the hypothesis that the presence of the augmented sense during exploration facilitates the creation of a mental map of the VR environment. The tactile perception of cardinal North provides the participant with a global orientation point, thereby facilitating mental maps to be created with the same orientation (i.e. North-up). Moreover, it facilitates spatial memory formation by providing different tactile outputs depending on the participants viewing angle/perspective. For instance, the opposite output of the augmented sense when a building is viewed from opposite directions (e.g. cardinal North and South), as the belt signal is intuitively associated with the visual experience.

The results of the study will be published in the near future and applied to continuously assess and improve the feelSpace belt and potentially also contribute to the development and testing of other SA devices.

Implemented Technical Improvements

In a recent Bachelor's project (Wölk et al., 2022) we investigated the possibility of using a lower amount of vibration motors in combination with a different tactile coding for the belt. More precisely, the aim of the study was to assess whether a reduced amount of vibration motors in the belt could result in a similar precision while making the augmentation device less complex, more resistant to technical failures (i.e. malfunction of a single vibration motor), as well as offering the possibility to produce even smaller sizes of the feelSpace belt. To this end, four conditions were tested and compared with each other. In the first condition participants completed the tasks without the feelSpace belt. In the second condition they wore the current iteration of the feelSpace belt with 16 vibration motors (s. The feelSpace belt). In the third condition ("8d-mode"), partcipants wore an iteration of the feelSpace belt where only one of eight vibration motors was activated at a time. Finally, in the eight motors two-step mode ("8-2st. mode"), the "8d-mode" was supplemented by paired activations to increase precision: each vibration motor covered 22.5° angular range and for the angular ranges in-between two vibration motors two neighboring motors were activated together, each using 50% strength.

The project assessed the hypothesis that "participants were able to walk further and straighter with the new tactile coding and reach a finish line after 50 meters more frequently than without the belt, and that they would be able to turn more accurately around their own axis according to a given angle" (Wölk et al., 2022, p.4). The different vibration patterns, as described above, were implemented in the feelSpace belt and tested in two different orientation tasks adapted from previous research (Brandebusemeyer, 2020; Kärcher et al., 2012). 40 sighted young healthy adults took part in the experiment. They were blindfolded during the two spatial tasks: a straight-line walking task, and a rotation task.

In the straight-line walking task participants were required to walk in a straight line for a distance of 50 meters. As outcome the deviation from the middle (optimal straight) line was measured. A deviation of up to one meter was considered optimal, while a deviation of more than six meters was considered too high and resulted in the end of the respective trial (Wölk et al., 2022). The feelSpace belt was set to compass mode (s. *The feelSpace belt as an augmented sense for cardinal directions*) to aid the blindfolded participants in keeping the straight-line direction. Moreover, participants were assigned different tactile referent points by varying the orientation offset along the north-south axis between -90° and + 90° in steps of 10°. By letting participants repeat the task walking into the opposite direction, the total 360° radius was covered. Overall, participants reached the finish line after 50 meters the most frequently when using the current iteration of the feelSpace belt with 16 vibration motors (29% success), followed by the "8-2st. mode" (24% success). The "8d mode" and the no belt condition were shown to be equally ineffective (17-18% success). While these results were not statistically significant, there was a significant difference in the distance walked by the participants before departing from the six-meter corridor. More precisely, the feelSpace belt with 16 vibration motors was significantly more effective than no belt and the "8d mode" (Wölk et al., 2022).

The rotation task assessed how precisely participants were able to rotate around their own axis. This is particularly relevant for blind and visually impaired users' navigation around intersections and traffic lights. Participants were asked to rotate 90°, 180° or 360° to the right, or to the left direction. After finalizing the turn, the deviation from the correct angle was measured ("turning error"). The results show that the turning error was higher in the no belt condition (*MED* = 18°) than in the three conditions where participants wore one of the iterations of the feelSpace belt (*MED*s ≤ 12°), $F(3, 117) = 11.34$, $p < .001$ (Wölk et al., 2022). This indicates that tactile SA can be applied to effectively help blind(-folded) people to rotate more accurately.

Upcoming Technical Improvements

We will use the secondment with Actronika to evaluate the use of the novel HapCoil-Plus high definition haptic actuator developed by Actronika for tactile SA. The secondment had to be delayed due to COVID-19, but is scheduled to take in the near future in 2022. In the following we will briefly describe the actuators by Actronika that we are planning to implement and provide an outlook to describe new possibilities that they offer for the advancement of the feelSpace belt and potentially also for other tactile SA devices.

The HapCoil-Plus has a relatively small size compared to other haptic actuators (16.5 x 17 x 84.7 mm^3; see Actronika Datasheet, 2020). The inertial drive design enables the HapCoil-Plus actuator to provide vibrations on devices with large surfaces, such as screens or controllers. It covers a frequency bandwidth of 10Hz to 1000Hz and allows for immersive sensations such as the replication of surface textures. For example, it "(…) could even make you believe you are touching leather or paper on the top of your smartphone screen" (Actronika datasheet, 2020, p.1). Additional key features that define the HapCoil-Plus are that it has a low resonant frequency of 45Hz, that it provides an optimally damped response, and that it has a low response time. In order to create realistic and immersive haptic sensations that can be reproduced by the HapCoil-Plus, Actronika developed the UniTouch platform and engine. While the UniTouch platform offers access to several high definition libraries that were created by Actronika, entirely new haptic stimulations or stimulation patterns can be created with the UniTouch engine.

The Use of High Definition Haptic Actuators in the feelSpace belt

The variety of haptic sensations that can be produced by the HapCoil-Plus offers a vast variety of new possibilities for tactile SA devices such as the feelSpace belt. The vibration motors that are currently implemented in the feelSpace belt provide a "buzzing" tactile sensation and they can be regulated in their intensity. In contrast, the quality of the tactile sensation (i.e. texture) that is perceived by the user cannot be adjusted. This limits the amount of information that can be conveyed by the device. With the possibility to simulate different textures, the output of the device could be enhanced and a higher amount of information could be conveyed. Together with the potential integration of additional sensors, such as distance or obstacle detection sensors, approach/retreat dynamics of the environment could be implemented into the SA device's output. For instance, the device could identify the absence or presence of obstacles that need to be avoided by the user and inform the user whether they are required to stop or if they are free to continue to walk/approach. Especially for the example of blind users this could potentially lead to an enhanced space perception, less navigation-related accidents or injuries, and an increased confidence in their ability to navigate through space. Moreover, the HapCoil Plus could directly be used to create tactile sensations that are perceived as more pleasant and less distracting for the user and thereby provide an improved user experience. Finally, it could be investigated whether the HapCoil-Plus could be an effective solution to reduce the amount of vibration motors in the feelSpace belt or other tactile SA devices (s. Implemented Technical Improvements).

Skinetic Vest

The Skinetic vest is a wearable device has been developed by Actronika (www.skinetic.actronika.com). It uses Actronika's high definition haptic actuators (see Upcoming Technical Improvements). The vest allows for sensory stimulation of a larger skin surface than, for instance, a belt. The increased stimulation surface allows for the transmission for more large-scale and more complex output signals, as for instance the feelSpace belt. As increasing complexity of the output signal is likely to require an extended period of training for the interpretation of the signal (i.e. more than the six weeks training that were shown to be effective in case of the feelSpace belt), it remains to be investigated whether users could actually benefit from it in an applied case. Future research could focus on investigating different design approaches to tactile SA to determine which design approaches are effective given a certain use case.

Audio-tactile Augmentation of two-dimensional Data for the Blind

During the secondment with Gaspar Ramôa (ESR 15; Inventivio), we tested three different approaches to guide a blind or visually impaired (BVI) user to a single element in a tactile graphic.

Access to complex graphical information is essential in connecting blind and visually impaired people with the rest of the world. Tactile graphics readers are an emerging technology that give BVI users access to dynamic two-dimensional data through audio and tactile feedback. Still, these have not yet matured and stumble on user interface (UI) design obstacles. A challenging task for blind people is locating specific elements and small areas in complex and detailed tactile graphics. To this end, we developed three audio navigation user interfaces (UIs) that dynamically guide the user's hand to a specific element or position using audio feedback. One is based on submarine sonar sounds (sonar-based), another relies on the X- and Y-coordinates of the target element (axis-based) in a common coordinate system, and the last one uses direct voice instructions (voice-based). The different UIs were implemented in the Tactonom Reader device, a tactile graphic reader that has been developed by Inventivio GmbH to enhance swell paper graphics with pinpointed audio explanations through fingertip camera detection and audio-labeled SVG files. In order to evaluate the effectiveness of the three different dynamic navigation UIs implemented in the Tactonom Reader, we conducted a within-subject usability test that involved 13 visually impaired or blind participants. Beyond comparing the effectiveness of the different UIs, we observed and recorded the interaction of the visually impaired participants with the different navigation UI in order to further investigate their behavioral patterns during the interaction. We observed that user interfaces that required the user to move their hand in a straight direction were more likely to provoke frustration, and were often perceived as challenging for blind and visually impaired people. The analysis revealed that the voice-based navigation UI guides the participant the fastest to the target and does not require prior training. This suggests that a voice-based navigation strategy is a promising approach for designing an accessible user interface for the blind.

The study has recently been submitted for publication and we are currently awaiting a response from the editorial board.

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References

Actronika (2020). HapCoil-Plus – Datasheet. *Retrieved from*: https://uploads-ssl.webflow.com/5eb037130a8b570a78e002a0/600ef34dbf53c92366d35ddd_HapCoil_Plus_HC171785P_datasheet.pdf

Brandebusemeyer, C., Luther, A. R., König, S. U., König, P., & Kärcher, S. M. (2021). Impact of a Vibrotactile Belt on Emotionally Challenging Everyday Situations of the Blind. *Sensors*, *21*(21), 7384.

Clay, V., König, P., & König, S. U. (2019). Eye tracking in virtual reality. *Journal of eye movement research*, *12*(1).

Kaspar, K., König, S., Schwandt, J., & König, P. (2014). The experience of new sensorimotor contingencies by sensory augmentation. *Consciousness and cognition*, *28*, 47-63.

König, S. U., Clay, V., Nolte, D., Duesberg, L., Kuske, N., & König, P. (2019). Learning of spatial properties of a large-scale virtual city with an interactive map. *Frontiers in human neuroscience*, *13*, 240.

König, S. U., Keshava, A., Clay, V., Rittershofer, K., Kuske, N., & König, P. (2021). Embodied Spatial Knowledge Acquisition in Immersive Virtual Reality: Comparison to Map Exploration. *Frontiers in Virtual Reality*, *2*, 625548.

König, S. U., Schumann, F., Keyser, J., Goeke, C., Krause, C., Wache, S., ... & König, P. (2016). Learning new sensorimotor contingencies: Effects of long-term use of sensory augmentation on the brain and conscious perception. *PloS one*, *11*(12), e0166647.

Münzer, S., Fehringer, B. C., & Kühl, T. (2016). Validation of a 3-factor structure of spatial strategies and relations to possession and usage of navigational aids. *Journal of Environmental Psychology*, *47*, 66-78.

Münzer, S., & Hölscher, C. (2011). Entwicklung und Validierung eines Fragebogens zu räumlichen Strategien. *Diagnostica.*

Ramôa, G., Schmidt, V., & König, P. (In publishing*). Developing dynamic audio navigation UIs to pinpoint elements in tactile graphics.*

Schmidt, V., König, S. U., & König, P., (Unpublished Manuscript). *The Effect of an Augmented ‘Sense for Cardinal Directions‘ on Spatial Knowledge acquisition*.

Wölk, S., Schwandt, J., & König, P. (2022). Comparison of user performance in tactilely aided orientation tasks. *Bachelor Thesis, University of Osnabrück.*