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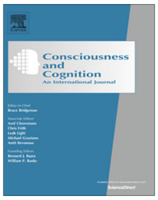

The experience of new sensorimotor contingencies by sensory augmentation

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ABSTRACT

Embedded in the paradigm of embodied cognition, the theory of sensorimotor contingencies (SMCs) proposes that motor actions and associated sensory stimulations are tied together by lawful relations termed SMCs. We aimed to investigate whether SMCs can be learned by means of sensory augmentation. Therefore we focused on related perceptual changes. Subjects trained for 7 weeks with the feelSpace belt mapping information of the magnetic north to vibrotactile stimulation around the waist. They experienced substantial changes in their space perception. The belt facilitated navigation and stimulated the usage of new navigation strategies. The belt's vibrating signal changed to a kind of spatial information over time while the belt's appeal and perceived usability increased. The belt also induced certain emotional states. Overall, the results show that learning new SMCs with this relatively small and usable device leads to profound perceptual and emotional changes, which are fully compatible with embodied theories of cognition.

1. Introduction

Action and perception are fundamental to human life. But how do they relate to each other and what are the implications of their relation? Classical theories in cognitive science assume a unidirectional relationship: first perceptual processing has to be accomplished for subsequent planning and execution of an action. Thus perception serves to build an "internal" representation of the "external" world (Marr, 1982). This approach has been very fruitful but has important limitations and fails to do full justice to the interdependence of perception and action (Brooks, 1991; Clark & Chalmers, 1998; Hurley, 2001, 2002). In recent years, this led to the emergence of an alternative, action-oriented paradigm turning the classical view upside down (Engel, Maye, Kurthen, & König, 2013; König, Wilming, Kaspar, Nagel, & Onat, 2013). It emphasizes the view that understands cognitive processes as deeply rooted in the embodied agent's interactions with the world (Clark, 2013; Varela, Thompson, & Rosch, 1991; Wilson, 2002). Embodied cognition is theorized as an active and multisensory probing of the environment (Mangen & Velay, 2010). From this viewpoint the relation between action and perception is understood as bidirectional: the two influence and change each other.

Sharpening the framework of embodied cognition, the theory of sensorimotor contingencies (SMCs, see Noë, 2010; O'Regan, 2011; O'Regan & Noë, 2001) suggests that action is constitutive for perception. The authors propose that motor actions and associated sensory stimulations are tied together by lawful relations termed sensorimotor contingencies. These

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are "rules or regularities relating sensory inputs to movement, changes and actions" (Clark, 2006, p. 2). Importantly the structure of these rules varies across e.g. vision, audition, touch, smell and taste, thereby differentiating the sensory modalities from each other (Macpherson, 2011a, 2011b; O'Regan & Noë, 2001, p. 941). A further distinction is made in the sensorimotor contingency theory between modality related SMCs that describe the structure of changes that is determined by the sensory apparatus itself and object related SMCs "that capture the multisensory patterns caused by actions towards objects" (Maye & Engel, 2012; O'Regan & Noë, 2001, p. 943). In the context of this theory perception requires the exploration of the environment in a way that is governed by both kinds of SMCs and the actively exercised mastery of them. While acting in the world the dependencies of motor action and associated changes of sensory input are learned and form how we perceive the world.

Experimental work in the field of sensory substitution supports the theory of SMCs: over forty years ago, Bach-y-Rita, Collins, Saunders, White, and Scadden (1969) examined brain plasticity in congenitally blind humans with a visual–tactile substitution apparatus which transmits visual information via tactile stimulation on the back. After training with the device blind adults used the information in a purposeful and goal-directed manner. The subjects could recognize objects and perceived them to be located in the external space. This approach has been further developed by several groups (Auvray, Hanneton, & O'Regan, 2007; Deroy & Auvray, 2012; Haigh, Brown, Meijer, & Proulx, 2013; Maidenbaum, Levy-Tzedek, Chebat, & Amedi, 2013; Ptito, Moesgaard, Gjedde, & Kupers, 2005; Striem-Amit, Guendelman, & Amedi, 2012). However, the perceptual experience mediated with a substitution device might be different from perceiving with the corresponding natural organ and therefore giving rise to transformed and extended perceptual capacities (Auvray & Myin, 2009). The reason according to the theory of SMC might be that the set of laws involved in, for example, seeing with the skin is not exactly the same as in seeing with the eyes. Angular resolution, drop of sensor density with eccentricity, variation of frequency, (color) sensitivity of receptors are just a few examples. However, sensory substitution, in general, strives to compensate a missing sensory modality through another and is, thereby, not restricted to visual–tactile input. (Deroy & Auvray, 2012; Hanneton, Auvray, & Durette, 2010; Ptito et al., 2005; Sampaio, Maris, & Bach-y-Rita, 2001; Tyler, Danilov, & Bach-y-Rita, 2003). In principle, it is irrelevant through which sensory channel the information is provided; what matters is that the stimulation obeys the sensorimotor rules of the sense to be substituted.

Given the evidence for successful sensory substitution, the next inevitable question is: can humans learn SMCs that we do not naturally have? Providing humans with sensory input that is not naturally available to them could provide a suitable approach to investigate this possibility. In fact, recent experiments (Nagel, Carl, Kringe, Märtin, & König, 2005) explored this hypothesis using a specially designed sensory augmentation device termed feelSpace belt. This belt mediates the information of the magnetic north via continuous vibrotactile stimulation around the waist. By this, it provides directional information for which humans, to our best knowledge, do not have a natural sensory system (e.g. Kärcher, Fenzlaff, Hartmann, Nagel, & König, 2012). Given the theory of sensorimotor contingencies and the idea of embodied cognition, adults who wear and train with the belt in natural environments for several weeks were expected to experience perceptual changes. Nagel et al. (2005) as well as Kärcher et al. (2012), the latter in a case study with a late blind participant, could demonstrate that the feelSpace belt actually led to subjective changes in space perception and revealed useful in navigational tasks. This work suggests that humans can learn new sensorimotor contingencies with an augmentation device resulting in qualitatively new perceptual experience.

Still central aspects of learning SMCs and the effects on spatial perception are unknown. Here we investigate the quality of changes in space perception in a larger cohort of people with normal vision over the whole training period with the feelSpace belt. We quantify perceptual experiences induced by the belt and investigate correlations of perceptual changes and training intensity. Having additional directional information we hypothesize that the belt device will also influence participants' impressions of their navigation style and performance. Finally, as the feelSpace belt is a complex device introducing a new kind of human–computer-interface the analysis of users' evaluation of the belt and the emotional impact is a mandatory step.

2. Methods

2.1. Participants

Over a period of 15 month, nine belt wearing participants (4 female) with a mean age of 23.67 years ($SD = 4.32$, range from 19 to 32) and five control participants (3 female) with a mean age of 23.00 ($SD = 1.26$, range 21–25) took part in our study. Participants were acquired according to the following criteria: healthy young adults, especially no neurologic, psychiatric, or chronic diseases, plenty of outdoor exercise (especially hiking and bicycling), good motivation and endurance, good introspection and openness to report about their experiences, good verbal skills, as well as time to wear and train with or without the belt, respectively.

In order to exclude systematic differences in relevant personality traits of belt wearing and control subjects we applied several psychological tests. The first test characterizes the way participants are action oriented and handle failure in terms of action vs. state orientation (Kuhl, 1994). These traits were measured by the German version of the action control scale (ACS-90) comprising three scales: action orientation subsequent to failure vs. preoccupation (AOF; *Chronbach's alpha* = .77), prospective and decision-related action orientation vs. hesitation (AOD; *alpha* = .82), and action orientation during successful performance of activities, which is the ability to stay within interesting activities without shifting prematurely to alternative activities (AOP; *alpha* = .36). The retest-reliability for all three scales ranged from .55 to .60. Groups did not differ regarding any aspects of action orientation as revealed by Mann–Whitney-*U* tests, all $Z \leqslant -1.17$, all $p \geqslant .30$.

Secondly, participants were screened regarding the big five personality traits (Costa & McCrae, 1992) as these traits are predictive for a bulk of everyday activities (Vernon, Villani, Vickers, & Harris, 2008): openness (*alpha* = .81), conscientiousness (*alpha* = .89), extraversion (*alpha* = .65), agreeableness (*alpha* = .75), and neuroticism (*alpha* = .86). The traits were measured by the German version of the NEO Personality Inventory (NEO-FFI, Borkenau & Ostendorf, 1993). The retest-reliability for all scales was above .85. Groups did not differ regarding the big five personality traits, all $Z \leqslant -1.67$, all $p \geqslant .11$.

2.2. Procedure

Participants were measured in four cohorts each lasting for eight to nine weeks including a seven week training period (see Table 1). Nine participants used the belt and were instructed to wear it during all waking hours over a period of seven weeks. This included an intensive outdoor training with, for example, bicycle tours or hiking in natural environments for at least 90 min each day. Belt wearing participants were instructed to pay attention to the belt while actively moving as well as to perceptual changes they might observe. They were allowed to switch off or take off the belt during prolonged periods without trunk movements, such as sitting in a lecture. Five additional participants served as a control group without belt experience. They were instructed in close analogy to the other participants. This included an outdoor training for the same amount of time, but without the belt. The control participants were asked to attend to how they navigate through the environment and whether they observed perceptual changes over time. Belt wearing and control participants were allowed to use maps and GPS. All participants filled out a daily diary to track their experiences, activities, sleep quality, mood, and technical problems with the belt (if applicable). At the end of each week, an additional in-depth evaluation was performed in the laboratory including closed- and open-ended questions, supplement interviews, as well as an evaluation of the belt device. Two month after the study, participants were once more tested in order to assess whether potential changes in spatial perception are long-lasting and to assess the retest-reliability of personality questionnaires in our sample.

2.3. Materials and instruments

2.3.1. FeelSpace belt

The technical aspects of the belt have been described before in detail (Kärcher et al., 2012). In short: The belt device is a sensory augmentation device providing directional information of magnetic north via vibration around the waist. It was designed in a way that ensures usability, robustness, and reliable vibrotactile stimulation up to 20 h non-stop without charging the battery packs. It consists of two battery packs, a control box, 30 vibrotactile piezo elements and a compass. The compass sensed the direction of the magnetic north pole. This information was translated into vibrotactile stimulation around the waistline by the vibrating elements. Only the northernmost of the vibration elements started vibrating when the belt was switched on because previous studies showed that participants feel irritated when more than one vibration element is active (Nagel et al., 2005). The vibrotactile frequency was set to the range from 170 to 185 Hz as an optimal sensitivity to tactile vibrations is achieved at frequencies between 150 and 300 Hz (Jones & Sarter, 2008). Importantly, the vibrotactile threshold is similar at any locus around the abdomen (Cholewiak, Brill, & Schwab, 2004).

2.3.2. AttrakDiff2

This questionnaire assesses the perceived pragmatic quality (PQ) of an interactive device, the hedonic quality (identification, HQI, and stimulation, HQS), and the device's overall appeal (APPEAL). Each of these four concepts is operationalized by seven word-pairs on a 7-point semantic-differential scale (Hassenzahl, Burmester, & Koller, 2003), for instance "motivating vs. discouraging" as a facet of appeal. The PQ scale is an assessment of the perceived usability (e.g. simple vs. complicated). The hedonic quality is split into two aspects: identification describes the possibility to communicate a desirable identity to others (e.g. isolating vs. coupling), while stimulation assesses the amount to which the product supports striving for personal development (e.g. original vs. conventional). Participants using the belt filled out the pencil and paper version of the AttrakDiff at the end of each week.

Table 1
Timetable of measurements.

	Before study	During study (week 1–7)	End of week 7	2 month after study
Daily diary	No	Yes	Yes	No
Weekly evaluation	No	Yes	Yes	No
FRS	Yes	No	Yes	Yes
AttrakDiff 2	No	Yes	Yes	No
ACS-90	Yes	No	No	Yes
NEO_FFI	Yes	No	No	Yes

2.3.3. Questionnaire measuring spatial orientation strategies

This questionnaire (abbr. FRS) measures the structure of different strategic aspects in spatial orientation by three scales validated by confirmatory factor analysis (Münzer & Hölscher, 2011). The "global-egocentric orientation" scale contains items displaying general ability and egocentric strategies that are based on knowledge of directions and knowledge of routes. The "cardinal directions" scale comprises indicators of knowledge of cardinal directions. The "survey" scale includes indicators of mental map formation. As shown by a first validation by Münzer and Hölscher (2011), these scales predict spatial learning in a real environment and show an incremental validity over relevant predictors of cognitive visual–spatial ability. Participants using the belt and control participants filled out the questionnaire before the training, after the seven weeks of training, as well as two additional months later.

2.3.4. Daily diary

Participants filled out each evening a specially designed questionnaire in terms of a daily diary. This diary has successfully been used in a previous case study by Kärcher et al. (2012). It comprises some control items measuring the kind of activities participants performed with the belt, whether and what kind of technical problems with the belt occurred, and how long participants wore the belt. These items were excluded in the daily questionnaire for control participants. However, both versions included a half-opened item measuring the specific elements of the daily training and their durations. Based on this information we were able to assess the duration of intensive training with and without belt. Furthermore, both versions contained several 5-point Likert-items assessing sleep quality of the last night and participants' state of health, their happiness, alertness, calmness, and listlessness. As suggested by Ohly, Sonnentag, Niessen, and Zapf (2010), these single items were selected according to their high factor loadings on different scales of questionnaires measuring components of emotional states (MDBF: Steyer, Schwenkmezger, Notz, & Eid, 1997; BEF: Kuhl, 1999; VGZ: Feist & Stephan, 2007). The daily diary additionally provided space to write down all experiences participants had during the last day. The analysis procedure for the resulting open-ended data is described below.

2.3.5. Weekly evaluation

In order to gather additional information about participants' spatial perception and potential dependencies on belt wearing and training, special designed evaluations of the past week were performed in the laboratory each week. This weekly evaluation has been successfully tested in Kärcher et al. (2012). We used a set of single-item scales (see result section) that were constructed on the base of interviews with pre-experimental test-participants. The questionnaire also contains several items measuring belt-related experiences. For the control group a reduced version without belt-related items was created. In very rare cases the items showed non-response (0.62%). Missing data were imputed by the values of the previous week, i.e. we selected a conservative procedure assuming no change when a value was missing.

Both versions of the questionnaire additionally included two questions in open-ended format. We asked in which way a new kind of spatial perception – as far as reported by the participants – is noticeable, and – as far as participants reported a mental map of the environment before the study – we asked them to describe whether this mental map has changed its nature during the study. The questionnaire of the belt group comprised two more open-ended questions: "*If you perceived the belt signal not as vibration but as something else please describe your sensations*", and "*If you have recognized some further unspecific changes which might be related to the belt's vibration, please describe these changes as precisely as possible*". The weekly evaluation finally included half-standardized interviews in order to clarify the former statements and facilitate their explication in a content analysis – described in detail below.

2.4. Data analysis

Quantitative data gathered by closed-item scales were analyzed by means of non-parametric statistics due to small sample sizes. For time-dependent changes we used Friedman tests, for group comparisons Mann–Whitney *U*-tests, and for paired samples Wilcoxon tests. Correlation coefficients are reported in terms of Spearman's Rho.

Open-ended questions enabled us to obtain insights in what actually is on the mind of our study participants (cf. Eckhardt & Jamison, 2002). These qualitative data from diary entries and from open-ended questions of the weekly evaluations were merged and analyzed in accordance with a qualitative content analysis procedure (Mayring, 2003):

1. Open-ended answers were transcribed.
2. Transcriptions were explicated by using context information, i.e. the wording of the corresponding item and audio data of the subsequent interview in order to specify participants' statements.
3. For quantification of the relevant aspects we developed the category system to systematically uncover important aspects in participants' experiences: a 3-level category system was developed in several iterations on the basis of all open-ended data. Then, two independent raters categorized explicated statements into five level-1 categories: (1) Space Perception, (2) Navigation, (3) Belt Experiences, (4) Belt-induced Feelings and Emotions, as well as (5) Residuals. Sub-level categories are further described in the result section.
4. The inter-rater agreement in terms of Cohen's Kappa was very high in the range of 0.82–0.94 on all three levels of the category system. In cases where the raters did not agree, a consensual agreement was subsequently forced in order to allow frequency analysis (Kaspar, Hamborg, Sackmann, & Hesselmann, 2010; Kaspar & König, 2011).

5. A frequency analysis of statements was computed with the aid of the category system. The core assumption of a frequency analysis of statements is that the frequency of specific statements indicates the extent to which specific cognitions reflect predominant experiences of study participants (cf. Hull, Levenson, Young, & Sher, 1983). For sub-level data of main categories we also counted the number of weeks (0–7) in which a subject made a statement of a specific category, whereby multiple statements assigned to the same category within a week were always counted as one statement in order to prevent a frequency bias due to either talkative participants or – in the context of the daily diary – due to multiple mentioning within a week. We always report the total number of statements as well as this corrected number.

3. Results

3.1. Duration of belt wearing and training

To control for comparable training times and motivation we evaluated these variables both for belt wearing and control participants. Participants of the belt wearing group recorded the duration of belt wearing and intensive training each day. Participants of the control group recorded the corresponding intensive training duration without belt. The grand mean duration of wearing the belt averaged across 49 days was 10.65 h/d ($SD_{Subjects} = 1.85$), the intensive belt training was 1.57 h/d ($SD = .17$) and the training of the control group 1.57 h/d ($SD = .55$). No changes over the seven weeks regarding belt wearing and intensive belt training, as well as control training were observable, all $\chi^2(6) \leqslant 8.93$, all $p \geqslant .18$. Thus the duration of the specific training can be considered constant over time in both groups. Furthermore, in the context of the weekly interviews participants rated their motivation to wear the belt and to train specifically during the past week. The belt wearing group (grand mean across weeks: $M = 3.97$, $SD = .30$) and the control group ($M = 3.97$, $SD = .34$) showed an overall high and time-independent motivation with a slight meanwhile decrease, $\chi^2(6) = 9.42$, $p = .15$ (belt); $\chi^2(6) = 9.72$, $p = .14$ (control) in the fourth week. The training motivation of the belt wearing group equalled the one of the control group. In summary, training and control group do not display any significant differences with respect to training duration or motivation.

3.2. Space perception

In order to quantify participants' knowledge about, and perception of, the space that provides the cognitive basis for navigational behavior, participants filled out the FRS questionnaire before the study, afterwards, and two additional months later. This questionnaire measures three strategic aspects in spatial orientation based on specific knowledge of space characteristics: cardinal directions, survey, and global-egocentric orientation. Control participants did not show a change in any of these aspects over the three measurements, all $\chi^2(2) \leqslant .55$, all $p \geqslant .76$. In contrast, participants wearing the belt showed a specific signature of change across the three measurements regarding all aspects of spatial perception: scale values increased during the training period, i.e. from first to second measurement (see Fig. 1). However, this improvement diminished during the 2 month after the study from the second to third measurement.

Regarding the knowledge of cardinal directions for orienting in the environment (first scale "cardinal directions" of the FRS) this signature was significant, $\chi^2(2) = 6.34$, $p = .04$ (Fig. 1). With respect to the second scale of the FRS, namely "survey", addressing the formation of a mental map a significant change over time occurred, $\chi^2(2) = 6.23$, $p = .04$, (Fig. 1). At the beginning of the study we also explicitly asked participants in both groups whether they had a mental map before the study began, but no difference between belt and control group was observable (belt: 78%; control: 80%), i.e. the difference in space

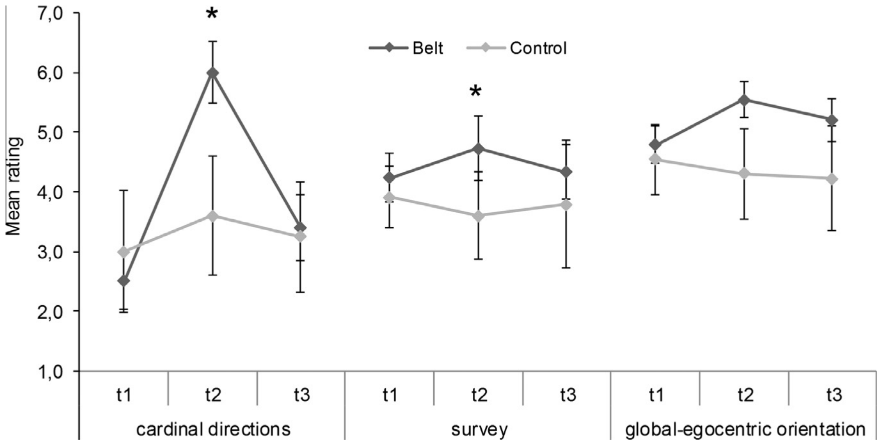

Fig. 1. Mean rating on three scales of the FRS questionnaire (ranging from 1 to 7) measuring different strategic aspects in spatial orientation (cardinal directions, survey, and global-egocentric orientation). Vertical lines indicate standard error of the mean. Asterisks mark significant changes over the three measurements.

perception between control and belt wearing group at the end of the training period was an effect of the belt's impact. With respect to participants' general knowledge of directions and routes (third scale "global-egocentric orientation" of the FRS) we observe a similar temporary increase as above, which however did not reach statistical significance $\chi^2(2) = 3.71$, $p = .16$ (Fig. 1).

These observations are complemented by the weekly questionnaires: all participants weekly rated the statement "*With the belt I can give more precise estimations on how streets are related to one another/Due to the training I can give more precise estimations on how streets are related to one another.*". This revealed no changes over time within the two groups, both $\chi^2(6) \leqslant 7.77$, both $p \geqslant .26$. But – when comparing the grand means (across weeks) – participants wearing the belt ($M = 3.92$, $SD = .22$) had the impression to be better than their control group counterparts ($M = 3.00$, $SD = .31$) in this respect, $Z = -2.48$, $p = .01$. Participants also weekly rated the items "*With the belt I am always aware where I am located in relation to my home/I am always aware where I am located in relation to my home*" and "*With the belt it is easier for me to indicate the position of different places to each other/Since I train my orientation it is easier for me to indicate the position of different places to each other*". Regarding both items significantly increasing values across weeks were found for the belt group, both $\chi^2(6) \geqslant 14.43$, both $p \leqslant .03$, but no time-dependent changes for control participants, both $\chi^2(6) \leqslant 6.78$, both $p \geqslant .34$.

To clarify whether the duration of belt wearing time and intensive training determine the effects as quantified by the FRS, we computed the difference scores between the first measurement (i.e. before the study) and the second one (i.e. after seven weeks belt wearing) for each scale and correlated them with the grand mean duration of intensive belt training as well with the grand mean duration of total belt wearing time. Overall, we found a significant positive correlation between the increase in global-egocentric orientation and the duration of belt training, $\rho = .65$, $p = .06$ but not with total belt wearing time: $\rho = .47$, $p = .21$. No significant but also moderately positive correlations revealed between the formation of a mental map (scale "survey") and intensive belt training, $\rho = .36$, $p = .34$, as well as between training duration and the improvement of cardinal directions for orientation (scale "cardinal directions"), $\rho = .38$, $p = .32$. The duration of belt wearing did not correlate with the latter two scales.

Overall, the belt, as long as it was used, supported the enhancement of participants' knowledge about space characteristics providing the basis for spatial orientation. Participants wearing the belt also had the impression to be better than their control group in global-egocentric orientation, while study participation apparently sensitized participants for cardinal directions in general. However, two months after the end of belt wearing the effects diminished. The duration of daily belt training revealed as an important mediator of the effect sizes. We observed significant changes of perceptual experiences and a positive correlation of these with intensity of belt training.

In addition to the quantitative data from rating scales, we analyzed the open-ended statements of the daily diary and weekly evaluation with the help of a custom developed category system (see Section 2). The main level categories cover space perception (Table 2), belt experience (Table 4), navigation (Table 5), as well as belt-induced feelings and emotional

Table 2
Results of frequency analysis of participants' open-ended statements assigned to the main category (1) Space Perception. Labels of level-2 and level-3 subcategories are depicted as well as the total number of statements assigned to the respective category. Moreover the corrected number of statements is shown i.e. the number of weeks (across participants of a group) in which at least one statement of a given category occurred (adjusted for multiple entries) and its relation to the number of participants who made such a statement.

Subcategories of category (1) Space Perception		Belt group			Control group		
Level-2	Level-3	Total number	No of weeks	No of participants	Total number	No of weeks	No of participants
(11) Spatial relations (SR)	(111) SR with self-reference	18	11	6	4	3	3
	(112) SR between locations, objects, and streets	17	12	6	2	1	1
	(113) Alignment toward cardinal directions	26	15	5	4	4	2
	(114) Residuals	23	16	6	2	2	2
(12) Matching between spatial information and representation	(121) Mismatch	29	15	7	5	8	3
	(122) Correction	18	15	6	2	2	2
	(123) Match	11	11	4	0	0	0
	(124) Residuals	6	5	2	0	0	0
(13) Mental perspective on the world	(131) Aerial perspectives	6	6	5	2	1	1
	(132) Ego-perspective	5	5	3	1	1	1
	(133) Residuals	2	2	2	0	0	0
(14) Enhanced mental perception of space	(141) Enlarged mental map	11	10	6	3	3	2
	(142) More detailed perception of space	17	14	5	11	8	3
	(143) Space perception beyond visibility	10	5	1	0	0	0
	(144) Residuals	10	7	4	5	4	3
(15) No change in mental perception of space		2	2	1		6	4
(16) Residuals		69	34	7	15	9	4

Table 3
Single-item scales (1–5) measuring how participants experienced the belt device. Mean values for the first rating (after week 1) and the last rating (after week 7) as well as results of Friedman tests (comparing all seven measuring times) are depicted.

Item	Week 1		Week 7		Test results	
	M	*SD*	*M*	*SD*	*Chi*^{2}	*p*
The belt restricted me in my daily activities	2.20	.32	2.00	.37	6.20	.40
I am always consciously aware of the belt while wearing it	4.50	.17	4.20	.19	25.94	<.01
I perceive the transmitted information as vibration	4.22	.15	2.77	.28	19.35	<.01
I do not perceive the transmitted information of the belt as vibration but as something different	2.00	.29	3.55	.24	22.04	<.01
After taking off the belt I still perceive a feeling of vibration	3.22	.32	1.66	.29	23.04	<.01
I consciously concentrate on the belt to use its information	4.33	.17	3.33	.33	11.42	.08

Table 4
Results of frequency analysis of participants' open-ended statements assigned to the main category (3) Belt Experience. Labels of level-2 and level-3 subcategories are depicted as well as the total number of statements assigned to the respective category. Moreover the corrected number of statements is shown i.e. the number of weeks (across participants of a group) in which at least one statement of a given category occurred (adjusted for multiple entries) and its relation to the number of participants who made such a statement.

Subcategories of category (3) Belt Experience		Belt group		
Level-2	Level-3	Total number	No of weeks	No of subjects
(31) Quality of belt signal perception (BSP)	(311) BSP is primarily acoustic	7	7	2
	(312) BSP is primarily tactil.	10	10	4
	(313) BSP is primarily space information.	34	23	6
	(314) Residuals	9	8	5
(32) Saliency of belt signal (BS)	(321) BS is more salient when it is needed	2	2	2
	(322) BS saliency increases when attention is directed to	7	7	5
	(323) BS gets salient with change of direction	5	3	2
	(324) Residuals	3	3	2
(33) Gradually reduced awareness of belt signal		43	25	9
(34) Residuals		90	34	9

states (Table 6). Examples and statistical analyses of these data are given in the corresponding result sections. In the following, we present the qualitative data assigned to the category (1) *Space Perception*.

First, statements were analyzed with respect to potential differences between belt wearing participants (BWP) and control participants (CP) (Table 2). Especially belt wearing participants reported dominant cognitions about spatial relations between locations, objects, and streets (category 112), e.g. "*It happens more and more often that I know about the relations of rooms and locations to each other, of which I was not previously aware.*" (BWP1), including their own position (111), as well as objects' alignment towards cardinal directions as a new feature (113), e.g. "*In a lot of places, north has become a feature of the place itself.*" (BWP5). Moreover, most of them reported to perform a cognitive matching between gathered spatial information and their mental map of the environment (12), indicating a learning process, e.g. "*The information from the belt refines my own mental map. There are for instance places where I thought to know where north is and the belt gave me another picture.*" (BWP4). The perception of space in terms of a mental map of the environment subjectively enlarged (141), e.g. "*Mental maps have a range. Now that my maps have all been newly realigned, the range of the maps has been much increased. From here I can point home – 300 km – and I can imagine – not only in 2D bird's eye perspective – how the motorways wind through the landscape*" (BWP5) and the space was perceived beyond visibility (143), e.g. "*Space has become wider and deeper. Through the presence of objects/landmarks that are not visually apparent, my perception of space extends beyond my visual space. Previously, this was a cognitive construction. Now I can feel it*" (BWP3). A more detailed perception of space in terms of a more detailed mental map was reported by belt wearing and control participants (142), while belt wearing participants occasionally emphasized that this perceptional change was also true for unfamiliar locations: "*Thanks to the continuous information of the belt and the certitude about North I have a better and more fine-grained mental map particularly in unfamiliar environments.*" (BWP4), "*I am more and more aware of how the mental map is constructed: it reflects roughly the whole environment and in familiar areas it is definitely clearer. Landmarks play a more important role than I thought.*" (CP5). Finally, five of nine belt wearing participants but only one control participant reported that they had an aerial perspective on the environment (131). To investigate whether participants perceived a change in space perception all had to rate weekly the item "*Overall I am developing a new sense of spatial perception with the belt/with training*" (yes vs. no): after the first week the percentage of participants who answered with "yes" did not significantly differ between groups, $Z = -.93$, $p = 44$ (control: 40%, belt: 66.67%), but after the sixth and seventh week 8 of 9 belt wearing participants answered with "yes", while all participants (5 of 5) of the control group denied the development of a new sense of spatial perception, $Z = -3.10$, $p < .01$. This discrepancy between belt wearing and control group was also supported by participants' qualitative reports where four of five control subjects explicitly stated that they did not perceive a change in space perception (15). One did not talk about the topic besides answering the weekly question. These qualitative differences are further emphasized by the quantitative difference of 31.1 statements (280 statements in total provided by nine BWS) vs. 12.6 statements (63 provided by five CS) per subject and week in the main category Space Perception (Table 2). Thereby, the mean number of statements per belt wearing subject slightly decreased from 5.7 (week 1) to 4.6 (week 7) over time, while control subjects provided 1.8 (week 1) and 1.0 (week 7) statements, respectively.

To conclude, the data show that belt wearing participants experienced substantial changes in their perception of space during the study and the difference to the control group is striking.

3.3. Belt perception

In addition to participants' perception of space characteristics, some quantitative items in the weekly evaluation addressed the perception of the belt signal itself. Participants answered several 5-point items from "*strongly disagree*" (1) to "*strongly agree*" (5). Table 3 depicts the wording of all these items, the means for the first rating after week 1 and for the last rating at the end of the study, as well as test results of Friedman tests. In all cases of significant changes over time – except the awareness of the belt while wearing it (which reached a meanwhile minimum after the fifth week: $M = 3.71$, $SD = .22$) – the change was of linear nature (not depicted) with a maximum value after week 1 and a minimum value after week 7, or vice versa.

Subsequently, we correlated the difference scores between the first and seventh week (week 7 minus week 1) with the total duration of daily belt wearing, as well as with the duration of intensive belt training. We found that, by trend, the longer the overall belt wearing was the more the transmitted information of the belt was perceived as something different than vibration, $\rho = .59$, $p = .09$. This correlation additionally increased and was significant when solely considering the duration of intensive belt training, $\rho = .76$, $p = .02$. No further correlation between belt-related experiences and the duration of belt wearing reached the significance level.

To conclude, quantitative ratings show that participants successively habituated to the belt and its vibration. They indicated changes in the quality of belt signal perception. The duration of daily belt wearing and intensive training did not correlate with most aspects of belt experience, but the quality of the transmitted information – originally vibrotactile – changed into something different with longer durations of belt wearing and training.

The content analysis of participants' open-ended reports revealed additional insights into salient aspects of participants' belt experiences, summarized in the corresponding category (3) *Belt Experiences* (Table 4). Although the information transmitted by the belt was partially perceived in the acoustic domain (311) and also in the originally tactile domain (312) six of nine participants reported at several measurements that the quality of the belt signal is primarily a kind of space information (313), e.g. "*Often I do not perceive the vibration any more. It is rather a direct feeling of knowledge – not even really a perception. It does not feel like any other sense*" (BWP3). Furthermore, the saliency of the belt signal primarily increased when attention was directed to the belt (322), indicating that the belt was not very salient all the time of wearing. In fact, all participants reported a gradually reduced awareness of the belt signal over time (33). Many statements were classified as residuals with respect to belt experiences (34). The statements ranged from "*For instance, it might be more useful to know that it vibrates 10–15° on the right of the belly button means one stands in a North to West direction.*" (BWP1); "*I feel phantom vibrations on my stomach – similar to as if one was wearing a cap all day long and during night one still thinks it would be on one's head. I also have the feeling to still hear the sound of the belt.*" (BWP3); "*I trained walking a path with the belt with closed eyes. With eyes open it naturally worked but the closed eye training definitely also trained my sensibility for the belt signal.*" (BWP8).

To sum up, with increasing belt wearing duration the belts vibrating signal is less consciously perceived and changes more to a kind of spatial information.

3.4. Effects on navigation

In addition to changes in participants' space perception we were interested in their evaluation of their specific navigational behavior. Therefore, participants weekly rated three items addressing navigation through the environment. This revealed a clear picture: the belt did not lead to the impression that one's sense of orientation improved in general, but when using the belt navigation performance benefitted from that: on the one hand, all participants moderately agreed to the item "*I have the feeling that my spatial sense of orientation improved since wearing the belt/since training*" but with no time-dependent changes within groups, both $\chi^2(6) \leqslant 4.78$, both $p \geqslant .57$, and no significant group differences at any week, all $Z \leqslant 1.32$, all $p \geqslant .24$. The grand mean for control participants was $M = 2.77$ ($SD = .46$) and for belt users $M = 3.16$ ($SD = .34$). However, when explicitly contrasting belt wearing time and time without the belt in terms of "*With the belt it is easier for me to orient myself in a new environment than without the belt*", we found a significant and continuous increase for belt wearing participants over time, $\chi^2(6) = 20.54$, $p = .002$, with a maximum value after the last week of the study (Fig. 2). In contrast, no time-dependent changes occurred in the group of control participants when correspondingly addressing their orientation training "*Since I train my orientation it is easier for me to orient myself in a new environment*", $\chi^2(6) = 4.42$, $p = .62$. Additional group comparisons showed significant higher values in the belt group after the fifth, $Z = 2.01$, $p = .06$, and seventh week, $Z = 2.30$, $p = .03$. This result is in line with the following one: belt wearing participants additionally rated the item "*When*

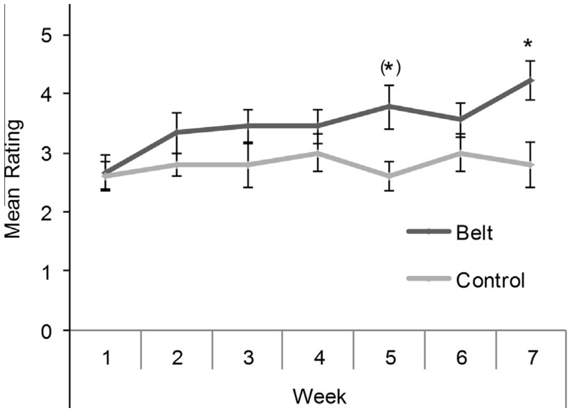

Fig. 2. Mean rating of belt/control participants' ability to navigate through new environments. Vertical lines indicate standard error of the mean. Asterisks indicate the results of (weekly) pairwise comparisons between belt and control group by means of Mann–Whitney-*U* tests [$^{*}p < .05$; $(^{*})\ p < .1$].

I take off the belt my spatial sense of orientation decreases", whereby their agreement with this statement significantly increased over time and reached a maximum value after the last week, $\chi^2(6) = 13.57$, $p = .04$.

All in all, belt wearing participants reported a clearly higher improvement of navigation skills compared to control participants, but interestingly this improvement was apparently tied to the belt and did not become independent.

With the content analysis of open-ended statements assigned to main category (2) *Navigation* (Table 5) we further explored navigational changes in belt wearing and control participants. Belt wearing participants reported to use the belt for indicating cardinal directions (211) or to stay on course (213), e.g. "*I felt good by just following a rough direction indicated by the belt (...)*" (BWP8), while control participants either used other navigational aids (e.g. GPS and maps) to orient towards cardinal directions (212), or they used landmarks (219). The majority of control participants did not consider cardinal directions for navigation (218). Hence, belt wearing and control participants apparently used different navigation strategies. Moreover, three of five control participants reported more conscious attention to the environment while no belt wearing participant expressed this strategy (220). In contrast, belt wearer reported automated navigation without mental reflection

Table 5

Results of frequency analysis of participants' open-ended statements assigned to the main category (2) Navigation. Labels of level-2 and level-3 subcategories are depicted as well as the total number of statements assigned to the respective category. Moreover the corrected number of statements is shown i.e. the number of weeks (across participants of a group) in which at least one statement of a given category occurred (adjusted for multiple entries) and its relation to the number of participants who made such a statement.

Subcategories of category (2) Navigation		Belt group			Control group		
Level-2	Level-3	Total number	No of weeks	No of subjects	Total number	No of weeks	No of subjects
(21) Navigation process	(211) Belt indicates cardinal directions	8	7	3	0	0	0
	(212) Navigational aids (not belt) indicate cardinal directions	2	2	1	17	8	4
	(213) Belt helps to stay on course	5	5	2	0	0	0
	(214) Belt points to start or destination location	2	1	1	0	0	0
	(215) Belt vibration on body surface is used for navigation	9	6	1	0	0	0
	(216) City maps are used for navigation	2	2	1	5	4	2
	(217) A mental map is used for navigation	1	1	1	2	1	1
	(218) Cardinal directions are not considered for navigation	1	1	1	7	7	4
	(219) Landmarks are used for navigation	3	3	1	18	14	5
	(220) More conscious attention to environment	1	0	0	4	4	3
	(221) Residuals	26	15	6	7	2	2
(23) Navigation ability	(231) Spontaneous navigation with little reflection	10	8	4	0	0	0
	(232) Belt facilitates navigation	29	15	4	0	0	0
	(233) Navigation without belt needs cognitive effort	3	2	1	8	8	5
	(234) Navigation ability without belt has not improved	0	0	0	2	2	2
	(235) Residuals	26	19	7	26	11	4
(24) Residuals		9	5	3	10	8	2

(231) and that the belt facilitated navigation overall (232), e.g. "*I am literally less disoriented*" (BWP8), or "*Today I stepped out of the train and I immediately knew where I have to go. This was a really nice experience! During the day I could always estimate my direction well. With the belt one does not have to always care so much whether there is a turn (in the way you go), one simply feels it without much thinking!*" (BWP9). In contrast, all control participants explicitly expressed that navigation (without the belt) needs cognitive effort (233). Consequently, the verbal reports support the results of the quantitative single-item scales: the belt clearly facilitated navigation and stimulated the usage of a different kind of navigation strategies.

3.5. Evaluation of the belt device

Participants evaluated the belt device regarding its overall appeal, usability i.e. pragmatic quality, and hedonic qualities after each week by means of the AttrakDiff2 questionnaire. A Friedman test revealed a successive increase in perceived pragmatic quality (PQ) of the belt over time with a maximum after the last week, $\chi^2(6) = 14.63$, $p = .02$, as well as, by trend, an increase in appeal (APPEAL) with a maximum after the seventh week, $\chi^2(6) = 11.41$, $p = .08$ (Fig. 3). No changes were found regarding the two aspects of hedonic quality (HQI and HQS), both $\chi^2(6) \leqslant 3.93$, both $p \geqslant .69$. The grand means of each scale (mean across seven weeks) were pairwise contrasted by Wilcoxon tests revealing higher ratings for the belt's HQS in contrast to the other characteristics, all $p \leqslant .02$, which themselves did not differ from each other, all $p \geqslant .17$. Hence, the perceived usability (PQ) of the belt in fact increased over the training period, which was paralleled by an increase in the belt's overall appeal. Moreover, the belt as an interactive product showed a constant and very high hedonic quality of stimulation (HQS) and consequently supported striving for personal development as defined by Hassenzahl et al. (2003) on the basis of the AtracDiff2. Overall, these results indicate both a high usability and a high joy of use.

The final ratings provided after the seventh week of training positively correlated with the grand mean duration of daily intensive training, but not with the total belt wearing time: only the correlation between hedonic quality of identification (HQI) and the duration of intense training reached hereby significance, $\rho = .74$, $p = .04$ (not shown in the figure). However, also the correlation between training duration and the other three belt qualities showed a medium to large effect size according to Cohen (1988), $\rho = .30$, $p = .47$ (APPEAL); $\rho = .52$, $p = .19$ (PQ); $\rho = .45$, $p = .27$ (HQS). When considering the total duration of belt wearing, including but not limited to intensive training, the correlation with HQS slightly increased, $\rho = .59$, $p = .12$, but all other correlation were negligible, all $\rho \leqslant .24$, all $p \geqslant .57$.

Consequently, the more time participants invested into intensive training the more they felt that by using the belt they communicated a desirable identity to others (HQI), and – by trend – the more they liked the belt's appeal and its usability. Though this relationship is only correlative, the training duration showed a clear positive relationship to the perceived belt characteristics.

3.6. The impact of the belt device on feelings and emotional states

Belt wearing participants provided a lot of open-ended statements in which they expressed belt-induced feelings and emotions. Consequently, they were assigned to the main category (4) (Table 6). In contrast to the belt wearing participants control participants hardly ever talked about feelings or emotions. On the sub-levels we found that, on the one hand, the belt provided a feeling of security (411), e.g. "*Even if without the belt I would at any given location know my surroundings just as well and manage just as well to find my way I still feel more comfortable with the belt and certain that I would find my way around anywhere without any problems*" (BWP9). The belt also induced curiosity and joy of use (412), the latter findings support the results of the belt evaluation (see above). On the other hand, malfunctions of the belt (414) induced some irritations. Inter-

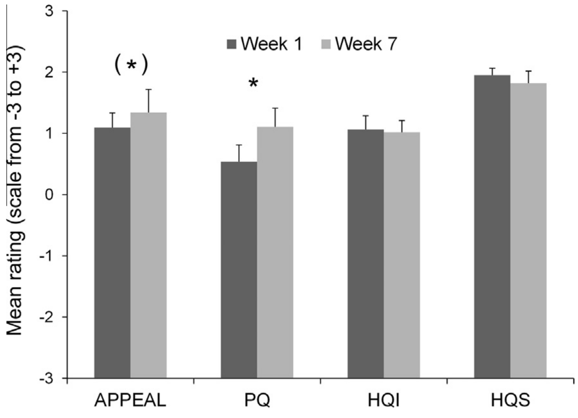

Fig. 3. Difference between week 1 and 7 in mean ratings of the belt's overall appeal (APPEAL), its perceived pragmatic quality (PQ), its hedonic quality identification (HQI), and its hedonic quality stimulation (HQS). Vertical lines indicate standard error of the mean. *Note:* the original scale (1–7) is re-scaled here (range from −3 to +3) to facilitate interpretation of absolute values. Legend: $^*p < .05$; $(^*)$ $p < .01$.

Table 6
Results of frequency analysis of participants' open-ended statements assigned to the main category (4) Belt-induced Feelings and Emotions. Labels of level-2 and level-3 subcategories are depicted as well as the number of weeks (across participants of a group) in which at least one statement of a given category occurred and the number of participants who made such a statement.

Subcategories of category (4) Belt-induced Feelings and Emotions		Belt group		
Level-2	Level-3	Total number	No of weeks	No of subjects
(41) Descriptions of belt related feelings	(411) Belt induces a feeling of security	17	10	4
	(412) Belt induces curiosity and joy of use	14	11	4
	(413) Use of belt results in cognitive exhaustion	6	3	2
	(414) Malfunctions of belt induce irritations	12	10	5
	(415) Wearing of correctly functioning belt induces irritations	28	19	8
	(416) Residuals	21	14	6
(42) Descriptions of feelings without belt	(421) Something is missing without the belt	27	19	9
	(422) Feeling of insecurity without the belt	4	3	3
	(423) Feeling of relief when taking of the belt	7	6	4
	(424) Residuals	1	1	1
(43) Feelings associated with the belt's return	(431) Looking forward to return the belt	2	1	1
	(432) Desire to retain the belt and to continue	8	6	4
	(433) Conflicting feelings towards the belt's return	1	1	1
	(434) Residuals	1	1	1
(44) Expectations towards the belt	(441) Belt exceeds expectations	2	2	2
	(442) Belt fits expectations	0	0	0
	(443) Belt experiences differ from expectations	5	4	4
	(444) Residuals	5	4	3
(45) Residuals		18	13	7

estingly participants experienced also the deviation of the local magnetic field through emitters as a malfunction of the belt, "*In the AVZ building* [a building on the University campus] *there are a lot of disturbing sources* [for the belt signal]. *The elevators are driving me crazy. Nowhere is an area where the belt is working properly. At the beginning I didn't realize or mind this so much. But now* [after 6 weeks of training] *I find this highly irritating.*" (BWP3). Also a correctly functioning belt induced some irritations (415). Moreover, while all participants expressed that something was missing when the belt was taken off (421), some reported a feeling of insecurity without the belt (422), but some also reported a feeling of relief when taking off the belt (423). Four of nine participants explicitly mentioned the desire to retain the belt and to continue the study (432). Finally, the expectations of the belt's impact prior to the wearing time were not consistent with participants' real experiences: either the belt device exceeded the prior expectations (441) or the experiences differed from the initial expectations (443), indicating that none of the subjects correctly anticipated the impact of the belt and the experiences with it. Overall, the most prevalent emotional effects of the belt device were apparently feelings of security, curiosity, and joy of use, but also some irritations.

Finally, we continuously tracked participants' quality of night sleep, state of health, happiness, alertness, calmness, and listlessness by means of quantitative items in the daily diary. Due to the expected strong influence of the belt on perceptual and cognitive processes we were interested in potential collateral influences on physical and mood-related aspects. Daily data were averaged for each week and weekly means were statistically compared. As no baseline was available for both groups, only within-group changes over time were of interest. Sleep quality did not differ over time in the belt group, $\chi^2(6) = 3.11$, $p = .80$, but sleep quality successively increased in the control group, $\chi^2(6) = 13.69$, $p = .03$. Regarding participants' own daily calmness no change was found for the belt wearing participants, $\chi^2(6) = 2.87$, $p = .86$, but control participants showed an slight increase over time, $\chi^2(6) = 11.12$, $p = .09$. Neither the control, nor the belt wearing group reported a change in their state of health, alertness, happiness, and listlessness, all $\chi^2(6) \leqslant 7.84$, all $p \geqslant .24$. Consequently, sleep quality and overall calmness increased in the control group over the study duration, but more importantly, the usage of the belt had no time-dependent effect on users' reported sleep quality, state of health, and general emotional state beyond the emotional effects elicited by the direct interaction with the belt or periods of deprivation.

3.7. Statements in the residuals categories

Finally, we give an impression of statements that fell into residual categories. This includes the level-1 category (5) *Residuals* as well as the residual categories on sub-levels 2 and 3 (category numbers will be presented in brackets). Although we do not apply statistics, they give a more complete impression of the effects of the belt device.

Some participants reported remarkable dreams which were assigned to the residuals category on level-1 (5). An example of a control participant illustrates that during the training period navigation was an important topic: "*In my dream I had to walk through Osnabrück* [the subject's home town], *although it did not look like Osnabrück and I got completely lost.*" (CP2).

Dreams of belt wearing participants included, for example, sensations that were induced by the belt and are related to spatial perception: "*In the last time* [during the belt training period] *my dreams center a lot around running/driving/jumping in circles. Connection? I think yes, because the vibration is circling around me.*" (BWP8); "*Shortly after falling asleep, I dreamt of a marble and its way through some sort of roller coaster: fast curves, up and down, loopings, etc. For the first time I had a clear feeling of orientation. It wasn't only movements, but there was also a relation between the movements. I could swear that I felt the orientation in my tummy. But that's strange because I was not bodily present in my dream. It was almost only about movements and positions. It was really great! I have never had such a clear and consistent feeling of room experience. Single moments were all connected and I knew what is the course of my marble.*" (BWP3).

Belt wearing subjects also reported reactions of other people towards the belt (5), e.g. "Other people find the humming of the belt annoying and say that they could not tolerate it, but nevertheless they find the experiments really cool." (BWP6).

Most of the statements in the residual categories concerned heterogeneous topics. First we give some of the control subjects: (5) "*I would like to have a belt, too. I imagine that developing a feeling for North is really useful.*" (CP5); (16) "*I now pay more attention to my mental map compared to before.*" (CP1); (16) "*Walking through the city with a friend. We played the game 'where is north'. It was fun.*" (CP3). Second we give a couple of examples of the belt wearing participants: (34) "*When I take off the belt, my tummy still feels more sensible as compared to before I wore the belt.*" (BWP1); (34) "*During a train ride it is practically not possible to use the belt.*" (BWP4); (45) "*I notice that it is really difficult to describe the changes that occur. I was rarely in situations where I am missing words or where I encounter so clearly my limits of my competence to find the words. Often I don't know whether I should talk about perception or knowledge regarding the belt. It is this problem which makes it so exciting and thrilling.*" (BWP3). Overall the residual statements of both groups covered a huge variability of topics. The amount and variety of statements was clearly increased in the belt wearing group.

4. Discussion

Following the theory of SMCs (O'Regan & Noë, 2001) perception requires learning and mastery of sensorimotor contingencies. In the present study we investigated whether new sensorimotor contingencies can be learned during seven weeks of training with the feelSpace augmentation device. Our focus laid on the question whether this newly acquired knowledge would be measurable in terms of reported perceptual, navigational and emotional changes. In order to assess the subjective experience during the study participants filled out a daily diary and passed weekly sessions of in-depth evaluation, both providing a bulk of quantitative and qualitative data. Overall, our results show that long-term training with the belt led to substantial changes in the perception of space and of the belt signal as well as to navigational changes. Furthermore, the usage of the belt was accompanied by positive effects on the emotional level while the belt's perceived usability and overall appeal increased over time accompanied by a high joy of use. The reported perceptual changes after long-term training with the feelSpace belt support the premise that new SMCs (which we do not naturally have) can be learned and mastered.

In more detail, our open-ended statements of belt wearing participants indicated a whole range of effects. Concerning space perception the belt triggered the development of specific perceptions of spatial relations of self and objects. Furthermore, it emphasized the alignment towards cardinal directions as a new feature of objects. Many subjects experienced an enlarged mental map. Specifically, in case the spatial information gathered by the belt did not match previously formed expectations about environmental characteristics the spatial maps were updated. Furthermore the measurement of knowledge about space characteristics showed that the belt, as long as it was used, supported the enhancement of participants' knowledge about space characteristics and provided a basis for spatial orientation. This was positively mediated by the duration of belt training per day. In addition, directly after the training period had ended, ninety percent of belt wearing participants, but no control participant, reported the development of a new sense of spatial perception. A difference that was not observed after the first week of training. Moreover, navigating through new environments became continuously easier with the belt in contrast to navigating without the belt. Although the control participants did a comparable training and paid attention to their environment, the statements concerning their perception of space differed considerably. These observations suggest that during prolonged training the belt has a marked influence on perceptual experiences of belt wearing participants.

At the same time the actual experiences of the belt's impact deviated from the participants' prior expectations: the experiences either differed from the initial expectations in their quality or even exceeded prior expectations. Overall, none of the subjects correctly anticipated the impact of the belt and the experiences with it. This shows that the participants did not just report what they expected or what they thought they should experience. Instead, it indicates that the reports of the belt wearing participants actually express an altered spatial perception.

In the present study we investigated whether the belt signal information would be used for spatial navigation suggesting the mastery of the newly learned SMCs. Our results revealed changes in the navigation behavior of the belt wearing participants. Quantitative data indicated that although the belt did not lead to the impression that one's sense of orientation improved in general, navigation performance benefitted from it whenever it was used. The belt facilitated navigation overall, while the belt wearer had to pay less conscious attention to the environment while navigating. In contrast, intensive training in the control condition was significantly less effective on navigation performance. Qualitative data additionally showed that belt wearing and control participants used different navigation strategies. Whereas control participants used landmarks, city maps and navigational aids like GPS, belt wearing participants mainly used the belt for navigation. The improvement of navigational skills appeared to be specifically tied to the use of the belt, indicating that belt wearing participants indeed reported newly acquired sensorimotor dependencies that matter to the altered experiences and behavioral capacities.

Consistent with sensory substitution studies (Bach-y-Rita & Kercel, 2003; Bach-y-Rita et al., 1969) we found that also the perception of the belt signal itself changed as time passed. Initially the signal was predominantly perceived as tactile evolving to being perceived as location and direction information. Over time, the perception of tactile stimulation receded more and more into the background. Instead the subjects' reports focused more on changes in spatial perception. Furthermore, two months after the end of belt wearing the effects subjects reported – at least in the FRS questionnaire – diminished. Hence, (only) the continuous usage of the belt over a long period was associated with characteristic changes in perception and the belt was needed for the maintenance of this enhanced perception.

The SMC theory distinguishes furthermore between modality-related and object-related SMCs (O'Regan & Noë, 2001). The former emphasizes the statistical regularities of afferent signals and own actions as imposed by the properties of the sensory apparatus. Using a compass to measure the orientation of the local magnetic field supplies qualitatively new sensory information. Even though none of the belt wearing participants talked about the magnetic field as such. Only when the magnetic field was distorted due to power lines subjects reported irritations or assigned the unexpected signals of the belt to technical malfunction. Remarkably, when this occurred systematically at specific locations the unexpected signals were assigned to the place and circumscribed. Instead, many more reports of the belt wearing participants related to the perception of space and belt signal. Especially with the background that the belt signals induced the experience of an alignment to cardinal directions. Taken together our results appear to support the idea that participants acquired at least in part a new sense of local properties of magnetic fields and cardinal directions which qualifies for the development of a new modality-related SMC.

As demonstrated above, the original vibrotactile information of the belt was integrated into processing related to navigation. This occurred in addition to the sensory information that is normally accessed for navigation (Foulke, 1971, 1982; Loomis et al., 1993). These observations do not contradict the notion of a modality-related SMC, but suggest that the complementary class of object-related SMCs being defined as "the capture of multisensory patterns caused by actions directed towards objects" (Maye & Engel, 2012) is important as well. This argues that the belt signals transcend modality-specific SMCs and have to be interpreted in part as object-related SMC. In this case, what is the object? We suggest that it is the typical environment where the subject navigates, effectively the whole earth (would not work on the moon). In view of the gross mismatch in size this suggestion might be surprising. Still human locomotion systematically changes the relation of subject and environment and this "object relation" is of fundamental importance for human behavior and survival. Considering the very long time scale of navigational behavior it might be worthwhile to explore whether the concept of SMCs can be extended to intention-related SMCs as suggested by Maye and Engel (2012), suitable for the presently reported perceptual effects. In summary we suggest that changes induced by the feelSpace belt straddle learning of modality related as well as object related SMCs and encourage potential extensions of these concepts (Maye & Engel, 2012; Noë, 2010; O'Regan, 2011; O'Regan & Noë, 2001).

Learning and associated neuronal plasticity is the one outstanding capability of the brain. Several studies support the hypothesis that learning processes associated with sensory substitution are mediated by physiological changes. Such neuronal plasticity can involve higher cortical areas (Amedi et al., 2007; Ptito et al., 2005; Striem-Amit et al., 2012). However, it is well established that in blind subjects stimulation by other modalities, e.g. tactile during Braille reading, lead to an activation of early visual areas (Sadato et al., 1996). This matches the idea that low-level sensory areas are less modality specific then was thought a few years ago (Calvert, Spence, & Stein, 2004; Klinge, Eippert, Röder, & Büchel, 2010; Spence & Driver, 2004; Wang, Celebrini, Trotter, & Barone, 2008). This view is, however, not undisputed and recent results suggest that multisensory integration is a late process occurring in higher areas (Quinn et al., 2014). Thus the question which cortical areas mediate multisensory integration is still open. Similarly, current studies on the physiological substrate favor the involvement of higher-level areas, but the issue is far from settled.

Although learning and plasticity is a hallmark of neural systems, not all skills can be learned at all periods of life. This restriction is made obvious by the concept of the critical period on the example of binocular vision (Wiesel & Hubel, 1963). The critical period in human children to develop a binocular vision is within the first years of life. Monocular deprivation during the critical period for example due to blindness through congenital cataract or strabismus will lead to an amblyopic eye. This means that the deprived eye will not develop normal vision if the cause for the deprivation is not corrected in time. Normal vision in this case cannot be learned later in life. Different studies support the concept of the critical period in early life also for the auditory (Sharma, Dorman, & Spahr, 2002) and vestibular system (Eugène, Deforges, Vibert, & Vidal, 2009). It is expected that also sensory substitution and augmentation are low-level cognitive processes having a critical period rather early in life. Hence it is even more remarkable that we and others (e.g. Auvray, Hanneton, & O'Regan, 2007; Bach-y-Rita & Kercel, 2003; Bach-y-Rita et al., 1969; Sampaio et al., 2001; Striem-Amit et al., 2012) can give evidence for significant perceptual changes in adult participants.

Moreover, the present effects of continuous and incidental bodily (vibrotactile) sensations on more abstract cognitions – such as egocentric strategies, knowledge about cardinal direction, and a mental map of the environment – indicate that even in later stages of the lifespan concrete bodily experiences can build the scaffold for the development of new conceptually related (here space-perceptual and navigational) abstract cognitions. Hence, the idea of a scaffolding process seems not to be limited to the early phase of life as recently discussed in literature on embodied cognition (e.g. Kaspar, 2013; Williams, Huang, & Bargh, 2009).

In this context, it is worth to compare the present study with previous studies employing sensory substitution or sensory augmentation as navigational help especially for blind subjects (Gallay, Denis, & Auvray, 2013; Kärcher et al., 2012; Maidenbaum et al., 2013; Ptito et al., 2005). Visual-electrotactile stimulation lead to a high performance in an orientation discrimination task (Ptito et al., 2005). Remarkably, even after very short training time the sensory substitution device acquires a high utility (Maidenbaum et al., 2013). Kärcher et al. (2012) reported qualitative differences in the effects of sensory augmentation with the feelSpace belt in congenitally and late blind participants. In a large scale-pointing task the congenitally blind participant had problems to interpret the belts signal, as the concept of large-scale 2D navigation was alien to him. Not until the concept was explained and cognitively grounded the participant could improve his pointing performance with the augmentation device. In contrast, the late blind participant building up a conceptual framework for navigation in early life could use the belts signal without further explanations or instructions. When the conceptual framework was available those adult participants could easily learn to integrate the new sensory information. These findings are in accordance with the study of Pasqualotto, Spiller, Jansari, and Proulx (2013). They could show that in a spatial object memory task congenitally blind participants preferred a self-based or egocentric reference frame whereas late blind and also sighted participants favored the use of an object-based or allocentric reference frame. This indicates the necessity of visual experience to develop an allocentric reference frame. In the context of the present study it appears that also the sighted participants successfully integrated the newly available information into a pre-existing framework of spatial navigation. Such a framework integrates, for example, visual and vestibular information. We find that sensory augmentation with the feelSpace belt much enhanced this framework.

Although not completely unexpected, the extent to which the belt caused numerous effects on the emotional level was surprising. In contrast to the control participants who hardly ever reported aspects on the emotional level belt wearing participants were frequently affected emotionally by the belt and its signal. Thereby, the effect of the belt on emotional aspects changed remarkably over the training period. This phenomenon is in line with the bulk of studies showing effects of bodily sensations not only on cognitive processes but also on affective states (cf. Barsalou, 2008). The subjective reports showed that technical aspects (inference fields) induced irritations and also a normally functioning belt was in some situations bothersome, e.g. when riding a race bike or leaning against a firm back. However, overall the belt supported a positive mood by providing a feeling of security, i.e. of "never get lost again", paralleled by a heightened curiosity and joy of use. Four of nine participants even expressed the wish to retain the belt for a longer period. At the same time the belt had no time-dependent effect on users' reported sleep quality, state of health, and general emotional state beyond the emotional effects elicited by the direct interaction with the belt or periods of deprivation. Taken together the belt induced consistent positive emotional responses and this result highlights that the impact of sensory augmentation devices can significantly surpass direct sensory experiences.

Importantly, participants did not report a feeling of stress or uncomfortable arousal when wearing the belt, indicating that the belt – although bothersome in some situations – provided a positive experience. However, participants reported a high study motivation overall probably facilitating habituation to the continuous vibrotactile stimulation. Note that also control participants were equally motivated and showed similar motivational dispositions so that group differences are not a signature of differences in subjects' motivation to interact with the environment. On the basis of the present results we are yet unable to assess the amount to which high motivation might compensate for possible negative facets of belt wearing (e.g. irritations, negative feeling, etc.) and the degree to which motivation might mediate effects on the reported changes in space perception and navigational behavior.

In this context, it is important to emphasize that the current version of the belt is robust and easy to use due to several years of technological improvement since the first study by Nagel et al. (2005). Hence, the belt device can be handled with minimal effort and can be used in an effective, efficient, and satisfactory way. This is supported by the above-average usability participants attributed to the belt while the perceived pragmatic quality of the belt even increased over time – indicating a high learnability of the device. Therefore, the belt device meets the central requirements for usability as stated by the International Organization for Standardization (ISO, 1998). Additionally, the hedonic quality of the belt was constantly high and independent of the study duration. Furthermore, the overall appeal of the belt increased from an above-average value at the beginning to an even higher value at the end of the study. This positive evaluation of the belt presumably sustains motivation to use it extensively and, as a distal consequence, might also facilitate the evolvement of new perceptual aspects by this sensory augmentation device. Importantly, these belt characteristics positively correlated with the (short) duration of daily intensive belt training. We only can speculate about the direction of this correlational effect as well as between training duration and the reported changes in space perception and belt experience. The results emphasize the important contribution of hedonic characteristics to the effects of the augmentation device. Beyond their significance in their own right they may moderate the other effects of sensory augmentation devices. The present data, however, do not allow a rigorous test of these correlation models due to the small number of participants. Further studies should address this point. We also like to point out that the duration of intensive belt training, but not the overall duration of belt wearing, correlated with quantitative measurements of space and belt perception as well as belt characteristics. Consequently, intensive interaction with the environment with strong bodily involvement seems to be the more important aspect than the time participants merely wear such a device.

Due to the complex study design and the high training demand on our participants we strived to find a balance between still acceptable burden for the participants and a training duration that is sufficient to lead to training effects. In parallel with previous research using the feelSpace augmentation device (Kärcher et al., 2012; Nagel et al., 2005) we could observe numerous training effects within seven weeks of training. However the first changes occurred within the first days of belt wearing as revealed by the daily diary. This finding is in line with sensory substitution studies that could evaluate sensory learning already after a few hours of specific training (e.g. Bach-y-Rita et al., 1969; Haigh et al., 2013; Ptito et al., 2005). Even though we and others see first changes in perception and behavior already after a few hours of specific training these effects evolve and intensify with further training duration. Some reports of the Eye-borg foundation indicate changes even after six month of wearing a sensory substitution device for color blindness (Wade, 2005). The device enables the color-blind person to hear the colors thus learning to discern colors through sound. With prolonged training duration (>6 months) we expect a deeper integration of the augmented signal and the development of a fully automated process.

Data quality would also benefit from a longer study duration enabling us to further increase the signal to noise ration of the data and investigating potential changes in qualitative reports in the long-term. However, this fact does not question the high quality of the present data. Investigating an embodied approach of conscious perception necessarily we have to deal with first person data. Such data are not measured in meters or seconds. In fact they are difficult to communicate. This creates the task to define objective measures of the observed effects. For example it is not to be expected if another research group repeats such experiments that subjects make literally identical statements. To address this task we used in our study comparable to other research groups (e.g. Creswell, 2003; Greene, Caracelli, & Graham, 1989; Tashakkori & Teddlie, 2003) a mixed method approach. Therefore we designed questionnaires with quantitative Likert items on the one hand. These were supplemented with open-ended qualitative single items on the other hand. Those qualitative data were quantitatively captured in a newly developed category system that enabled us to organize and group statements content and to subsequently analyse the subjective reports by means of frequency statistics. This combines the advantage of an unconstrained and unbiased description of the perceptual live of our participants, thereby understanding better of what is on their mind (cf. Eckhardt & Jamison, 2002) with a statistical exact quantitative evaluation. This makes it possible to generalize and draw conclusions from these qualitative data. Our high inter-rater reliability (Cohen's Kappa > 0.82) indicates a truthful mapping of participants' statements on the developed category system. A comparison of results from quantitatively assessed and quantitatively evaluated qualitative data revealed mutual support and complementation of the outcomes. Thus the use of a mixed methods approach makes our first person data accessible to an objective analysis.

5. Conclusion

The present results show that vibrotactile stimulation around the waistline indicating the direction of the magnetic north led to substantial changes in the perception of space and also the perception of belt signal itself and to navigational changes. These effects support the premise that sensorimotor contingencies can be learned with the aid of a sensory augmentation device even in later stages of the lifespan and that mastery of new sensorimotor contingencies leads to perceptual changes. This finding is also compatible with the concept of embodied cognition pointing out the active and multisensory probing of the environment (Mangen & Velay, 2010) and resulting functional and neurophysiological links between bodily sensations and abstract cognition (e.g. Barsalou, 2008).

Hence, the feelSpace belt is a suitable gadget for both blind as well as seeing participants in order to facilitate orientation and navigation through the environment. From a practical point of view, several settings are conceivable in which this device could help to enhance performance – for example when walking through environments devoid of characteristic landmarks such as desserts or the surface of the moon – and to enable us when vision is limited or completely absent. In order to fathom the range of potential application areas as well as limitations of the current version of the belt further systematic studies are necessary, whereby also the duration of intensive belt training should be enhanced to scrutinize long-term effects. However, at the same time ethical consideration gets more serious. In the narrow sense, potential negative side effects for study participants must be weighted against potential benefits. In a broader sense, we have to decide whether it is desirable at all to learn SMCs that we do not naturally have as far as the human sensorimotor system works sufficiently well from a physiological and functional point of view with respect to the environment we currently live in. The surprisingly intense and positive emotional effects give an optimistic outlook onto these questions. Thus, the possibility to change space perception and improve navigation by means of a relatively small and usable device indicates numerous starting points for scientists investigating limits and potentialities of sensory augmentation.

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