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Sensory Substitution: Using a Vibrotactile Device to Orient and Walk to Targets

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Abstract

Sensory Substitution Devices (SSDs) aim to substitute one sensory modality through another one. This study investigates how active exploration helps users of SSDs to detect information that is specific to relevant environmental properties. A vibrotactile SSD was developed that generates stimulation that is contingent on the users' movements. Target direction was specified by the location of vibration and target distance by the 'size' and the intensity of vibration. A series of experiments was performed with blindfolded participants. In Experiments 1a to 1c, participants used the SSD to align their central body axis with pre-specified targets. These experiments differed in the number of actuators that were used and whether on-line perception-action coupling was present. In Experiment 2, participants approached targets with forward locomotion along a straight line. Experiment 3 combined the previous experiments and studied the concomitant walking and steering toward targets. Oscillatory movements that facilitated information pick-up were observed in all experiments. The exploratory oscillations were shown to depend on the on-line perception-action coupling and were related to cases of hyperacuity, where absolute errors were found to be smaller than the areas of sensitivity of the actuators. It is concluded that future research on sensory substitution should pay more attention to the role of active exploration that generates action-relevant information which in turn improves the utility of the device.

Public Significance Statement: The present study demonstrates how a vibrotactile sensory substitution device can be used to successfully locate different targets. It shows how a sufficiently high number of vibrotactile actuators are required to create a 'haptic' informational flow field that specifies target location and distance. The study shows how natural exploratory behaviors facilitate the pick-up of action-relevant information and underpin successful perception-action coupling.

Keywords: augmented reality, ecological psychology, electronic travel aids, haptic flow, sensory substitution

Sensory Substitution: Using a Vibrotactile Device to Orient and Walk to Targets

The idea of using one sensory modality as a substitute for another modality is not new. Since the early sixties, the popularity of developing and testing devices that use alternative forms of sensory information has grown. As an illustration of this growth, a recent Google Scholar search using the term *sensory substitution* over the five decades between 1960 and 2009 yielded 13, 198, 373, 615, and 2570 hits per decade, respectively, and 4140 hits since 2010.[1] Reviews of different Sensory Substitution Devices (SSDs) include those developed by Jones and Sarter (2008), Dakopoulos and Bourbakis (2010), and Visell (2009). As can be noted in these reviews, SSDs are potentially useful in a wide range of situations. Vibrotactile SSDs, for example, may be useful in situations in which vision is not available, or less available, due to, say, smoke in the case of fire fighters, weather conditions in the case of pilots, or biological damage in the case of visually impaired users (Carton & Dunne, 2013; Cholewiak & Collins, 2000).

The number of potential users of SSDs is large. In 2010, the estimated number of people with visual impairment was 285 million, 39 million of whom were estimated to be blind (Pascolini & Mariotti, 2011). Compared to the number of possible users, the number of SSDs that are available on the market and/or that are actually being used is low (Lenay, Gapenne, Hanneton, Marque, & Genouëlle, 2003). The apparent shortage of SSDs is indicative of the unsatisfactory aid that these devices offer in everyday tasks (Durette, Louveton, Alleysson, & Hérault, 2008; Hersh & Johnson, 2008; Lobo, Travieso, Barrientos, & Jacobs, 2014). The overall purpose of our research project is to improve the understanding of why SSDs tend to be unsatisfactory in everyday life. Our hope is that by improving this understanding, we contribute to improvements in the theoretical grounding of future SSDs and, thereby, to the applicability of SSDs. To anticipate, we believe that the functioning of SSDs can be improved by focusing on the specificational nature of the information delivered to users and on the active detection of that information. Before we address these issues, we will

[1] Search performed on January 24, 2017.

discuss several reasons that have previously been suggested for the limited use of SSDs by visually impaired users.

Prominent examples of SSDs from the 1960s and 1970s include the Optacon (Craig, 1976; Linvill & Bliss, 1966), the Optohapt (Geldard, 1966), and the TVSS (Bach-y-Rita et al., 1969). These SSDs stimulated the skin on the fingertips, points distributed over the body, and the back, respectively. Initial results with these SSDs were promising and the researchers were optimistic concerning the role of the skin as a suitable sensory surface for sensory substitution. In later decades, there was a belief that using more sensitive receptor areas would lead to more effective SSDs. This belief led to the development of devices such as the TDU (Tongue Display Unit), which applies electrotactile stimulation to the tongue (Bach-y-Rita, Tyler, & Kaczmarek, 2003). Even highly sensitive receptor surfaces such as the tongue, however, are not nearly as sensitive as the eyes. This fact is nicely illustrated by a study of Sampaio, Maris, and Bach-y-Rita (2001). These authors used the Snellen tumbling E, typically used to test visual acuity, to quantify the acuity of trained TDU users. The 50% correct-response level for the TDU users was observed at a 20/240 Snellen ratio. In the US, individuals with such acuity values for vision would be considered legally blind. A first reason that has been suggested for the unsatisfactory performance of SSDs in everyday life, therefore, is that the sensitivity of the used receptor surfaces may be insufficient.

In addition to the limited sensitivity of the receptor surfaces themselves, the usability of SSDs may be restricted by the cognitive processing capabilities associated with the receptor surfaces (Gallace, Tan, & Spence, 2007; Loomis, Klatzky, & Giudice, 2012; Spence, 2014). Spence (2014), for example, argued that cortical plasticity is not sufficient to overcome the processing limitations associated with tactile stimuli. According to Spence, such limitations make it unlikely that users of tactile SSDs can cope with the high spatiotemporal variation of the stimulation that is required to substitute the general function that regular vision plays in our everyday life. Hence, a second reason for the unsatisfying usability of SSDs may be a limitation in cognitive processing capabilities for information presented via the skin as compared to the cognitive processing

capabilities for visually detected information.

We believe, however, that the above-reviewed reasons are not as crucial as has previously been argued. A third possible reason for the less than expected applicability of SSDs may be that the design of the SSDs does not sufficiently take into account what information is used, how this information specifies task-relevant properties, and how exploratory actions allow for the detection of the information (Jansson, 1983; Lenay et al 2003; cf., Guarniero, 1974). This third reason is consistent with a substantial number of studies that use SSDs that allow for the active detection of relevant information. These studies have used tasks involving the recognition of forms and objects (Auvray, Hanneton, & O'Regan, 2007; Bermejo, Di Paolo, Hüg, & Arias, 2015), the detection of vertical obstacles (Díaz, Barrientos, Jacobs, & Travieso, 2012; Lobo et al., 2014; Travieso, Gómez-Jordana, Díaz, Lobo, & Jacobs, 2015), the orientation of the body-axis toward obstacles (Faugloire & Lejeune, 2014), and wayfinding (Favela, Riley, Shockley, & Chemero, 2014; Ito et al., 2012). Let us describe one of these studies.

Díaz et al. (2012) explicitly focused on the role of active exploration in sensory substitution. The tested SSD consisted of a vertical array of 24 actuators on the torso, which vibrated as a function of distance. If a user of the device stood straight up in front of a flat ground surface, all actuators vibrated with the same low intensity. The activation pattern changed whenever the relation between the user and the environment changed, either due to movements by the user or due to the presence of an obstacle on the ground surface (see Figure 1 of Díaz et al.). In their first experiment, Díaz et al. showed that the threshold for the detection of obstacles with the SSD is lower for a use with exploratory movements than for a use without such movements. The exploratory movements typically consisted of forward and backward walking and/or tilting the upper body. In their second and third experiments, dynamic groups that received vibrotactile stimulation generated on-line by their own exploratory movements had lower detection thresholds than yoked groups that received stimulation corresponding to previously registered exploratory movements. This demonstrates that, for an optimal performance, the vibrotactile stimulation provided by SSDs should be contingent on

the user's movements.

Although Díaz et al. (2012) demonstrated the importance of active exploration with action-contingent vibrotactile flow, they did not analyze the exploratory movements themselves. The present study further investigates active exploration and information use in sensory substitution, using a different experimental framework: spatial orientation and locomotion. We believe that this is an appropriate framework. First, orientation and locomotion are important for people with and without visual impairment. Second, the framework entails real-world tasks that allow scientists to test SSDs and to quantify performance. As argued by Faugloire and Lejeune (2014), a majority of the studies with SSDs on the tactile guidance of movement do not report complete quantitative measures of performance. For example, the reported measures may be limited to the time that users take to complete the task, without quantifying errors in performance. Third, visually guided locomotion toward targets has been studied extensively. This has led to rich knowledge about the operative information (e.g., Bastin, Craig, & Montagne, 2006; Morice, François, Jacobs, & Montagne, 2010). It may be fruitful to relate research on sensory substitution to the previous knowledge about the information that is used for the visual guidance of locomotion.

An elegant experimental paradigm to study visually guided locomotion has been proposed by Fajen and Warren (2003; cf. Fajen, Warren, Temizer, & Kaelbling, 2003). The experiments reported in that study were performed in a large virtual environment, in which targets and obstacles could appear in the form of vertical cylinders. In Experiment 1, Fajen and Warren used targets placed at different initial distances and angles, while in Experiments 2 and 3 both targets and obstacles were used. Participants, who had a 60º-wide field of view, were asked to walk toward the targets and to avoid obstacles. Fajen and Warren also proposed a model, which describes steering behavior with dynamic terms for the targets (attractors) and obstacles (repellers). Arguably, the main contribution of Fajen and Warren's study is the demonstration that route selection can emerge from an on-line coupling of action to simple optical variables, making explicit route selection and planning unnecessary. The most relevant result for us, at this point at least, is that locomotion

toward a target was shown to be based on the body-referenced direction to the target and the distance of the target. We use θ to refer to the body-referenced direction of the target (Bootsma & Craig, 2002; Bastin, Jacobs, Morice, Craig, & Montagne, 2008).[2]

To summarize, visually guided locomotion can be characterized as an on-line information-action coupling. Our approach to sensory substitution also gives a prominent role to information-action coupling. The purpose of our study is twofold. First, we investigate the movements that underlie active information detection with a vibrotactile SSD. Second, we aim to illustrate the suggested benefits in performance when SSD-based perception is conceived as active information detection. We designed an SSD that allows for the detection, through vibrotactile stimulation on the abdomen, of the information that has been shown to be used in visually guided locomotion (Fajen & Warren, 2003). The body-referenced direction of the target, θ, is indicated by the location of the vibration (e.g., van Erp, van Veen, Jansen, & Dobbins, 2005), and the distance to the target is indicated by the intensity and size of the stimulation (Cancar, Díaz, Barrientos, Travieso, & Jacobs, 2013). In the remaining part of this article, we describe the SSD, indicate how it presents the information to the user, and report on three experiments that assess how users actively detect and use this information to navigate in an environment without sight of the target.

Experiments 1a to 1c focused on the orientation of the mid-line of the torso with respect to a virtual target, as did the experiment reported by Faugloire and Lejeune (2014). In Experiment 1a, 72 actuators were placed on the torso in 3 horizontal rows of 24 actuators each. The vibration was continuously updated according to the participant's heading. Experiment 1b tested the relevance of the perception-action coupling. The same number of actuators was used as in Experiment 1a, but without on-line coupling. That is, participants stood still while the vibration was present and

[2] Multiple θ-like variables have been claimed to be relevant for the visual guidance of movement (Craig et al., 2009; Michaels, Jacobs, & Bongers, 2006). Several of these variables are easily confused with θ as defined by us, including the direction of the target with respect to a fixed reference frame or with respect to the movement direction of observers (rather than with respect to body orientation).

oriented toward the target only after the vibration had ended. Experiment 1c tested the importance of the number of actuators. The difference between this experiment and Experiment 1a was that the rows contained 3 instead of 24 actuators.

Experiments 2 and 3 were performed with the full set of 72 actuators and with an on-line perception-action coupling, as in Experiment 1a. Whereas Experiment 1a focused on information that would specify the direction of the targets, Experiment 2 focused on information about distance. Participants in Experiment 2 walked to targets located directly in front them. The task used in Experiment 3 was a combination of the tasks used in the previous experiments: Participants walked toward targets located at different angles and distances in front of them. Experiment 3 hence was a vibrotactile version of the first experiment in Fajen and Warren (2003).

General Method

Ethics Statement

This research project was approved by the respective research ethics committees of the Queen's University of Belfast and the Universidad Autónoma de Madrid. Written informed consent was obtained from all participants.

Apparatus

The SSD used in this research consisted of an elastic band (95 × 16 cm) with 72 vibrotactile actuators attached to it in an area of 40 × 12 cm (Figure 1). The actuators were coin motors with a diameter of 12 mm and a height of 3.4 mm. The motors were organized in three rows of 24; the horizontal distance between the actuators was approximately 1.7 cm. The elastic band was placed on the abdomen. The tactile information presented through the SSD specified the distance between the participant and the target (i.e., vibration intensity and number of actuators activated) and the angle between the person and the target (i.e., the relative location of active actuators). The data that corresponded to the participant's actual position were generated from the motion capture system and were incorporated into a software program to calculate in real time the angle and the distance between the participant and the target. This information was converted into a signal that stimulated

the appropriate actuators. The actuators were controlled by a Pro-mini arduino microcontroller that received the signal through a wireless Xbee device, model S2. A NiMh Battery of 4000 mA/h supplied the energy for the actuators. The battery and microcontroller were housed inside a backpack: The SSD was completely portable.

The position and orientation of the participant were measured using a passive infrared motion capture system (Qualisys AB, Sweden). A system with Oqus cameras (10 in Experiments 1a, 2, and 3; 6 in Experiments 1b and 1c) recorded the position of five reflective markers attached to the SSD, at 100 Hz. Given that the vibration of the actuators depended on the position and orientation of the participant with respect to the predefined virtual target, the voltage level required to create the necessary vibrations was computed on-line. These computations were updated approximately 43 times a second.

Procedure

Prior to the experiments, verbal instructions were given to participants along with a demonstration and explanation. The information provided was: “We have developed a new tactile device for people who are visually-impaired. With this device you will receive tactile stimulation on your abdomen that should help you locate and move toward a target in this room. The device has 72 small motors attached to a large elastic band that will be placed on your abdomen. You will feel different levels of vibration that will indicate how close you are to the target and whether you are walking directly toward the target. The more intense the vibration of an individual motor, the closer you are to the target with the inverse also being true (that is, the less intense the vibration, the further away you are from a target). Equally, the greater the number of motors that are active and vibrating, the closer you are to the target; with fewer motors vibrating indicating that you are further away. The motors also vibrate at different positions on the band, which correspond to the location of the target. For example, if the motors on your right hand side vibrate, then the target is located on your right. As you turn your body toward the target on the right, the pattern of vibration of the motors will move toward the center. When the vibration is located in the center, this indicates that

the target is straight ahead." After this explanation, the participants were blindfolded and were offered the opportunity of exploring the surface of the SSD with their hands. Subsequently, the experimenter placed the part of the SSD with the actuators on the abdomen. All experiments were preceded by three familiarization trials. Participants remained blindfolded. No explicit mention was made about trial duration.

Activation Level of Actuators

The three actuators arranged in a vertical line always had the same level of activation. If they were activated, the intensity of the vibration was a function of the distance between the participant and the target, following the equation: $V = V_{max} - c \times D_{pt}$, where V is the voltage level expressed as a percentage of the maximal voltage level V_{max}, D_{pt} the distance between the participant and target in centimeters, and *c* a constant that maintains the vibration intensity in a useful range. The voltage level V_{max} corresponded to an estimated frequency of the actuators of about 65 Hz (see Appendix A of Díaz et al., 2012). In the experiments, *c* was set at 0.12. This means, for example, that when D_{pt} was 100 cm, the voltage level was 88% of V_{max}. The voltage level was set at zero whenever, according to the equation, it should have been negative. Actuators worked like virtual sensors. They were activated when they detected the virtual target in their (vibrotactile) field of view. The targets were virtual in the sense that, although they determined the vibration patterns of the SSD, they did not exist as real objects in the experimental set up. Actuators were turned off when the virtual target went outside their field of view.

The total field of view of the SSD was fixed at 60º. This was motivated by the 60º visual field of view in the experiments of Fajen and Warren (2003). For all participants, the total field of view was divided in 24 units of 2.50º, corresponding to the fields of view of each of the 24 columns of actuators. The leftmost actuators in the device detected targets when these were located in the range between 30º to 27.5º to the left of the body axis, the second column of actuators detected targets between 27.5º to 25º to the left, and so forth, until the rightmost column of actuators that detected targets in a range between 27.5º to 30º to the right of the body axis. As mentioned, these

fields of view were the same for all participants, independently of their waist size, and hence independently of the exact body location of the actuators. Thus, in contrast to the SSDs used in previous studies (e.g., Faugloire & Lejeune, 2014; van Erp et al., 2005), the direction of sensitivity of the actuators did not exactly match the direction of the physical position of the actuators with respect to the body midpoint. Even so, straight ahead was always indicated by the actuators closest to the body midline.

Figure 2 provides an illustration of how the SSD functions. If we establish the participant's orientation as being P_o (measured using the motion capture system), the SSD takes into account a field of view that corresponds to 30º on either side of P_o (see dashed lines in the figure). The virtual target T has a fixed diameter of 20 cm that occupies a vibrotactile angle γ, which depends on the distance D_{pt} between the participant and the target (Figure 2a). The angle γ, in turn, determines the number of actuators that detect the target (i.e., actuators that have the target in their field of view; Figure 2b). When the distance D_{pt} reduces, the angle γ increases, and, as a consequence, the number of active actuators increases (Figures 2b-2c). To facilitate the illustration, the actuators in Figures 2b and 2c are depicted on a straight line before the body; in the experiments the actuators were placed on the body. Figure 2d shows the results of applying the above-mentioned equation to determine the intensity of vibration to the situation depicted in Figure 2c. Figure 2e indicates the actuators that are active as a function of distance, for a target that is approached straight ahead.

Two experimental variations that affect the functioning of the SSD were included. First, in Experiment 1b, participants did not move during the period in which they received the vibrotactile stimulation. This experiment was hence performed without perception-action coupling. Second, in Experiment 1c, the 60º field of view was replaced by a 135º field of view, and the partition of the field of view was reduced from 24 segments (corresponding to 24 columns of actuators) to 3 segments (corresponding to 3 columns of actuators). This was done to test the role of the number of actuators and to approximate the experimental conditions of Faugloire and Lejeune (2014).

Data Analysis

Using the data recorded with the motion capture system, we carried out several analyses on performance and movement variables. A mean of 0.5% of the frames per trial were not properly registered. To fill the gaps in trials with missing frames we used the linear interpolation function *extrap* in Matlab (Mathworks, Inc.). The data were filtered with a forward and backward fourth-order low-pass Butterworth filter with a cut-off frequency of 12 Hz. We computed errors in performance as the difference between the target location and the participant's position or orientation at the end of the trial. We measured these differences as real values (signed errors) and absolute values (magnitude of errors). When performance referred to target location behaviors, the sign of the error was negative when the final position was before the target (undershoot) and positive when the final position was after the target (overshoot). When performance referred to the orientation of heading, the sign of the error was positive when the final heading position was to the right of the target and negative when it was to the left of the target. The maxima and minima in the time-series of the angle θ were determined and used to compute the number of oscillations. An oscillation was defined as a full cycle from a maximum to a minimum and back to a maximum; which is to say, a change from a maximum to a minimum or vice versa counted as a half oscillation. Huynh-Feldt corrections were applied in the case of the rejection of the sphericity assumption in repeated-measures ANOVAs. Welch ANOVAs were applied in the case of rejection of homogeneity of variances in one-way ANOVAs. In those cases, Games-Howell tests were applied instead of Tukey's HSD post hoc comparisons. The Satterthwaite approximation for the degrees of freedom were applied in the case of a significant result in the Levene's Test for Equality of Variances in a t-test. To estimate the effect sizes, the partial eta-squared, η_p^2, was applied when reporting significant effects in ANOVAs and Cohen's *d* when reporting significant effects in a t-test.

Experiment 1a: Orienting the Body Axis to Targets

The present series of experiments on SSD-based locomotion uses an experimental paradigm that has previously been used to study visually controlled locomotion (Fajen & Warren, 2003). The task studied by Fajen and Warren implies forward locomotion as well as turning. As a first step

toward the application of this task in sensory substitution, our Experiments 1a to 1c addressed the capacity of participants to use an SSD to turn their anterior-posterior body axis toward targets. Whereas Experiment 1a used the SSD with its full functionality, Experiments 1b and 1c did not: in Experiment 1b we removed the on-line perception-action coupling and in Experiment 1c we reduced the number of actuators.

Previous work in the field of sensory substitution that used this task includes the study by Faugloire and Lejeune (2014; cf. Tsukada & Yasumura, 2004). The SSD of Faugloire and Lejeune had eight vibrotactile actuators placed around the abdomen. As in our Experiments 1a to 1c, participants were asked to rotate toward the direction indicated by the vibration. The experiment of Faugloire and Lejeune included conditions with fast (200 ms on / 200 ms off) and slow (1 s on / 4 s off) vibration rhythms, for which average absolute errors of about 10º and 15º were observed, respectively. Let us emphasize two interesting aspects of these results. First, the errors were smaller than the area of sensitivity of the individual actuators (which was 45º). Second, the faster rhythm led to better performance. In line with the arguments outlined in our introduction, according to Faugloire and Lejeune the faster rhythm is more beneficial because a more direct coupling of the stimulation to the user's actions allows for an active search to pick up and use goal-relevant information.

Our Experiment 1a differed in two crucial aspects from the one by Faugloire and Lejeune (2014). First, we used 3 rows of 24 actuators placed on the front of the abdomen, whereas Faugloire and Lejeune used eight actuators placed around the full 360º of body. Relatedly, the area of sensitivity of each actuator in our study was 2.50º while it was 45º in the study of Faugloire and Lejeune. Second, the activation was updated with a frequency of 43 Hz, rather than in rhythms with 2.5 (or fewer) bursts per second. Updating the vibration frequency with 43 Hz means the vibration had no off phases: The vibration was present whenever the target fell within the field of view of the SSD.

Method

Seven women and four men (M_{age} = 27.6, SD = 4.4) who were students or members of university staff at the Queen's University of Belfast participated in the experiment. None of them had previous experience with SSDs. All participants had normal or corrected-to-normal vision. Participants were asked to rotate their body about the longitudinal axis in order to face a virtual target. The vibration provided by the SSD was adapted on-line using the information specifying the angular direction of the virtual target with respect to the participant. The distance between the participant and the target (D_{pt}) was fixed at 200 cm. This resulted in a constant angle γ of 5.72º (Figure 2a) and a constant intensity of vibration. Which actuators were activated depended on the participant's orientation with respect to the target. If the participant changed his or her orientation, the actuators that were activated would change accordingly. For example, if the target and the participant were perfectly aligned, the vibration would be at the body's center, but if the center of the torso was oriented to the left of the target, then the actuators on the right part of the abdomen would be activated.

The three familiarization trials used the following target locations: -30º, 0º, and 30º. After the familiarization trials, participants started the test trials. Six locations with respect to the center (0º) were used for the test trials: ±5, ±15, and ±25º, each being repeated 3 times (18 trials in total).[3] Participants started each trial from the final position of the previous one. The trials were presented in quasi-random sequences that were chosen so that participants, if performing perfectly, did not have to rotate more than 40º between consecutive trials. Participants indicated verbally when they believed that a correct alignment was achieved, upon which the experimenter ended the trial. The duration of the experiment was approximately 15 min.

Results

[3] Due to programming error, targets with a smaller x coordinate than the participant were displaced to the left with an angle that was identical to γ. The same programming error was present in Experiment 3. We believe that this error did not have any effect on the results of Experiment 1a and that, if anything, without this error the results of Experiment 3 might have been slightly more favorable with respect to the usefulness of the device.

Overall description of performance. After being asked about the difficulty of the task, all participants reported that the use of the SSD in this experiment was intuitive and simple. Four trials (2.0% of the total number of trials) were not properly recorded and were discarded from the analyses. Two further trials were not correctly recorded at the moment of the decision; the error and position variables from these trials were not included in the analysis. At the start of a trial, participants almost always started to turn their upper body to one side and then to the other. These sweeping movements of the upper-body sometimes involved slight movement of the feet. The upper-body movements were repeated with decreasing amplitudes until participants stopped and announced that they had made a decision (Figure 3c).

Heading direction. Three ANOVAs were performed with target location as the within-subjects factor. The first ANOVA examined the final heading direction of participants. A strong significant effect of target location was observed, $F(4.1, 114.3) = 5042.1$, $p < .001$, $\eta_p^2 = .99$. This demonstrates that the participants' final heading was a function of the actual target locations, and hence that the SSD allowed participants to distinguish the targets.

Signed angular deviation. The second ANOVA was performed on the signed errors, computed with the angle *D* in Figure 3a. This ANOVA did not reveal a significant effect of target location, $F(3.9, 100.6) < 1$. Hence, in contrast to studies that showed larger errors for the outer targets when pointing in the absence of visual information (Adamovich, Berkinblit, Fookson, & Poizner, 1998; Craig & Bourdin, 2002), we did not observe such differences. The average signed deviation was -0.2º (*SD* = 1.8). The signed deviation was not significantly different from the angle $D = 0º$, $t(191) = -1.6$, $p = .11$. Hence, at the moment of the decision, the variability of heading was approximately equally distributed to the left and right of the targets.

Absolute angular deviation. The ANOVA on the magnitude of the errors, also computed using the angle *D*, did not reveal a significant effect either, $F(3.9, 100.8) < 1$. The average magnitude was 1.4º (*SD* = 1.1). This mean is lower than the angle of sensitivity of a single actuator (2.50º). In fact, the magnitude of the deviation was not significantly different from half of the

sensitivity of a single actuator (1.25º), $t(191) = 1.5$, $p = .11$.

Trial duration. The mean duration of the trials was 7.2 s (*SD* = 2.9). As evidenced by the low correlation between the magnitude of deviation and trial duration ($r[190] = .11$, $p = .15$), the trial duration was not related to the accuracy of the orientation.

Movement variables: Number and amplitude of oscillations. On average, participants oscillated 3.1 times per trial (*SD* = 1.7). Several oscillatory movements were observed in most of the trials: Only 5.1% of trials showed a single oscillation. Three or more oscillations were seen in 47.4% of the trials. The mean angular velocity was 11.8 deg/s (*SD* = 5.42). The mean angular range, defined as the maximum minus the minimum heading direction in a trial (Figure 3c), was 44.4º (*SD* = 20.7). The cumulative angular distance covered by the oscillatory movements was, on average, 86.7º (*SD* = 56.4). The average amplitude of the oscillations was 14.0º (*SD* = 16.7). The amplitude of the last half oscillation before a decision was made was 6.8º (*SD* = 6.8; Figure 3c).

Discussion

The present experiment showed that blindfolded users of the SSD performed more than one oscillatory trunk movement in 94.9% of the trials. The amplitude of the exploratory trunk movements decreased over cycles. The final direction of the torso closely corresponded to the direction of the target: The average absolute error was 1.4º. This deviation is below the angular area of sensitivity of each actuator of 2.50º.

The absolute errors in the present experiment are substantially smaller than the absolute errors of about 10º to 15º reported by Faugloire and Lejeune (2014). The more accurate performance in our experiment may be related to the higher number of actuators on our SSD: It is to be expected that a device with areas of sensitivity of the individual actuators of 2.50º allows more accurate orientation than a device with areas of sensitivity of 45º per actuator. In addition, the high accuracy may be related to the absence of off phases in the vibration and the update frequency of about 43 Hz. This almost immediate perception-action coupling may have enhanced the usefulness of the oscillatory trunk movements.

It may also be interesting to note that the trial duration was longer in our experiment (7.2 s) than in the experiment reported by Faugloire and Lejeune (2.9 s). This difference may be attributed to the more extended exploration in our experiment.

Experiment 1b: Orienting Without Perception-Action Coupling

Participants in Experiment 1b received vibratory information concerning the direction of the target while standing still. They were asked to turn their body axis in the direction of the target after the vibration had ended. This means that the task was performed without on-line perception-action coupling. We hypothesize that, as compared to Experiment 1a, less exploratory oscillations will be observed in Experiment 1b, and that this reduction will go together with larger absolute errors and shorter trial durations.

Method

Experiment 1b was identical to Experiment 1a with the following exceptions. Twelve students at the Universidad Autónoma de Madrid participated (10 women and 2 men; M_{age} = 29.0, *SD* = 9.8). No on-line perception-action coupling was used. Instead, in all trials, including the familiarization trials, the vibration remained stable with regard to the body during a 7.2-s period in which participants were asked not to move. The used duration corresponds to the average trial duration in Experiment 1a. When the vibration had ended, participants turned their body axis so as to align it with the direction of the target. Before the following trial, the experimenter directed participants back to the original orientation.

The size of the body at the level of the SSD along the lateral and antero-posterior axes was measured and used to compute the directions of the used actuators with regard to the midpoint of the body, assuming the shape of the body to be elliptical (Faugloire & Lejeune, 2014). These individually computed reference directions of the actuators were used in the error analyses of this experiment. Note in this regard that no feedback was given in the familiarization trials, and hence that participants could not know the direction of sensitivity of the actuators as described in the General Methods. Evaluating performance with respect to the direction of sensitivity of the

actuators instead of their physical location on the body would have led to substantially larger errors.

Results

The average signed deviation between the direction of the vibration with respect to the body and the final heading of participants was -0.3º (*SD* = 17.3). The magnitude of the deviation was 12.4º (*SD* = 11.7). The trial duration was 5.1 s (*SD* = 1.9). The number of oscillations per trial was 1.9 (*SD* = 1.1). The average amplitude of the oscillations was 13.3º (*SD* = 21.9). T-tests showed that the participant means of these measures differed significantly from those observed in Experiment 1a for the magnitude of deviation, $t(212.3) = -13.98$, $p < .001$, $d = -1.3$, the trial duration, $t(332.0) = 8.18$, $p < .001$, $d = 0.90$, and the number of oscillations, $t(317.0) = 8.50$, $p < .001$, $d = 0.85$. Specifically, when on-line perception-action coupling was prohibited in Experiment 1b, the absolute angular deviation was greater, the trial duration shorter, and the number of oscillations fewer. Similar t-tests did not reveal differences for the signed deviation, $t(212.8) = 0.10$, $p = .93$, and the amplitude of the oscillations, $t(1003.7) = 0.67$, $p=.51$.

Discussion

The present experiment demonstrates that the accuracy that was observed in Experiment 1a is at least partly due to the on-line perception-action coupling. The finding that the number of oscillations is reduced in the absence of such a coupling indicates the importance of this coupling to facilitate the exploratory behavior that appears to improve performance accuracy. The exploratory oscillations were also shown to have a cost: In Experiment 1b, with fewer oscillations per trial, participants reached their decisions sooner. One may want to note, however, that the trial duration of 5.1 s in the present experiment was still longer than the trial duration of 2.9 s observed by Faugloire and Lejeune (2014).

Experiment 1c: Orienting With Few Actuators

In Experiment 1a we observed highly accurate performance using an SSD with 24 columns of actuators that had a field of sensitivity of 2.50º each. Experiment 1c tests the extent to which the number of actuators and the associated fields of sensitivity contribute to the observed performance.

As did Faugloire and Lejeune (2014), we used actuators that had a field of sensitivity of 45º. Whereas Faugloire and Lejeune used eight actuators, covering the full 360º circumference of the body, we used three columns of actuators, giving rise to a total field of view of 135º. The columns of actuators that were used were the one on the body midline and two columns located on the left and right.

We hypothesize that, due to the lower resolution of the sensory information, larger errors will be observed in this experiment compared to Experiment 1a. Predictions concerning the exploratory oscillations are less straightforward. With an area of sensitivity of 45º, the majority of the oscillations observed in Experiment 1a would fall within the field of sensitivity of the central actuators and, therefore, they would not lead to changes in the activation of the actuators. Given this, oscillations below a certain amplitude would not be useful, and participants may reduce the number and the amplitude of the oscillations. On the other hand, participants may also increase the amplitude of the oscillations so as to make it more likely to stimulate the actuators on the sides of the SSD (i.e., explore the extreme positions of the device).

Method

Experiment 1c was identical to Experiment 1a with the following exceptions. Twelve students at the Universidad Autónoma de Madrid participated (7 women and 5 men; M_{age} = 30.6, *SD* = 7.8). The participants did not participate in other experiments of this study. The elastic band with actuators was placed on the body in such a way that the thirteenth column of actuators from the left was located at the body midline. The columns of actuators that were used in this experiment were Columns 7, 13, and 19 for small participants, Columns 6, 13, and 20 for average-sized, and Columns 5, 13, and 21 for large participants.[4] Independent of the location of these actuators on the body, the center of the fields of sensitivity of these actuators was always directed to -45, 0, and 45º.

Results

The average signed deviation was 0.5º (*SD* = 14.4). The magnitude of the deviation was

[4] The experimenters categorized participants on the basis of their waist size to have similar locations of active actuators on the body when using the SSD.

12.3º (*SD* = 7.5). The trial duration was 8.1 s (*SD* = 3.5). The number of oscillations per trial was 2.8 (*SD* = 1.6). The average amplitude of the oscillations was 14.0º (*SD* = 18.8). T-tests showed that the participant means differed significantly from those observed in Experiment 1a for the magnitude of the deviation, $t(226.2) = -21.2$, $p < .001$, $d = -1.98$, the trial duration, $t(404.1) = -2.8$, $p = .005$, $d = -0.28$, and the number of oscillations, $t(410) = 2.4$, $p = .015$, $d = 0.23$, but not for the signed deviation, $t(222.3) = -0.76$, $p = .45$, and the amplitude of oscillation, $t(1948.1) = -0.1$, $p = .92$. To further illustrate the differences between the experiments, Figure 4 shows that the reduction in the amplitude over cycles was steeper in Experiment 1b, without on-line perception-action coupling, than in Experiments 1a and 1c.[5]

Discussion

The present experiment confirmed our main hypothesis: The magnitude of the errors in this experiment was larger than in Experiment 1a. The number of exploratory oscillations was closer to the number observed in Experiment 1a than to Experiment 1b. Hence, with the on-line perception-action coupling present and using actuators with a field of sensitivity of 45º instead of 2.50º, the accuracy of performance was still reduced but not the exploratory behaviors. Taken together, Experiments 1a to 1c demonstrate that, for an accurate orientation performance, a large number of actuators (resolution of the sensory flow field) and a sufficiently direct perception-action coupling are both needed.

Experiment 2

Experiment 1 addressed orientating the body axis toward the targets. The next step in our study of haptic navigation using an SSD concerns the approach to the target, without turning. Experiment 2 addressed the performance of individuals who, using the SSD, walked toward a

[5] Let us also mention that the standard deviations of the amplitudes shown in Figure 4 were slightly higher for Experiment 1c than for Experiment 1a for all half cycles. For the last four half cycles shown in the figure, these standard deviations were 12.8, 12.3, 10.4, and 9.0 for Experiment 1a, and 14.9, 18.1, 17.4, and 12.9 for Experiment 1c. In line with our reasoning in the Introduction of Experiment 1c, we believe that this difference is due to the fact that on some occasions the amplitude was reduced because the target remained within the field of sensitivity of the central column of activators, whereas on other occasions the amplitude was increased so as to try to reach the target with the fields of sensitivity of the side actuators.

virtual object placed a few meters in front of them. To be able to do this, the SSD provided information about the distance between the participant and the target, D_{pt}. This information was simultaneously provided in two ways: through the vibrotactile angle γ and the intensity of vibration (Figure 2).

Being able to control the approach to a target while walking is an essential part of spatial navigation with SSDs, but it has rarely been studied in an extensive way. Jansson (1983) used an SSD that provided vibrotactile information to the abdomen of two blind participants and asked them to walk 2 m and then point to a target. Although Jansson reported successful behavior, he did not report measurements concerning the errors in performance. Van Erp et al. (2005) addressed the issue of tactile information about distance in a more explicit manner. These authors showed that vibrotactile stimulation applied to the waist allowed participants to successfully locomote along routes indicated by (invisible) waypoints. As mentioned above, the device tested by van Erp et al. indicated the direction of the waypoints by the location of the vibration. Distance was coded by varying the length of the off-phase between vibratory pulses that had a fixed duration of one second. Van Erp et al. reported that the alternative ways to code distance did not lead to significant differences in performance. In fact, not coding distance led to (non-significantly) better performance than any of the tested ways to code distance.

The lack of a performance advantage of the distance information provided in the study by Van Erp et al. (2005) may have been due to the reduced benefit of knowing distance in the used task, rather than to the possible difficulty of the participants to detect and use the information. Given that the distance to the target is the only parameter that needs to be controlled by participants in the present experiment, our experiment provides a clearer test of the hypothesis that SSD users are in fact able to take advantage of distance information. In addition, the experiment allows us to test if exploratory oscillations occur also in this task.

Method

This experiment was performed by the same 11 participants as Experiment 1a.[6] If they wanted to, the participants could take a short break between the two experiments. We asked participants to walk in a straight line until they reached the target. In contrast to the previous experiments, in this experiment the SSD provided information about the distance between the participant and the target, D_{pt}, but not about the participant's orientation. Consequently, the vibrotactile angle γ and the intensity of vibration varied normally, but the actuators that were turned on were always the ones in the middle. Participants started each trial from the starting point and they walked toward a virtual target placed at a distance of 300, 500, or 700 cm. The experimenter asked participants to follow a straight line. If participants deviated from that line, the experimenter advised them to turn in the correct direction. If a participant reached the target, the intensity of vibration and the number of vibrating actuators were at the maximum levels allowed by the SSD. If the target was passed, the intensity of vibration diminished as D_{pt} moved away from zero again. The three familiarization trials used target distances not used during test trials: 200, 400, and 600 cm. After the familiarization trials, participants performed 3 (distances) × 5 (repetitions) = 15 experimental trials, presented in a random order. The experiment took approximately 20 min.

Results

Overall description of performance. On some trials participants walked in a relatively straight line, with some lateral deviations due to body sway, and stopped around the target area. In other trials they passed the target and recovered the position by walking backward (Figure 5). In general, participants reported that it was easy to decide where to stop, but that sometimes it was useful to feel how the intensity of vibration and the number of actuators decreased when the target had been overshot. Eight trials (4.8% of the total number of trials) were not properly recorded and were not used in the analyses.

Final position. A repeated-measures ANOVA was performed with target location (3 levels) as the within-subjects factor and the final position of participants (the y coordinate in Figure 5a) as

[6] Experiments 1b and 1c were performed by different participants because they were conducted later than the other experiments.

a dependent variable. The ANOVA revealed a significant effect, $F(2, 100) = 8779.5$, $p < .001$, $\eta_p^2 = .99$. This demonstrates that the vibrotactile SSD allowed users to distinguish the target locations.

Signed and absolute errors. Two repeated-measures ANOVAs were performed with target distance (3 levels) as the within-subjects factor, with the signed and absolute errors as dependent variables. As shown in Table 1, significant effects were obtained for both dependent variables; performance was most accurate for the farthest target because participants showed less overestimation for that target. The average signed error was 15.9 cm. This means that, on average, participants stopped 15.9 cm after the center of the target. Because the target was circular and had a diameter of 20 cm, this was 5.9 cm beyond the edge of the target. The average magnitude of the error was 19.7 cm (*SD* = 14.7).

Trial duration. Performing the task required more time than in Experiment 1. Participants used a mean of 19.1 s (*SD* = 13.3) before they decided that they were at the target. Trial duration was not related to accuracy as measured by the magnitude of the error ($r[155] = -.12$, $p = .13$).

Movement variables: Number and amplitude of oscillations. The behavior of overshooting the target and tracking back happened in 66.9% of the trials (*SD* = 47.2). In those trials, at least one oscillation of more than 10 cm was observed (Figure 5b). In 20.4% of the trials participants oscillated more than once. The number of oscillations (*M* =1.8, *SD* = *3*.4) was not related to the magnitude of the final error ($r[155] = -.09$, $p = .25$). The average velocity was 37.3 cm/s (*SD* = 9.0). The distance covered in a straight line was 577.3 cm (*SD* = 168.1), which is higher than the minimum distance needed to perform the task without error (500 cm; the mean of the three distances to the target). As implied by the design, the size of the vibrotactile angle at the end of the trial (γ; Figure 2a) closely related to the magnitude of the error ($r[155] = -.87$, $p < .001$). This angle, together with the intensity of vibration, may hence have been used to reduce the error.

Discussion

Experiment 2 showed that the SSD can be used to successfully complete navigation tasks that involve moving toward and stopping at targets located in front of participants. Participants

reduced the distance to the target from the initial 3 to 7 m to an average final 5.9 cm beyond the edge of the target. This indicates that participants were able to detect and use the distance information provided by the devise. In 66.9% of the trials, the final position was reached after overshooting the target and tracking back.

The lack of previous studies that quantified the distance error prevents us from making comparisons with other SSDs. Relatedly, however, Loomis, Da Silva, Fujita, and Fukusima (1992) reported average distance errors of 55 cm for individuals who were blindfolded after a period of visual preview and then walked to targets placed at distances that were similar to the present ones (4-12 m). Our results can hence be interpreted as indicating that on-line control when using an SSD is superior to control on the basis of vision that is occluded just before the initiation of the action.

Participants in our experiment had an average walking velocity of 37.3 cm/s. In their first experiment, van Erp et al. (2005) reported an average walking velocity of about 4.3 km/h (119.4 cm/s), which is substantially faster than in our experiment. A possible explanation for this difference could be the following. In the study by van Erp et al., although the orientation to the invisible waypoints was based on the vibrotactile stimulation, other aspects of the control of walking were based on regular vision. Also, given that the waypoints in the study by van Erp et al. had a diameter of 15 m, the accuracy of the control was not as important as in our Experiment 2.

Experiment 3

Experiments 1 and 2 considered orienting toward and approaching a target as two separate tasks. This experiment addressed a more general task: steering and locomoting toward a goal as described in the first experiment by Fajen and Warren (2003). The information provided by the SSD was a function of the distance between the participant and the target, D_{pt}, the vibrotactile angle of the target, γ, and the body-referenced direction of the target, θ. The main purpose of Experiment 3 was to explore the generality of the oscillations observed in the single-dimensional orientation task in Experiment 1a. We hypothesize that the exploratory oscillations will be observed also in this more general task.

Method

Experiment 3 was performed by seven of the participants that also performed Experiments 1a and 2. Four of these participants performed Experiment 3 three weeks after Experiments 1a and 2. The rest of the participants completed the three experiments on the same day, separated by optional short breaks. Participants were asked to walk from a starting position to the virtual target. Similar to Fajen and Warren's (2003) procedure, during the first meter, the SSD did not vibrate. Beyond that point, the SSD provided information about the distance to the virtual target by increasing the intensity of vibration and the number of actuators that were turned on as the distance decreased. The SSD also provided information about the direction of the target in relation to the participant's orientation. Participants could feel the vibration only if the field of sensitivity of the device (60º) was directed toward the target. Participants were asked to navigate toward the target using all the functionalities of the SSD mentioned in the general method. In the three familiarization trials, the targets were located at 30º and 200 cm, 0º and 600 cm, and -30º and 200 cm. After the familiarization trials, participants completed 12 test trials, using two repetitions of the following six positions: ±5º and 500 cm, ±10º and 400 cm, and ±15º and 300 cm. The experiment took approximately 30 min.

Results

Overall description of performance. Participants reported that it was more difficult to reach the target in Experiment 3 than in Experiments 1a and 2. One trial (1.2% of all trials) finished early without the participant finding the target. This trial was not used in the analyses. In four other trials (4.8% of the total number of trials) participants declared that they were unsure of their decisions. Those trials were analyzed along with the rest of the trials. Participants usually moved the upper body turning from one side to the other while they were walking, even during the first meter, which did not include vibration. As in Experiment 1a, participants moved the torso with large oscillatory movements at the beginning of a trial and with smaller oscillatory movements later in the trial, as they homed in on the target (Figure 6).

Final position. We examined the effect of target location with repeated-measures ANOVAs. The first two ANOVAs used the x and y coordinates of the participants' final position as dependent variables. As shown in Table 2, these ANOVAs revealed significant effects for both coordinates. This demonstrates that the SSD was useful to distinguish the target locations.

Two-dimensional spatial error. The spatial error was defined as the ordinary Euclidian distance between the participant and the target at the end of the trial. This Euclidian distance is depicted by the segment referred to as *error* in Figure 6a. The average spatial error was 37.1 cm (*SD* = 21.8). The repeated-measures ANOVA on the spatial error revealed a significant effect of target location (Table 2). This means that the targets were not detected with equal accuracy. Pairwise comparisons with Bonferroni's adjustment for multiple comparisons revealed significant differences ($p = .007$) between the errors for the targets located at -15º and 15º (50.1 vs. 21.4 cm, respectively).

Single-dimensional spatial errors. When the spatial errors of the coordinates were considered individually, they correlated significantly with the errors as measured by the 2D Euclidian distance between the target and the participants' final position. Nevertheless, the errors in the y direction contributed more to the 2D errors ($r[81] = .99$, $p < .001$) than the errors in the x direction ($r[81] = .25$, $p = .024$).

Angular deviation and trial duration. At the moment of the decision, the correlation between the heading direction and the direction of the target was $r[81] = .29$, $p = .008$. The average signed angle *D* at that moment was 4.5º (*SD* = 36.6). The magnitude of this deviation was 18.9º (*SD* = 31.6). Trials with a smaller final magnitude of the angular deviation also had a smaller spatial error ($r[81] = .42$, $p < .001$). The mean time taken to complete a trial was 29.6 s (*SD* = 10.9). In this experiment, the duration was inversely related to the accuracy of the decision: the longer a trial, the greater the error ($r[81] = .30$, $p = .005$).

Movement variables: Number and amplitude of oscillations. On average, participants oscillated the body-referenced target angle 16.1 times per trial (*SD* = 6.5; Figure 6c). The mean

angular range covered in a single trial was 113.6º (*SD* = 31.0). The amplitude of the last half oscillation before the decision was 8.4º (*SD* = 8.1). On average, participants walked at 15.6 cm/s (*SD* = 3.0), which is approximately twice as slow as in Experiment 2. The walking speed was related to the final spatial error ($r[81] = -.39$, $p < .001$). Slower trials were less accurate. Participants covered a mean cumulative angular distance of 580.9º per trial, which is more than six times the angular distance per trial in Experiment 1a (86.7º). On average per trial, the target occupied a vibrotactile angle γ of 25.5º (*SD* = 4.5), participants had 4.9 (*SD* = 1.41) actuators activated in each row (see Figure 6b for an example), and the intensity of vibration was at 75.1% (*SD* = 11.1) of the maximum.

Discussion

Participants in this experiment were able to use the SSD to orient and walk toward targets in all but one of the trials. The average final deviation was 37.1 cm, which is 27.1 cm from the edge of the target. We therefore consider performance to be relatively successful. As was the case in Experiment 1a, oscillatory movements were observed. This shows that the oscillations are not a peculiarity of a purely rotational task. The oscillations may have been allowed by the on-line perception-action coupling and they may have facilitated the detection of the direction θ. We believe that having identified and quantified the exploratory oscillatory movements is an experimental contribution that goes beyond the findings of previous studies on SSD-based navigation (Cardin, Thalmann, & Vexo, 2007; Faugloire & Lejeune, 2014; Jansson, 1983; Tsukada & Yasumura, 2004; van Erp et al., 2005).

Two issues deserve mention with regard to the opinion expressed by participants that Experiment 3 was more difficult to perform than Experiments 1a and 2. First, from Figure 6b, one may wonder whether the expansion of the vibrotactile stimulation along the approach may have partially masked the information about the direction θ at the end of the trials. Second, the programming error that was present in Experiment 1a (look back to Footnote 3) was present also in Experiment 3. The importance of both of these issues, however, should be considered in relation

with the significant correlation between the target direction and the heading of participants at the end of the trial, which indicates that participants' behavior was consistent with the target direction.[7]

General Discussion

The present article reports a series of experiments involving orientation and navigation using an SSD with an on-line perception-action coupling. The information provided by the SSD was shown to be sufficient to guide users toward invisible targets. In addition to replicating findings of Faugloire and Lejeune (2014) on the accuracy of SSD-based orienting toward targets, we were able to extend the findings to more complex tasks, and complement them with an analysis of the exploratory movements.

Experiments 1a to 1c addressed the ability of users of the SSD to align their body axis with the targets. Experiment 1a used the full functionality of the SSD, leading to average absolute errors of 1.4º. Experiment 1b was performed without on-line perception-action coupling. This led to absolute errors of 12.4º. Experiment 1c was performed with fewer actuators than Experiment 1a (3 instead of 24 columns). This led to absolute errors of 12.3º. Taken together, Experiments 1a to 1c show that accurate performance requires a sufficiently large number of actuators as well as an on-line perception-action coupling.

In the experiments with an on-line perception-action coupling (Experiments 1a and 1c), the absolute errors (1.4 and 12.3º, respectively) were smaller than the areas of sensitivity of the actuators (2.50 and 45º, respectively). This is reminiscent of the phenomenon of hyperacuity in regular visual perception. In their study on sensory substitution, Lenay et al. (2003) described cases of hyperacuity as cases with "perceptive resolutions superior to those of the material resolution of the matrix of stimulators". As we do, Lenay et al. attributed hyperacuity in sensory substitution to the presence of sensory-motor couplings. Another case of hyperacuity is the one reported by

[7] As a critical note, one may argue that the oscillations observed in this experiment were merely the result of a habit that was developed during Experiments 1a and 2. We believe, however, that the distinctive features of the exploration in Experiments 1a, 2, and 3 indicate otherwise. For example, the mean angular range in Experiment 3 was approximately 2.5 times larger that the mean angular range in Experiment 1a, and the oscillations in Experiment 2 did not involve rotations of the upper-body.

Faugloire and Lejeune (2014). These authors observed absolute errors of about 10º (or more, depending on the experimental condition) while their SSD had areas of sensitivity of 45º per actuator. With absolute errors of 12.4º and areas of sensitivity of 2.5º, hyperacuity was not observed in our Experiment 1b, in which the on-line perception-action coupling of the SSD was suppressed.

The patterns of errors and the hyperacuity that we observed in our experiments are consistent with the claim that an on-line perception-action coupling is beneficial because it permits the detection of information through exploratory movements. Further evidence for this claim is provided by the following. First, in Experiments 1a and 1c the number of oscillations was higher than in Experiment 1b. Second, the trial duration was longer in Experiments 1a and 1c than in Experiment 1b. Our interpretation of these results is that, in our experiments with an on-line perception-action coupling, participants explored more, and, therefore, needed more time to complete the task and performed more accurately.

Participants in Experiment 2 walked toward targets placed straight in front of them. Participants stopped, on average, 16 cm after the center of the target, which had a diameter of 20 cm. It is interesting to relate this distance to a particularity of our experiment and the SSD. In this experiment, all actuators of the SSD were activated when participants were at the center of the target. When participants continued beyond the target, the first actuators of the SSD that were turned off were the ones placed the furthest from the body center. These actuators were turned off when participants reached a distance of 15 cm from the center of the target. Hence, the average location where participants stopped was very close to the limit where the first actuators stopped vibrating. Participants who first passed the target and then walked backward were possibly exploring the coupling between the amount of active actuators and their displacement.

In contrast to Experiments 1 and 2, which concerned single dimensions (either turning or walking to the target), Experiment 3 involved two dimensions (turning as well as forward walking). Despite the arguably higher complexity of the task, participants successfully steered and walked toward the target in 98.8% of the trials. As was the case in Experiment 1a, oscillatory movements

around the longitudinal body axis were observed. This demonstrates that the exploratory movements are an important aspect of SSD-based locomotion in general, rather than being a particularity of the single-dimensional orientation task.

The finding that exploratory movements are important is consistent with previous studies about SSDs (Díaz et al., 2012). The finding is also consistent with previous studies concerning perception without SSDs, for example in the areas of regular vision (Bingham & Stassen, 1994) and dynamic touch (Solomon & Turvey, 1988; Turvey, 1996). When perceivers estimate properties of manually held rods, for example, they base their estimates on inertial properties of the rods. To detect the inertial properties, the rods need to be wielded. Moreover, perceivers wield the rods in different ways depending on which of the inertial properties are relevant. This task-specific wielding helps them to selectively perceive either the length or the width of the rods (Arzamarski, Isenhower, Kay, Turvey, & Michaels, 2010). Analogous to these findings from dynamic touch, we interpret our findings as showing the advantages of task-specific active exploration. Such exploration allows perceivers to detect and use task-relevant information.

Concerning the information, our SSD provided users with haptic analogues of variables that are known to be relevant for visually guided locomotion (Fajen & Warren, 2003; Fajen et al., 2003). These variables include the egocentric angle of objects and information about distance. The latter type of information was provided through the intensity of the vibration and the vibrotactile angle. The vibrotactile angle followed the same laws of angular size as a function of distance that hold in the case of optics: the closer the object, the larger the angle, and, hence, the larger the number of active actuators. It is well known that expansion-related optic flow variables are highly relevant to the visual guidance of action (Lee & Reddish, 1981; Tresilian, 1999). We find it interesting to speculate that such variables may also be useful in sensory substitution (Cancar et al., 2013). More generally, we believe that it may be fruitful to take into account current knowledge about optic flow variables, and to conceive SSDs that permit access to haptic flow analogues of such variables.

In the introduction, we reviewed three (mutually non-exclusive) reasons concerning the low

applicability of SSDs in everyday life. The first reason was the low sensitivity of the skin. Obviously, the sensitivity of the skin is not comparable to the sensitivity of the eyes, and this is relevant to sensory substitution. On the positive side, however, our results indicate that this shortcoming can partially be mitigated by improvements in the contingency of the stimulation with the users' exploration. It is illustrative to reformulate the observed hyperacuity to skin-based measures. Remember that the horizontal distance between the centers of the actuators in our SSD was about 1.7 cm and that the constant and absolute errors that we observed in Experiment 1a were, respectively, 8% and 56% of the angular sensitivity of each actuator. Translated to skin-based measures, these errors can be said to represent 0.14 and 0.95 cm, respectively. The two-point threshold of the skin at the abdomen is about 3 to 4 cm (Weinstein, 1968). Our results therefore indicate that SSDs that allow dynamic user-controlled information detection allow users to achieve levels of performance that go beyond the sensitivity of the skin as measured with the classic two-point threshold.

A second reason that has been suggested for the low applicability of SSDs in everyday life concerns cognitive processing limitations. According to this argument, the central nervous system is not able to process the wealth of information that it may receive if one simultaneously presents information to many actuators and changes the levels of activation at a fast update rate. Consider three counterarguments. First, our Experiment 1a shows that increasing the number of actuators and the refresh rate with respect to previous studies (Faugloire & Lejeune, 2014), reaching values well beyond the detection thresholds, leads to substantial improvements in heading accuracy. Second, according to participants and to the authors' own experience, the use of our SSD is not accompanied by any sign of cognitive overload. Third, in agreement with non-elementaristic approaches (Runeson, 1977, 1994), one may argue that the variables that are detected using SSDs are global sensory flows that dynamically change over time (cf. Meng, Ho, Gray, & Spence, 2015). If such higher-order variables are what is relied on instead of the set of vibrations of the individual actuators at particular moments, then increasing the number of actuators and the refresh rate should

be expected to lead to a more precise detection of these variables, rather than to an increased risk of cognitive overload. In sum, cognitive processing capabilities associated with tactile perception may not be as crucial as previously argued.

This brings us to the third reason for the low applicability of SSDs: the insufficient attention that has been devoted to active exploration and existing knowledge about task-relevant information. Our study shows that this reason may be crucial. Participants actively explored haptic analogues of information that had previously been shown to be relevant to the visual control of locomotion, and they achieved reasonably accurate performance. This research direction should be further developed in future work. Among other issues, such future research should consider locomotion in more complex task environments, including obstacles and targets instead of only targets. As argued by Fajen and Warren (2003), locomotion as well as route selection in more complex environments can be understood with simple information-action couplings. We believe that these, and other information-action couplings from the literature on the visual control of action, are well suited for implementation in SSDs.

To conclude this article we would like to revise a few of the practical implications of our study. The most direct implications are that SSDs must provide an active perception-action coupling, include a substantial number of actuators, and take into account the information used by individuals who perform similar tasks with vision. A less direct implication is provided by the observation that, with active exploration, users may move so that the tactile stimulation is at the best-suited body location, in our case the body midline. At the body midline, the skin is more sensitive than at other body locations. Our SSD thereby provided a natural analogue of the fovea. Future SSDs may enhance the benefits of this effect by increasing the density of actuators around the body midline at the expense of the density at more lateral body locations.

To indicate a final implication of our research, remember that our SSD included horizontal rows of actuators on the torso because this was deemed optimal for the detection of the informational basis of orienting and walking to vertical targets. Obviously, however, different

actions are guided by different sources of information, and hence require different configurations of actuators. In previous studies, which considered the detection of and the interaction with ground level obstacles, we used vertical rows of actuators, either on the torso (Díaz et al., 2012; Travieso et al., 2015) or on the lower leg (Lobo et al., 2014). This implies that, to be of more general use, several configurations may have to be combined in a single SSD. Users of SSDs that consist of multiple special-purpose configurations, based on the above-described principles, may find these devices more useful for everyday-life tasks than the majority of existing devices.

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Table 1

Results of Repeated-Measures ANOVAs with Target Distance (d_1 to d_3) as Within-Subjects Factor for Experiment 2

	d_1		d_2		d_3				
	M	*SD*	*M*	*SD*	*M*	*SD*	*F(2,100)*	*p*	η_p^2
Signed Error (cm)	18.3	18.2	20.3	17.1	9.0	19.1	7.1	.001	.12
Absolute Error (cm)	20.8	15.2	21.6	15.4	16.3	13.2	3.2	.045	.06

Note. Target distance d_1 is 300 cm, d_2 is 500 cm, and d_3 is 700 cm.

Table 2

Results of Repeated-Measures ANOVAs with Target Location as Within-Subjects Factor (6 Levels) for Experiment 3

Dependent Variable	*M*	*SD*	*F*	*df (Factor, Error)*	*p*	η_p^2
Final x-Coordinate (cm)	-2.0	62.6	860.7	3.8, 45.0	<.001	.99
Final y-Coordinate (cm)	360.7	91.8	237.9	3.3, 39.3	<.001	.95
Spatial Error (cm)	37.1	21.8	3.9	4.0, 47.7	.009	.24

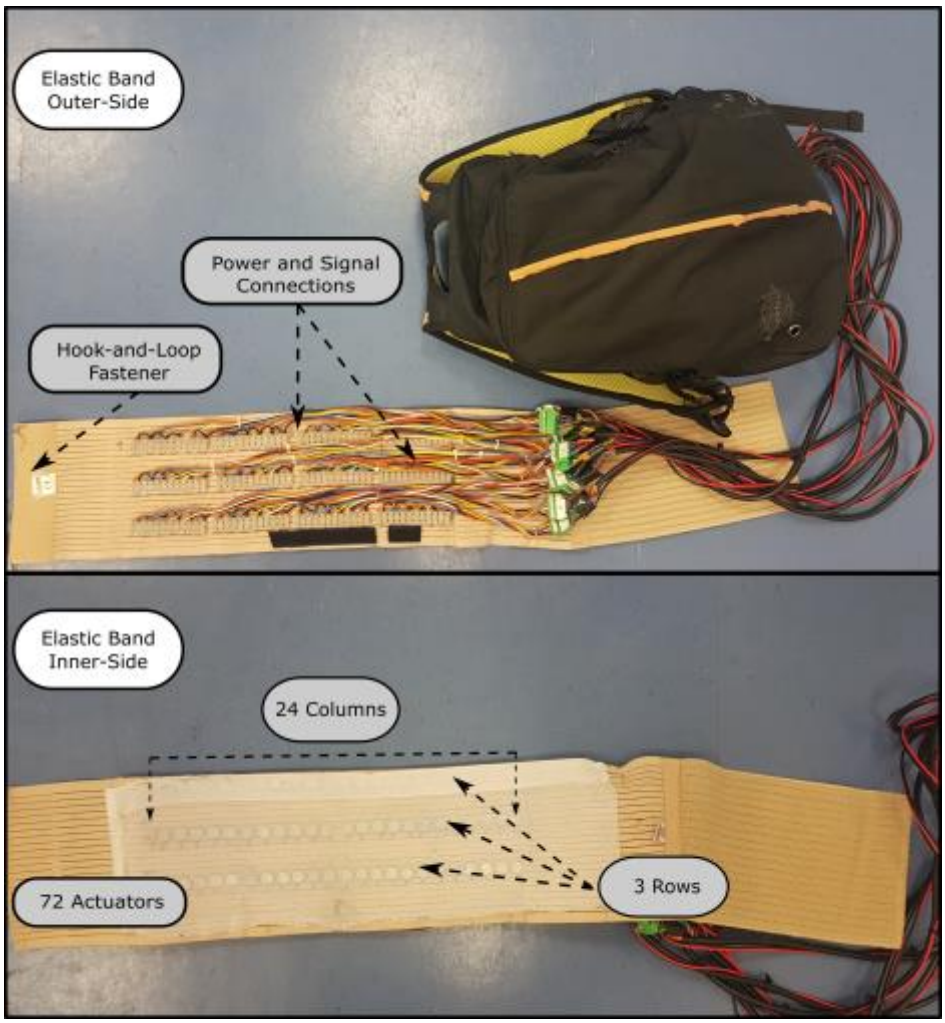

Figure 1. Picture of the SSD used in the experiments.

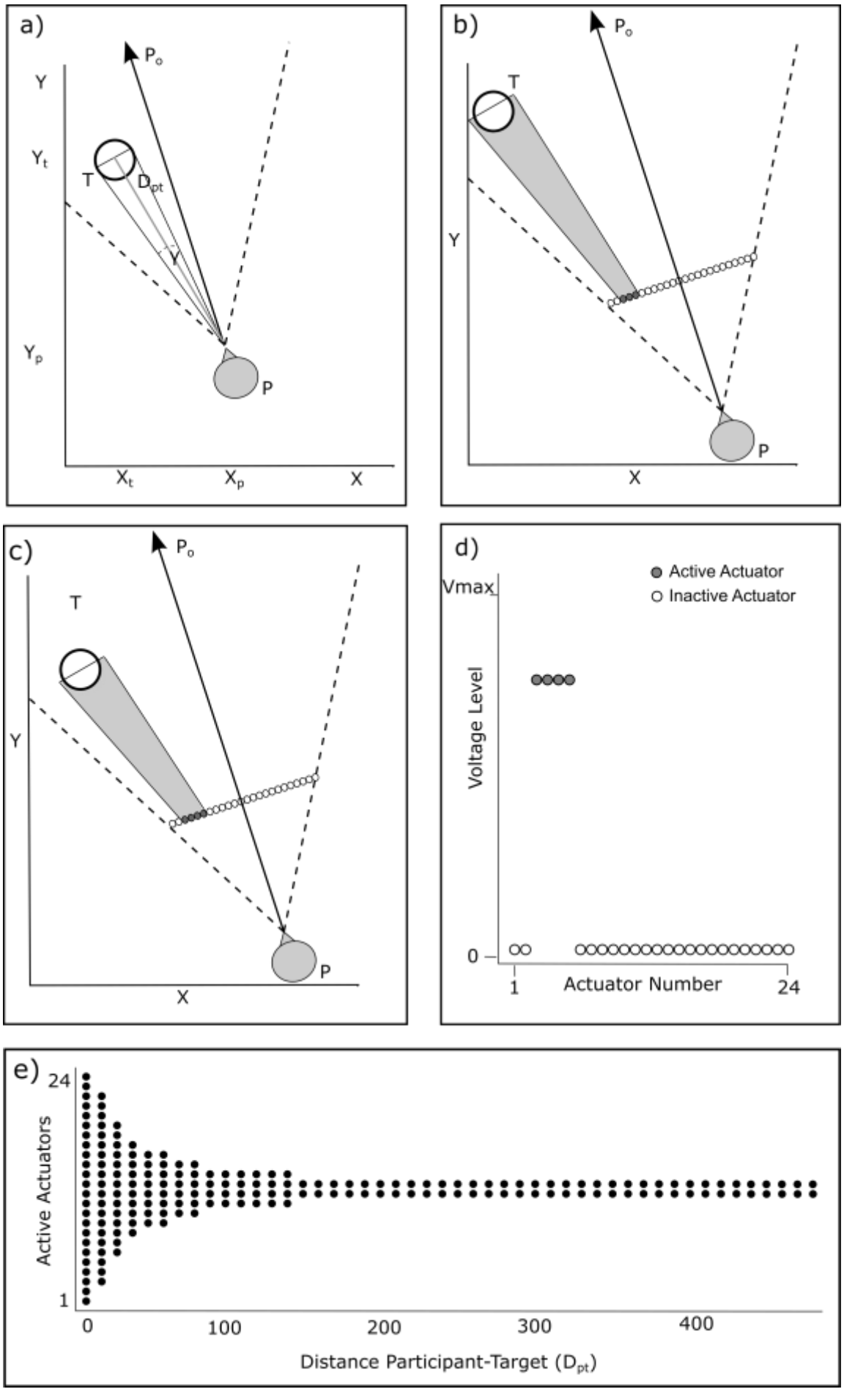
a)
P_o
Y
Y_t
T
D_{pt}
γ
Y_p
P
X_t
X_p
X
b)
P_o
T
Y
P
X
c)
P_o
T
Y
P
X
d)
Active Actuator
Inactive Actuator
Vmax
Voltage Level
0
1
Actuator Number
24
e)
24
Active Actuators
1
0
100
200
300
400
Distance Participant-Target (D_{pt})

Figure 2. Functional description of the SSD. (a) Participant, P, with a heading direction, P_o, and a target, T, placed at a distance, D_{pt}, that occupies a certain angle, γ. Dashed lines represent the field of view of the SSD. (b) Three actuators are marked in grey, representing the actuators that are active in the situation depicted in (a); open circles represent actuators that are not active. (c) As the participant approaches the target, the number of active actuators increases to four. (d) Voltage level of the actuators in the situation depicted in (c). (e) Actuators that are turned on and off as a function of $D_{pt.}$ The shown pattern corresponds to a participant that increases the distance to a target located straight ahead. The figure provides a top view: Each circle in the figure represents a horizontal column of three (equally vibrating) actuators in the actual device.

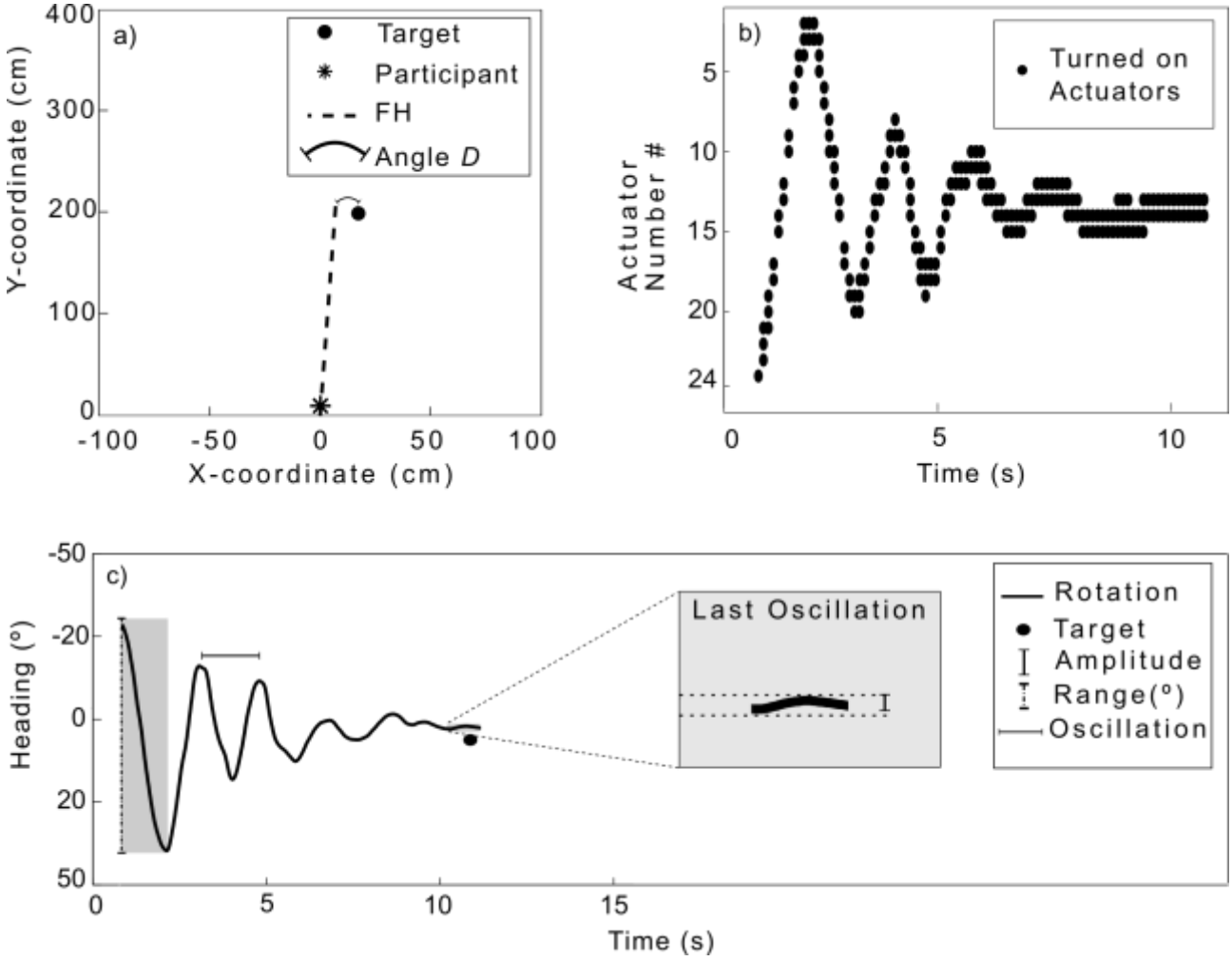

Figure 3. Example of a trial from Experiment 1 with a target located at 5º. (a) Heading direction at the last frame of the trial (FH = Final Heading). (b) Vibration patterns provided by the SSD during the trial. (c) Participant heading (with respect to the experimental set-up) during the trial, with an enlargement of the last oscillation shown in the grey square. Range = maximum angular space explored during the trial; Amplitude = Amplitude of last half oscillation.

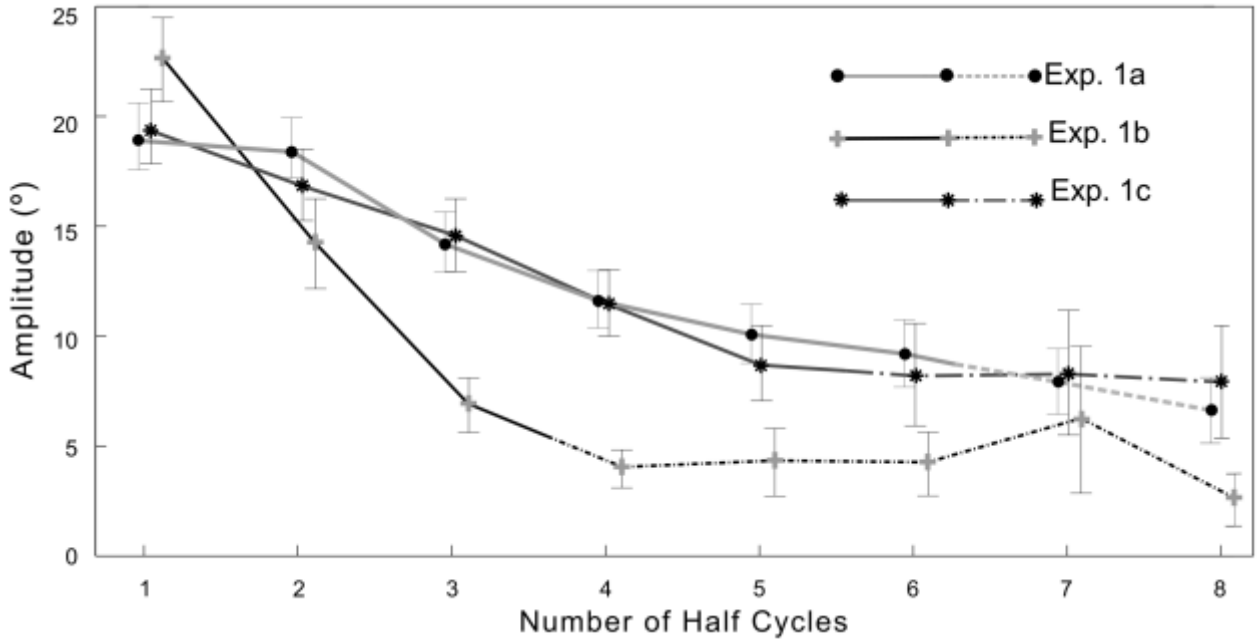

Figure 4. Average amplitude per half cycle of the oscillations observed in Experiments 1a to 1c. In all experiments, the amplitudes were large early in the trial and declined later on. The further to the right in the figure, the less observations were available to compute the means. For example, only eight trials in Experiment 1b showed eight half cycles. All other means were based on more trials. Continuous lines indicate that the number of half cycles was still below the average number of half cycles observed in the condition; discontinuous lines indicate that the number of half cycles surpassed the condition average. The standard error of the mean is represented in the figure by the error bars.

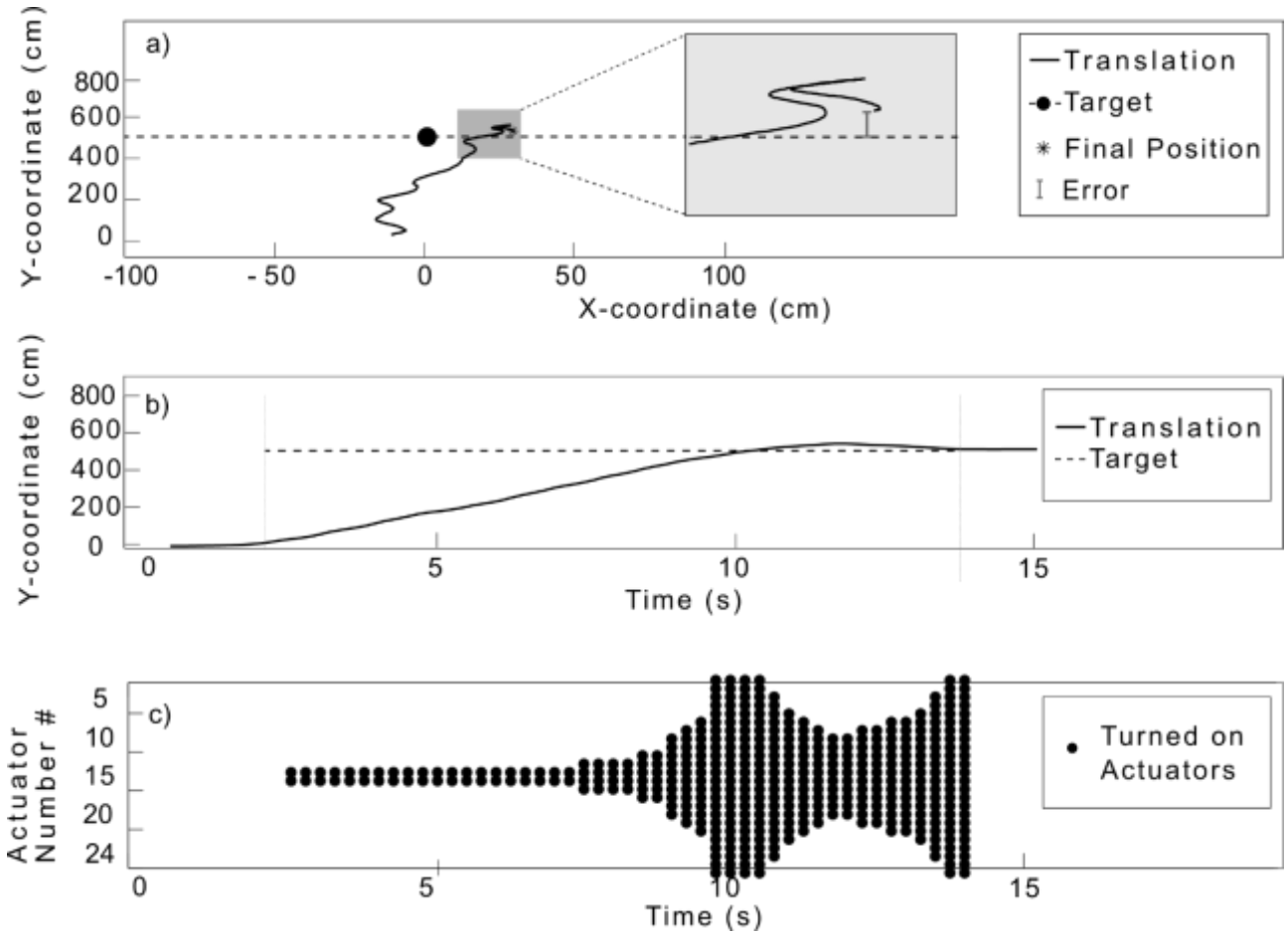

Figure 5. Example of a trial from Experiment 2. (a) Participant's approach to the target. The dashed line indicates the location of the target. An enlargement of the final part of the trial can be seen in the grey square. (b) Evolution of the y coordinate of the participant's position during the trial. (c) Vibration patterns corresponding to the exploration depicted in (a) and (b).

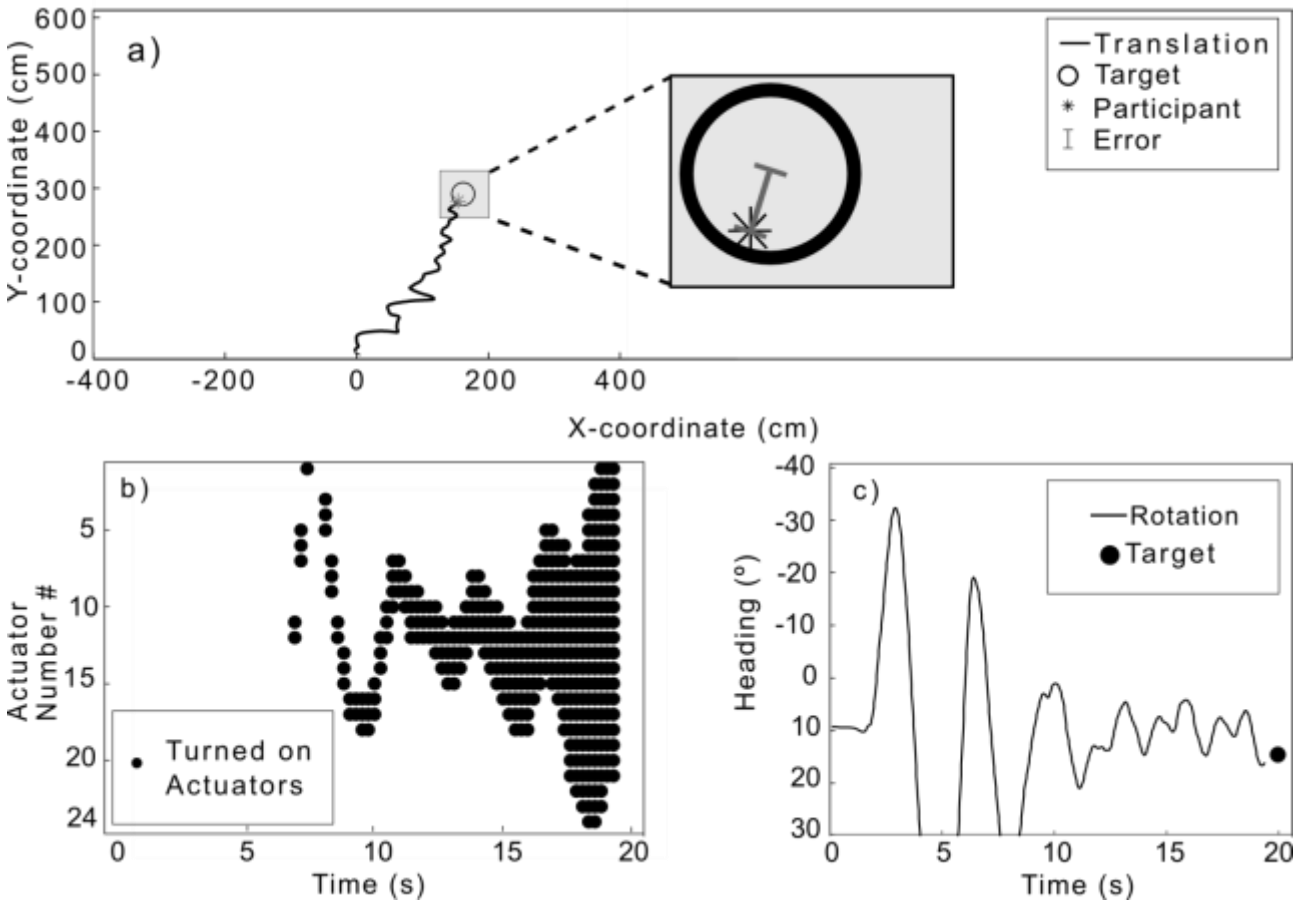

Figure 6. Example of a trial from Experiment 3. (a) Evolution of the two-dimensional position of the participant during the trial, with an enlargement of the final part of the trial in the grey square. (b) Vibrational patterns corresponding to the movement depicted in (a). Note that during the first 100 cm the SSD does not vibrate. (c) Evolution of the heading direction during the trial.