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The haptic moving room

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Abstract

In the moving room paradigm, visually perceived movements of the walls of a room affect the postural sway of individuals in the room. In this experiment, we used a virtual reality (VR) headset to provide visual information about the room, and a tactile device to provide haptic information about the front wall of the room. The tactile device consisted of 48 vibrotactile motors that were pressed against the abdomen and that provided continuous haptic stimulation. In experimental trials, the virtual room oscillated slowly (0.1 Hz) or quickly (0.75 Hz). Participants who stood on a force platform observed the room visually, haptically, or visually and haptically. The registered postural sway reflected the oscillations of the room in all conditions, including the purely haptic ones. The fact that participants coupled their body sway to the room in the visual conditions replicates previous findings that the moving room paradigm can be applied in VR. Although the coupling was less pronounced in the haptic conditions, the existence of this coupling demonstrates that a completely new type of flow information is spontaneously integrated in the elementary and highly practiced perceptual-motor activity of balance control. Applications in the fields of sensory substitution and rehabilitation are discussed.

Introduction

The group of devices that are commonly referred to as *sensory substitution devices* (Bach-y-Rita et al., 1969; Eagleman & Perrotta, 2023) are devices that allow users to do with one perceptual system (often audition or touch) what is typically done with another perceptual system (often vision). For example, humans often perceive and regulate their spatial relations to objects and surfaces in the world by detecting information about these relations in optical patterns. A sensory substitution device would relay such information in acoustic patterns or in patterns of skin deformations, hence enabling the person to use other perceptual means for the regulation of activity. As a relevant aside, note that this description of sensory substitution devices does not make use of the terms *sensory* and *substitution*. Even though sensory substitution is a commonly used term, and hence hard to avoid if one aims to keep in contact with the field, both parts of that term have been questioned with arguments that should sound convincing to ecological psychologists (Lenay et al., 2003).

Many sensory substitution devices have been developed for daily-life activities. These activities include object and pattern recognition (Auvray et al., 2007; Bermejo et al., 2015; Chebat et al., 2007; Kaczmarek & Haase, 2003; Sampaio et al., 2001), object localization (de Paz et al., 2023; Lenay & Steiner, 2010; Lobo et al., 2018; Satpute et al., 2019; Siegle & Warren, 2010), and navigation while avoiding obstacles (Chebat et al., 2011; de Paz et al., 2019; Favela et al., 2018; Kolarik et al., 2014, 2017; Lobo et al., 2019). In this study, we consider another essential sensory-motor activity: the control of posture. The control of posture is essential among other reasons because it is an elementary activity that is involved in the majority of hierarchically higher-order activities, such as orienting or locomoting (Gibson, 1966, p. 57; cf. Riley et al., 1999).

It is well known that body posture is usually controlled on the basis of proprioceptive, vestibular, and visual information (Horak et al., 1990). The role vision has been demonstrated

in the moving room paradigm (Lee & Aronson, 1974; Lee & Lishman, 1975; Schöner, 1991; van Asten et al., 1988). In this paradigm, individuals look at the walls of a room that move back and forth (while the floor remains stationary). The oscillations of the room, which are specified in detectable optic flow patterns, induce body sway in the anterior-posterior (AP) direction (the direction of the room movement), but not in the medio-lateral (ML) direction. The coupling between the body and the room is typically stronger for lower room frequencies (around 0.1 Hz) than for higher ones (around 0.75 Hz; Oullier et al., 2002; van Asten et al., 1988).

In several experiments in this paradigm, the relation of the observers to the room was perceived with perceptual systems other than vision. For example, Stoffregen et al. (2009, 2010) provided acoustic information about the oscillations of the room and Jeka et al. (1997, 1998) asked participants to touch an object (with their fingertips) and then moved the object at different frequencies in different experimental conditions (cf. Jeka et al., 1996). In all cases, the postural sway of individuals was coupled to the movements of the room. The overall conclusion of such experiments, therefore, is that the detection of information about the changing spatial relation of the individuals and the room is crucial to the control of posture, but not the type of flow that is used. With the present experiment, we aim to take such results one step further, testing whether postural oscillations can be induced also with a type of flow that is completely new to participants.

Our main purpose, then, is to test whether postural sway is affected by a haptic device that provides a continuous vibrotactile flow that is contingent on the motion of a moving room. Thus far, several vibrotactile devices have been used to provide information for the control of posture (see Sienko et al., 2018, for a review). For example, in an experiment by Peterka et al. (2006; cf. Goodworth et al., 2009, 2011), participants with vestibular deficits used a device in which vibrotactile feedback was switched on whenever the wearer started to

lose balance. The device thereby enhanced the haptic system and allowed users to detect information that is normally detected with the vestibular system. To the best of our knowledge, however, it is not known whether the use of vibrotactile flow instead of optic flow leads to similar postural sway patterns in the moving room paradigm. To provide the vibrotactile flow to participants, we adapted a recently developed sensory substitution device (Ibáñez-Gijón et al., 2023) and integrated it in the current experimental set-up.

Materials and Methods

Participants

Nine participants performed the experiment (seven females and two males with ages between 18 and 28 years). All of them were students at the University of Cincinnati with normal or corrected-to-normal vision. The experiment was approved by the local ethics committee (IRB: CR08_2012-2827). All participants signed a consent form and received course credit for their participation. None of them had previous experience with the tactile device or the moving room paradigm.

Apparatus

We created and rendered a 3D room in virtual reality (VR) with Unity (Unity Technologies, San Francisco, CA). The virtual room was presented on a VIVE head-mounted display (HTC Computer Manufacturing Company, Taoyuan City, Taiwan) with SteamVR (Version 1.21.12). In the experimental conditions with oscillations, the walls of the room moved sinusoidally with an amplitude of 8 cm. A red dot on the front wall provided a visual reference. Participants stood on a force platform (AMTI AccuSway^{plus} System). Visible marks indicated the precise position of participants on the platform. In addition, participants wore the tactile device. The used device, which is described in more detail below, included 48 coin motors that were attached to an orthopedic waistband. With the waistband, the motors were pressed against the abdomen of the participant. The area of the waistband with the

motors had an extension of approximately 26 (width) x 10 (height) cm. Figure 1 shows (a) an individual wearing the tactile device and the VR headset, (b) the inner side of the tactile device, and (c) the virtual room.

In the experimental trials that used the tactile device, all coin motors vibrated continuously. The intensity of vibration, V , was higher when the distance to the front wall, d , was shorter. This means that the vibration increased when the participant leaned forward and decreased when he or she leaned backward. Given the paradigm that we used in this study, changes in d , and hence in V , could also be due to the movement of the room. The precise function that related V to d was the following sigmoidal curve:

$$V = \frac{1.75}{1 + e^{2.25 \cdot (d - 3.5)}} + .9 .$$

In this equation, distance d is expressed in meters and vibration V in arbitrary units. During the preparation of the experiment, we tested the tactile device with various parameterizations of the sigmoid. The reported parameters were selected because they led to subtle yet noticeable changes in vibration with the room oscillations. Although the room oscillations were clearly noticeable with the tactile device, the information provided with the device was obviously poorer than the visual information. To highlight one aspect in this regard, the tactile information reflected only the movement of the front wall, not of the side walls.

The original version of the tactile device included a depth camera and worked in a fully autonomous way to facilitate locomotion of visually-impaired individuals in real-world conditions (Ibáñez-Gijón et al., 2023). This means that the use of the original device, in contrast to our experimental set-up, was not restricted to the laboratory. To integrate the device in the current set-up, the camera was removed and the device was modified to allow external input for the control of the motors. The components of the device included a 26000

mAh power pack, the power rectification and distribution circuits, a Raspberry Pi (Compute Model 4) connected to a custom designed input-output (I/O) board, and three flexible printed circuit boards (PCBs) that each contained 16 eccentric rotating mass (ERM) coin motors and a pulse width modulated (PWM) control chip (TLC59116). The PCBs were arranged horizontally, hence forming a matrix of coin motors with 3 rows and 16 columns (look back to Figure 1b). An inter-integrated circuit (I2C) bus was used to connect the PWM chips to the Raspberry Pi, using a daisy chain topology. All the components of the device were integrated in an ergonomic way in the waistband, as was the case for the device described in Ibáñez-Gijón et al. (2023). A functionally similar but differently engineered device with a much less ergonomic design can be found in Cancar et al. (2013).

With the exception of the processing within the tactile device, all aspects of the experiment (SteamVR, Unity 3D, force platform) were controlled with a personal computer (Intel Xeon processor E5-1650). The information about the participant position that was used to compute the distance between the participant and the front wall was provided by the movement registration of the VR headset. A cable with a comfortable length (look back to Figure 1a) was used for the communication between the personal computer and the headset. The communication between the personal computer and the tactile device relied on a wireless user-datagram-protocol (UDP) connection over a 2.4 GHz Wi-Fi network.

Procedure

In the actual experiment, participants stood on the force platform in the virtual room. The instructions to the participants were to stand in a comfortable and relaxed manner with their gaze at eye height near the red dot on the wall. They were informed that the room would move, but they were not asked to couple their posture to the room, nor were they asked to resist such a coupling. Relatedly, we did not inform them that the purpose of the force

platform was to measure their postural control. Instead, we mentioned that the platform and the visual marks on it were used to set their position in the room.

As a first experimental factor, three sensory modalities were used: visual, haptic, and combined. The visual information from the VR headset was used in the visual conditions and the vibrotactile information from the tactile device in the haptic conditions. Both types of stimulation were used in the combined conditions. In the conditions without vision, the VR headset was worn but participants were asked to close their eyes. As a second experimental factor, two frequency conditions were used: fast and slow. In the fast conditions, the room oscillated at 0.75 Hz and in the slow conditions at 0.1 Hz. These frequencies were the highest and lowest ones used in the experiment of Oullier et al. (2002). All trials of a particular modality were grouped in a block. The three modality blocks were performed in a random order.

For each modality, participants performed six experimental trials ($2 \text{ frequencies} \times 3 \text{ repetitions}$), plus an initial 40-s baseline trial with the stimulation corresponding to the block of trials but without oscillation of the room. A total of 12 room cycles were used per experimental trial. The registration started 5 s before the first cycle and ended 5 s after the last one. This means that the slow trials lasted 130 s and the fast trials 26 s. The order of the frequencies was randomized within the modality blocks. Participants were informed verbally when a trial began and ended. After each block, participants rested for 2 min. In total, participants performed 21 trials ($3 \text{ modalities of stimulation} \times 2 \text{ frequencies} \times 3 \text{ repetitions} + 3 \text{ baseline trials}$).

Before the actual experiment, a short training with the tactile device was performed. During this training, participants wore the tactile device and were placed in a virtual scene with a vertical cylinder. In a first phase, participants were asked to locate the cylinder and to orient their body axis toward it by using vision and the tactile device. They were encouraged

to explore and move. This allowed them to relate the changes in vibration to their exploration and to the visual stimulation. In a second phase, the cylinder was moved toward them and away from them in an oscillatory pattern. This was done in order to give participants some experience with moving objects. Both training phases were repeated without visual information. During the part of the training without vision, the experimenter asked participants to verbally report the movements of the moving cylinder. The experiment and the training were conducted in a single one-hour session.

Data analysis

The force platform provided time-series of the center of pressure (COP) in the ML and AP direction at 50 Hz. Both movement directions were analyzed. For the experimental trials, with 12 cycles of the room, we restricted the analyses to the time-period corresponding to the middle 10 cycles. For the baseline trials, we eliminated the first and last 5 s, obtaining time-series of 30 s. The so-obtained timeseries were resampled to 1000 frames each. After removing linear trends with the function “detrend” of MATLAB (R2022b), the time-series were submitted to a Fourier analysis performed with the function “fft”. For each trial, we stored the Fourier power (the absolute value of the complex-valued outcome of the “fft” function) at the main frequency (the frequency of the room oscillation) for further analysis. In addition, we analyzed the phase of the Fourier component at the main frequency with respect to the phase of the room (the angle of the complex-valued outcome of the “fft” function). Similar analyses were performed on the time-series averaged per condition, which is to say, averaged over repetitions and participants. As a measure of effect size, partial eta squared (η_p^2) is reported for ANOVAs and Cohen’s d (d) for t tests.

Results

In this Results section, we first specifically address our main hypothesis, which is to say, we first examine if the haptic information about the oscillations of the room induces

oscillations of participants in the AP direction. To do so, we compare the movement of participants in the haptic experimental conditions (with room movement) to the haptic baseline (without room movement). After confirming our main hypothesis, we turn to a more general comparison among the experimental conditions in the AP movement direction, including the visual and combined modalities. Results for the ML direction, for which no relevant couplings were expected, are presented in a third subsection.

Oscillations in the AP direction induced by the haptic information

Figure 2a presents the averaged time-series of the COP in the haptic condition. The figure concerns the AP component of the movements in the slow condition (0.1 Hz), in which the largest effect was expected. Note that the room (dashed curve) performed 10 full cycles. The COP (continuous curve) followed the room at least to some extent, although other movement frequencies and noise can also be observed. Figure 2b presents the COP for the haptic baseline condition. Whereas the figure shows relatively clear oscillations of the COP when the room moved, no such oscillations are seen in the baseline condition. The figure thus indicates that haptic information induced oscillations in the COP.

Figures 2c and 2d present the magnitude spectra obtained with the Fourier analyses on the averaged time-series shown in the upper panels. If one focuses on the magnitude of the Fourier component at the frequency of the room, one sees a peak in the curve on the left, but not on the right. This indicates that the COP had more strength at that frequency when the room oscillated than when it did not. To statistically test this result, we computed the Fourier magnitude at 0.1 Hz for each trial of each individual. A single-tailed paired t test compared this magnitude averaged per participant in the haptic condition to the same magnitude in the baseline condition. The difference was significant ($t[8] = 1.93$, $p = .045$, $d = 0.65$), meaning that the haptic information provided with the tactile device indeed induced oscillations of the COP.

The same analysis was performed for the fast condition (0.75 Hz). The t test for this condition also indicated a significant effect ($t[8] = 1.95$, $p < .044$, $d = 0.65$). Again, the magnitude was higher in the experimental condition than in the baseline.¹

Oscillations in the AP direction as a function of sensory modality

Figures 3a and 3b show the Fourier magnitudes for the three types of modalities (different curves) and the two room frequencies (Panels A and B). Note that the curve for the slow haptic condition (continuous curve in Panel A) is the same as the one in Figure 2c. For the slow condition, all curves show a peak at the main frequency (0.1 Hz). This peak is lower for the haptic modality than for the other modalities. For the fast condition, the peaks at the main frequency (0.75 Hz) are lower than for the slow condition, most particularly for the haptic curve, for which the peak almost disappears. We should mention, however, that the curves in this figure, as well as in Figure 2, concern Fourier analyses performed on time-series averaged over individuals and repetitions. This leads to nice figures because oscillatory components that are not phase aligned tend to cancel out due to the averaging in the time domain, hence reducing the amplitudes for such components in the frequency domain.

For the inferential statistics, which relied on data per individual, we did not average the trajectories in the time-domain. Instead, we computed the Fourier analysis on the individual time-series and then averaged the spectral magnitudes at the main frequency over the three repetitions of each individual (as we did for the above-mentioned t tests). The

¹ Note that the time intervals in the experimental and baseline conditions were not identical in these analyses. For example, the interval is 100 s in Figure 1a and 30 s in Figure 1b. If one limits the analysis to a part of the time-series, it is possible to analyze the results using identical intervals in the experimental and baseline conditions. T tests that were identical to the presented ones except for using such equal-length intervals (30 s [3 cycles] for the slow condition and 13.3 s [10 cycles] for the fast condition) were significant with $p < 0.001$ and $d > 1.6$ for both frequencies. The analyses reported in the main text are thus the ones with the more conservative results.

overall averages of these values are presented in Figure 4a. Reference values obtained from the baseline conditions are presented in Figure 4b. Note that, due to the different averaging procedures, the values in Figure 4a are higher than the peaks in Figures 3a and 3b. Judged from the figure, the Fourier magnitudes seemed to be higher in the slow condition than in the fast condition and higher for the visual and the combined modalities than for the haptic modality.

To test these findings, a repeated-measures ANOVA was performed on the individual-averaged Fourier magnitudes of the experimental data, with frequency and modality as factors. The only significant effect was the one of modality ($F[2,16] = 5.7, p = .01, \eta_p^2 = .42$). The effect of frequency ($F[1,8] = 2.2, p = .18, \eta_p^2 = .21$) and the interaction ($F[2,16] = 0.3, p = .75, \eta_p^2 = .04$) were not significant. Thus, although the previous subsection demonstrated that the tactile device induced oscillations in the COP, these oscillations were not as strong as the ones in the conditions with vision, be it vision alone or vision in combination with the tactile device.

To conclude our analysis of the movements in the AP direction, we consider the relative phase data. For these analyses we return to the Fourier analyses performed on the averaged data. For each experimental condition, the Fourier analyses provided the phase lead or lag of the averaged participant data relative to the room, expressed in degrees. Given that the periods of the room oscillations are known (10 s for the slow condition and 1.33 s for the fast condition), the phase data obtained with the Fourier analyses can be expressed as the relative timing of the participants with regard to the room. Expressed in seconds, in the visual conditions the movements of participants appeared to be advanced with regard to the room (0.55 and 0.65 s in the slow and fast visual conditions and 0.43 and 0.71 s in the slow and fast

combined conditions). In contrast, the movements of participant appeared to be delayed with regard to the room in the haptic conditions (0.40 and 0.33 s for the slow and fast conditions).²

Movement in the ML direction

Given that the room oscillated in the AP direction, no couplings between the room and the COP were expected in the ML direction. Figure 5 presents the results for the ML direction that are analogous to the results in Figure 4 for the AP direction. As expected, the results in the experimental and baseline conditions are largely similar. The above-reported statistical results that were significant for the AP direction did not reach significance for the ML direction ($ps > .05$).

Discussion

The present study examined whether continuous haptic information about the oscillatory movements of a room induces postural sway of individuals in the room. To do so, participants wore a VR headset as well as a vibrotactile device. The room in which participants were immersed oscillated slowly (0.1 Hz) or quickly (0.75 Hz). The room was observed visually (using the VR headset), haptically (using the tactile device), or with both perceptual systems. With Fourier analyses, it was observed that the sway patterns of participants had higher values in the power spectra at the frequency of the room in all conditions. The strongest effects were observed in the visual and combined conditions. This makes sense because visual perception is more natural than vibrotactile perception and because the visual flow was richer than the vibrotactile one. Even so, the effects in the haptic

² We should note that in the fast condition it is difficult to determine whether a Fourier component is advanced or delayed with regard to the room. For example, we claim that participants in the fast combined condition were 0.71 s advanced. Given the short period of 1.33 s, however, one could also claim that they were $1.33 - 0.71 = 0.62$ s delayed. We opted for the former interpretation because it provides a more consistent pattern over conditions, which is to say, it leads to the view that participants were approximately 0.5 s phase advanced in all conditions with vision.

conditions were significantly larger than in the baseline conditions in which the room did not move.

The fact that the room induced movements of participants in all conditions replicates the most typical result of the moving room paradigm (Lee & Aronson, 1974; Lee & Lishman, 1975; Oullier et al., 2002; van Asten et al., 1988). More specifically, Chander et al. (2019) showed (with non-oscillatory movements) that the moving room paradigm is effective also in VR. These authors argued that their finding has implications for stability training and rehabilitation (cf. Chander et al., 2020). This is so because several applications are based on controlled perturbations of balance, which may be achieved in a convenient manner with a virtual moving room. Our results in the conditions with vision are in line with the ones reported by Chander et al. (2019; cf. Bardy et al., 1999, 2002). That is, these results demonstrate that the moving room paradigm works appropriately also with a virtual room.

The main contribution of our study, however, is the demonstration that the moving room paradigm works in the conditions with vibrotactile stimulation. This result is relevant to the field of sensory substitution as well as to the field of stability training and rehabilitation. With regard to sensory substitution, it is important to emphasize that the haptic flow provided by the tactile device does not occur in natural environments. It is completely new to users of the device. In this sense, it is remarkable that users couple their sway to the haptic flow so spontaneously, naturally, and apparently unconsciously, without instructions to do so, and only after a brief training with the device. This indicates that the coupling of distance information to vibration intensity is a promising route in sensory substitution. Consistent with this observation, other distance-based sensory substitution devices are also intuitive to use even after short familiarization periods (Eagleman & Perrotta, 2023; Kilian et al., 2022; Lobo et al., 2018), which may be an advantage over light-intensity based sensory substitution devices (Bach-y-Rita et al., 1969; Guarniero, 1974, 1977).

In relation to the field of stability training and rehabilitation, remember from the introduction that multiple vibrotactile devices have been used as aids for the control of posture (Bao et al., 2018; Bechly et al., 2013; Goodworth et al., 2009, 2011; Peterka et al., 2006; Sienko et al., 2013). These aids often detect deviations from an upright posture (and the velocity of changes in posture) and communicate the deviations to the users through the onset of vibration whenever a certain threshold is exceeded. Such postural aids are similar to our haptic device in the sense that posture is registered and that some aspect of the registered posture is coupled in an on-line manner to vibration. The spontaneous coupling of posture to the vibrotactile flow in our haptic conditions can therefore be interpreted as a positive result for this more applied line of research.

Several particularities of our haptic device may be interesting to mention in this context. As a first difference between our device and many of the above-mentioned postural aids, one should note the continuous nature of the changes in vibration intensity and the relatively large number of actuators of our device. In other words, our haptic flow was continuous over space and time. In natural environments, a wealth of perceptual information can typically be found in transformations of energy patterns over space and time (Gibson, 1966, p. 163). As was our haptic flow, such transformations are mostly continuous. In the specific case of posture, proprioceptive, vestibular, and optic flows indeed tend to vary continuously. One may therefore speculate that the haptic flow that we provided was effective at least in part because it was provided in a spatiotemporal continuous manner, hence being in relevant aspects similar to the flow patterns that are used in natural situations.

As another interesting difference of our haptic device and typical postural aids, let us briefly discuss the role of the virtual room in our study and relate it to the concept of attentional focus (Wulf et al., 1998). The above-mentioned postural aids were described in the articles, and probably to the users, as being informative about the posture of the users

themselves. We described our device as being informative about the distance to the wall of the room in which participants were immersed. Even in the conditions without vision, participants were aware that the vibration was set as a function of the distance to the wall. As a consequence, one may expect a more external focus of attention for users of our device and a more internal focus of attention for users of the above-mentioned aids. In the literature on motor control and learning, the benefits of an external focus of attention are well-documented. An external focus of attention can be beneficial especially for movements that are usually controlled unconsciously, because an internal focus of attention may cause a disruptive shift to a more conscious type of control (Wulf, 2013, p. 91). On the basis of this reasoning, we believe that describing postural aids as being about the posture of the user or as being about the relation of the user to the environment (i.e., the distance to a wall) may be an interesting difference to consider in the field of stability training and rehabilitation.

Other research that must be considered in this discussion is the work by Jeka and colleagues (e.g., Jeka et al., 1997, 1998). These authors demonstrated that haptically perceived movements of objects affect the control of posture. The work of Jeka and colleagues thereby shows obvious similarities to our work. However, there are also relevant differences. First, participants in the experiments of Jeka and colleagues touched an oscillating object with a fingertip. Touching objects with a fingertip is more common and natural than receiving vibrotactile flow information through a tactile device on the torso. The finding that touching an object with a fingertip affects the control of posture may therefore be considered less surprising than our results. Second, participants in the experiments of Jeka and colleagues stood with one foot in front of the other, hence weakening their balance in the ML direction, and the authors analyzed oscillations in the less stable ML direction. This contrasts with the more natural stance of participants in our experiment and our analysis of oscillations in the AP direction.

To discuss a more subtle and speculative difference between the research of Jeka et al. (1997, 1998) and ours, we follow the line of reasoning of Riley et al. (1999) as applied to the research of Jeka and colleagues. Jeka and colleagues assumed that the fact that participants touched an object in their experiments provided additional perceptual information for the control of posture. We may refer to this as the perceptual interpretation of the observed effects. Riley and colleagues proposed an alternative interpretation: Participants may have organized their postural control differently because they were explicitly instructed to perform the task of lightly touching the object. In other words, the different organization of posture may have been due to the strict requirements of the touching task itself, not to the additional information provided by it. In our experiments, in contrast to the ones by Jeka and colleagues, participants did not receive explicit instructions related to the haptic stimulation. One may therefore argue that there was no relevant higher-order task related to the haptics in our experiment, making our results less in line with the alternative interpretation proposed by Riley and colleagues, and hence more in line with the perceptual interpretation.³

To summarize, the experiment presented in this article demonstrates that continuous haptic flow provided by a haptic device affects the basic perceptual-motor activity of balance control. Similar results have been observed in previous moving-room studies for optic flow (Lee & Aronson, 1974), acoustic flow (Stoffregen et al., 2009), and stimulation of the fingertips with a moving object (Jeka et al., 1997, 1998). Maintaining balance in a moving room paradigm may therefore be an example of the partial sensory equivalence of perceptual systems that was discussed by Gibson (1966, p. 54).

³ Let us also note that, for the purpose of rehabilitation, we believe that the comfort and ease of use of the equipment of Jeka et al. (1997, 1998), in which the moving object is touched only with a fingertip, cannot be matched by the majority of vibrotactile devices (including, for example, the ones by Peterka et al., 2006, and ours), which must be put on, kept clean, etc.

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Figure Captions

Figure 1. Experimental set-up and material. A: Individual with VR headset and the haptic device standing on force platform in experimental laboratory. B: Inner side of the haptic device with vibrotactile motors. C: Virtual room from perspective of participant.

Figure 2. Results for haptic modality of slow condition in AP direction. A: COP of participants (continuous curve) and room oscillations (dashed curve) as a function of time, averaged over all experimental trials (both in arbitrary units). B: Averaged COP of participants in haptic baseline trials (continuous curve). In these trials, the room did not move; the sinusoidal dashed curve is presented only to facilitate visual comparison with Panel A. C: Magnitude spectrum of Fourier analysis on time-series in Panel A. The dashed segment indicates the room frequency. Panel D: Magnitude spectrum of Fourier analysis on time-series in Panel B.

Figure 3. Magnitude spectra of Fourier analyses. The analyses were performed on averaged COP trajectories for all modality conditions for slow (A) and fast (B) frequency conditions, in AP direction. Vertical segments indicate the frequency of the room.

Figure 4. Fourier magnitudes of COP trajectories in AP direction. A: Average Fourier magnitudes at room frequency for all six experimental conditions. B: Average magnitudes (at these same frequencies) for baseline conditions. Error bars represent standard errors.

Figure 5. Fourier magnitudes of COP trajectories in ML direction. A: Average Fourier magnitudes at room frequency for all six experimental conditions. B: Average magnitudes (at these same frequencies) for baseline conditions. Error bars represent standard errors.









