Journal of Experimental Psychology:
Human Perception and Performance
2009, Vol. 35, No. 4, 1221–1231

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0096-1523/09/$12.00 DOI: 10.1037/a0014251

Coupling of Head and Body Movement With Motion of the Audible Environment

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The authors asked whether standing posture could be controlled relative to audible oscillation of the environment. Blindfolded sighted adults were exposed to acoustic flow in a moving room, and were asked to move so as to maintain a constant distance between their head and the room. Acoustic flow had direct (source) and indirect (reflected) components. Participants exhibited strong coupling of postural motion with room motion, even when direct information about room motion was masked and was available only in reflected sound. Patterns of hip–ankle coordination closely resembled patterns observed in previous research involving coupling of sway with a visible moving room. The results demonstrate that blindfolded adults can control the dynamics of stance relative to motion of the audible environment.

Keywords: posture, audition, acoustic flow, perception-action, stance

Over the past 25 years there has been an explosion of theory and research on the use of perceptual information for the precise control of action. Research on perceptually guided action often contrasts with more traditional perceptual research in which the outcome of perception is conscious awareness of some aspect of the stimulus or of the environment. The distinction between perception that leads to conscious awareness, on the one hand, and the use of perception in the control of action, on the other, is important in terms of the design of experiments and the results that they yield. Perception–action paradigms often reveal more precise perceptual sensitivity than has been found in perception-only paradigms. An example is the perception of time to contact, in which judgments of when a moving object will arrive at the point of observation (e.g., McLeod & Ross, 1983) are less accurate and more variable than interceptive action that depends on knowledge about timing (e.g., Bootsma & van Wieringen, 1990). In part, this is because it can be difficult to use words to express quantitative details of perception. Verbal reports are also problematic in the context of continuously evolving relationships between the observer and the environment. A good example is running to catch a fly ball on a windy day, where running speed and direction must be continuously modulated on the basis of visible changes in the ball's trajectory (e.g., Oudejans, Michaels, Bakker, & Dolne, 1996). Finally, the perceptual control of action can exhibit accuracy and precision in situations that typically do not give rise to conscious percepts. An example is research relating visual information to the control of standing posture due to the fact that we are rarely aware of body sway or of the actions that we take to stabilize it.

The majority of research on perceptually guided action has addressed the role of vision, that is, the perception and control of action relative to referents in the illuminated environment. Much of this research has been inspired by the discovery of parameters of optic flow that are related to motion in the animal–environment system, such as motion of objects relative to the illuminated environment (e.g., Lee, 1976) and motion of the perceiver relative to the illuminated environment (e.g., Gibson, 1966). Experiments have demonstrated that these parameters can be used for precise control of skilled movements, such as interceptive action (e.g., Bootsma, 1989; Stoffregen & Riccio, 1990) and the control of standing posture (e.g., Lee & Lishman, 1975; Stoffregen, 1985). Research has shown that humans use head movements in the localization of sound sources (e.g., Blauert, 1983; Gibson, 1966; Wightman & Jenison, 1995). Beyond this, research on the perception and control of action relative to referents in the audible environment has not been widespread. In studies of human audition, action often is prevented, for example, through the use of head restraint (e.g., Getzmann & Lewald, 2007). Research on

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Preparation of this article was supported by SKILLS, an integrated project (IST Contract 035005) of the Commission of the European Community, and by the National Science Foundation (BCS-0236627), with additional support from the Institut Universitaire de France. We thank Sofiane Ramdani for his advice regarding data analysis.

The experiments were conducted as part of the PhD thesis of ChungGon Kim at the University of Minnesota. Portions of the data were reported at the XI International Conference on Perception and Action, Storrs, CT, July 2001.

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perceptually guided behavior in bats has revealed extraordinary levels of auditory sensitivity, as well as remarkable precision in the control of action relative to audible referents (e.g., Simmons, 1989; Stoffregen & Pittenger, 1995). The auditory abilities of bats, taken together with the well-documented precision of visually guided action in humans, suggest that it would be useful to study the ability of humans to control action relative to the audible environment.

Several studies have examined relations between acoustic stimulation and the control of whole-body movement. These studies have demonstrated an influence of acoustic stimulation on standing body sway. In each of these studies, the acoustic stimulus had an arbitrary relation to the dynamics of body sway. Sounds either were stationary (Easton, Greene, DiZio, & Lackner, 1995; Petersen, Magnusson, Johansson, Åkesson, & Fransson, 1995; Russolo, 2002; Sakellari & Soames, 1996) or moved in axes or patterns that were unrelated to the axes or patterns of body sway (Petersen et al., 1995; Sakamoto, Osada, Suzuki, & Gyoba, 2004; Tanaka, Kojima, Takeda, Ino, & Ifukube, 2001). An exception is a study by Soames and Raper (1992), who exposed standing participants to sound fields that oscillated in the body's mediolateral or anterior–posterior axis with frequency 0.1 Hz. Soames and Raper found that body sway increased during exposure to moving sound, and that changes in body sway were specific to the axis of motion of the sound stimulus.

In the present study, we generated dynamic acoustic stimuli that were meaningfully related to some of the dynamics of body sway. We asked participants to use this acoustic information for the control of voluntary activity. We sought to determine whether participants could use reflected sound fields to couple head movements to motion in the environment. We also investigated coordination of rotations around the hips and ankles in support of this suprapostural task.

Optic Flow and Control of Stance

There is a large literature relating postural control to optic flow. Parameters of optic flow are influenced by parameters of motion of the point of observation, such as its direction and velocity. When there is oscillatory motion of the point of observation, the frequency of oscillations in optic flow is determined by the oscillation frequency of the point of observation. Large, sudden patterns of optic flow can knock a person down (e.g., Lee & Aronson, 1974; Stoffregen, Schmuckler, & Gibson, 1987). Optic oscillations that resemble the amplitude and frequency of stance often lead to entrainment of body sway with the flow. For example, Lee and Lishman (1975) exposed standing participants to optic flow in a moving room that oscillated along the line of sight. Measurements of torso motion revealed that the magnitude of body sway was greater when the room was moving. Dijkstra, Schöner, and Gielen (1994) showed that movements of the torso became coupled to oscillatory optic flow in terms of cross-correlation, gain, and relative phase. People often are not aware of this entrainment, or that there is any motion, at all (e.g., Stoffregen, 1985).

Recent research has examined the nature of the movements that are used to achieve coupling of body sway with optic flow. Several studies have examined the coordinative rotation of the ankles and hips when body motion is coupled to a visual stimulus that oscillates back and forth along the line of sight. In this work, participants have been asked to perform a tracking task in which they move so as to maintain a constant distance between their head and the oscillating stimulus (i.e., they should move their head back and forth with the visual oscillation). Participants are not given any instructions about posture or body motion; they are free to choose any type of body motion that will support the tracking task (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002; Faugloire, Bardy, & Stoffregen, in press; Oullier, Bardy, Stoffregen, & Bootsma, 2002). These studies have revealed characteristic patterns of hip–ankle coordination that are related to the amplitude and frequency of target oscillation. In the present study, we adapted this tracking task to the context of dynamic acoustic stimulation to evaluate the influence of acoustic motion on coordination of the hips and ankles.

Acoustic Array and Acoustic Flow

Optics and acoustics are not equivalent, but there are properties of the animal– environment system that simultaneously influence the spatiotemporal structure of both optics and acoustics. We can conceive of ambient acoustic energy in terms of an *acoustic array* (Jenison, 1997), with spatiotemporal variations in intensity (loudness) and frequency (pitch). Movement of sound sources in the environment or of sound-reflecting surfaces produce changes in the spatiotemporal pattern of loudness and pitch. In addition, movement of the point of observation relative to the acoustically reflective environment will produce global changes in the spatial patterns of loudness and pitch. These dynamic patterns, whether they arise from movement of objects, of the observer, or both, can be understood as *acoustic flow* (e.g., Müller & Schnitzler, 2000). Optic flow and acoustic flow have both direct (source emission) and indirect (reflected) components. However, optic and acoustic flow are not equivalent or redundant; we do not claim that they provide the "same" information in different forms of energy (e.g., Stoffregen & Pittenger, 1995). The fact that motion of the perceiver creates acoustic flow means that (as with vision) it might be possible for perceivers to use acoustic flow to perceive and control their own motion.

Research on reflected sound typically has been limited to its possible effects on the perception of the distance of stationary sound sources from stationary observers (e.g., Brankhorst & Houtgast, 1999; Guski, 1990; Mershon, Ballenger, Little, McMurtry, & Buchanan, 1989; Wightman & Jenison, 1995). Research on auditory vection can be interpreted in terms of the perception of self-motion from acoustic flow (e.g., Lackner, 1977; Sakamoto et al., 2004), but few studies have examined the influence of acoustic flow on the control of stance. Soames and Raper (1992), which we described earlier, used only direct sound sources, that is, moving sounds that arrived directly from speakers. They did not control or manipulate reflected sound. As noted above, in other previous research, dynamic acoustic stimuli have not been related to the dynamics of standing posture. A novel aspect of our study was the attempt to demonstrate functional coordination of postural adjustments to patterns of acoustic flow.

The Present Study

We sought to demonstrate that acoustic flow, as created in a moving room, can be sufficient for the control of bodily orientation in blindfolded sighted persons. We used oscillatory stimuli that simulated the frequency of natural body sway. We varied the nature of the locus of motion-related acoustic stimulation, using combinations of direct and indirect components from acoustic flow. We used the suprapostural tracking task developed by Bardy et al. (1999), and adapted it for use with stimuli whose motion was audible rather than visible. In using this task, we sought (a) to assess the use of acoustic flow for the control of voluntary, whole-body actions, and (b) to assess the role of hip–ankle coordination in support of acoustic suprapostural tracking. In Experiment 1, we predicted that standing participants would be able to use dynamic acoustic stimulation to control voluntary whole-body movements. Specifically, we predicted strong coupling between body movements and room motion during the tracking task. In Experiments 2 and 3, we tested the prediction that reflected acoustic flow would be sufficient for coupling of body movements with room motion. We also predicted that hip and ankle rotations would be used to support performance of the tracking task, and that relative motion of the hips and ankles would correspond to an antiphase mode of coordination.

General Method

Participants

Participants were members of the University of Minnesota community (students, faculty, and staff). All participants were healthy and fully ambulatory, with no history of vestibular disease, recurrent dizziness, or falls. All participants had normal or corrected-to-normal vision. Undergraduate students participated in exchange for course credit; all others participated on a volunteer basis. Each person participated in only one experiment. The experimental protocol was approved by the Institutional Review Board of the University of Minnesota.

Apparatus

We generated dynamic acoustic stimuli through the use of a moving room (Lee & Lishman, 1975; Stoffregen, 1985). The room was a 2.4-m cube mounted on wheels that rolled along rails (Figure 1). The cube was built of hollow aluminum beams (4.5 cm × 7.5 cm). Mounted on the exterior surface of the beams were sheets of plywood 1.75 cm thick. Interior surfaces of the plywood were covered with marble-pattern adhesive paper. The lower half of the rear wall was absent, providing access. The room was moved by an electric motor under computer control. The room was relatively light (about 135 kg), and room motion produced no measurable vibration through the concrete floor of the laboratory.

The moving room was housed in a large laboratory that extended 11.6 m × 27.1 m horizontally. The laboratory was under the stands of an ice hockey arena. As a result, the long axis of the laboratory was slight curved, and the height of the ceiling varied from 4.9 m to 6.4 m. The walls of the laboratory were concrete block, and the floor and ceiling were poured concrete. The moving room was located approximately in the center of the laboratory.

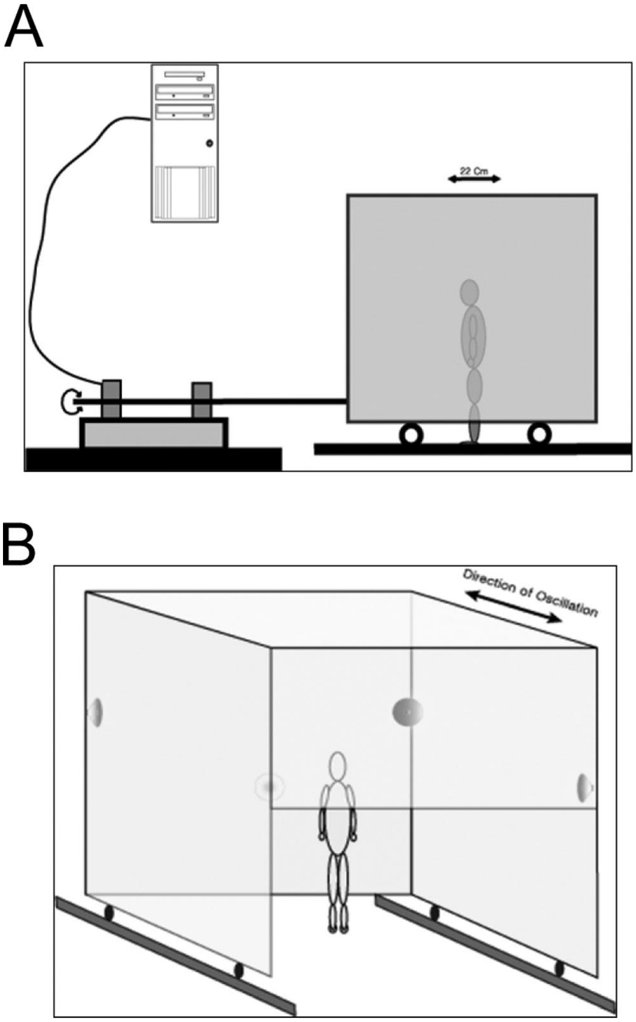

Figure 1. Experimental setup. (A) The moving room, showing the motor and computer controller. (B) The moving room with speakers attached at each corner.

The main source of sound within the room was pink noise presented via four speakers (the placement of the speakers is described separately for each experiment). Pink noise is a variant of white noise. In white noise, more acoustic energy is emitted in lower octaves than in higher octaves. In pink noise, an equal amount of acoustic energy is emitted in each octave. The pink noise was generated by a Pentium 3 computer and amplified by a Cambridge SoundWorks 5.1 DTT 2500 digital amplifier. The source sound was in the frequency range from 20 Hz to 20000 Hz, but the speakers' response range was 200 Hz to 18000 Hz. Therefore, the actual frequency range presented to participants was 200 Hz to 18000 Hz.

We measured sound intensity at the center of the moving room (i.e., the position occupied by experimental participants) with a digital sound meter positioned at a height of 1.7 m. In the absence of any motion, background noise was at 53 dB. Motion of the room (i.e., motion of the rolling wheels and the electric motor) raised the background level to 57 dB. When the room was stationary, the pink noise was at 79.5 dB. When pink noise was played during room motion, the sound level oscillated between 76.5 dB and 82.5 dB.

Motion of the head and room were recorded using a magnetic tracking system (Fastrak, Polhemus, Inc., Colchester, VT). An emitter created a localized magnetic field, and motion of sensors within this field was detected with a resolution of 1 mm. The emitter was placed on a stand at head height and was positioned to be approximately 25 cm behind the participant's head. Calibration of the magnetic system revealed that this resolution was identical within a radius of 50 cm around the sensor and that it was not affected by room motion. Data from each sensor were sampled at 40 Hz. One sensor was attached to the room and the other to the posterior surface of a bicycle helmet worn by the participant. During experimental trials, participants wore a cotton blindfold that was shaped to the contours of the face, thereby obscuring the entire visual field. The blindfold was secured by elastic straps.

Procedure

After completing the informed consent procedure, participants removed their shoes and entered the moving room (ducking under the upper half of the rear wall). They were asked to stand at the center of the room, with their feet about 20 cm apart and their heels on a mark on the floor, facing the front wall, and with hands in their pockets, or clasped behind the back. Participants donned the blindfold and over that a bicycle helmet to which was attached a sensor of the magnetic tracking system. Participants were asked to adjust the blindfold so that they could not see anything. They were informed that the room would move and that they might be able to hear the motion. Participants were asked to listen to the motion of the room and to move their head backward and forward so as to maintain a constant distance between their head and the front wall of the room. Participants were instructed to do their best to move in phase with the room and to move so that the amplitude of their head movements matched the amplitude of room movements. Each participant completed four trials. There were no practice trials.

Instructions were given prior to each trial, and trials began after the participant gave a ready signal. After completing each trial, participants were instructed to take a brief break for 10 to 15 s.

Pink noise was presented through all four speakers and was present whenever the room was moving. Room motion consisted of oscillations at 0.2 Hz along the participant's line of sight with peak-to-peak amplitude of 22 cm. At the beginning of each trial, the amplitude of room motion was gradually ramped from 0 cm to 22 cm, over a period of 5 s. Data collection began when room motion reached its full amplitude. Data collection lasted for 60 s per trial.

Data Analysis

Our primary interest was in participants' performance of the tracking task, that is, in the strength of coupling between motion of the room and anterior–posterior movement of the head. To assess the strength of this coupling, we used data about anterior–posterior displacements of the room and the head to compute gain, phase, cross-correlation, and average mutual information, which are described below. For inferential tests, our criterion α was .05. Additional analyses are described under Experiments 2 and 3.

We considered the gain of head movement relative to the amplitude of room motion (amplitude$_{\text{Head}}$/amplitude$_{\text{Room}}$). A gain value of 1.0 would indicate that head movement amplitude (in the anterior–posterior axis) was identical to room motion amplitude. A gain value greater than 1.0 would indicate that head movement amplitude was smaller than the room motion amplitude. We computed the gain as the ratio between the amplitude at the peak frequency of the frequency spectrum from the fast Fourier transform analyses of the head movement and room motion. For inferential tests of gain, we used *t* tests.

We also evaluated the relative phase of head–room displacements. The value of relative phase, measured in degrees (from –180° to + 180°), indicates the nature of temporal synchrony between room motion and head movement. Negative values of phase indicate that head movement lags behind room movement, whereas positive values indicate that head movement anticipates room motion. A phase of 0° means that that there is perfect temporal synchrony. We used the point estimate of phase (Dijkstra et al., 1994). Relative phase data were analyzed using circular statistics (Batschelet, 1981).

We next examined the maximum cross-correlation between room motion and head movements. Considering the frequency of the moving room oscillations (0.2 Hz), we decided to analyze, for each trial, the cross-correlation of head movements and room motion at each of 201 time lags, from Lag = –100 to Lag = +100 samples (equivalent to lags of up to 2.5 s before and after 0, or one entire cycle of the moving room oscillation). We then chose the correlation coefficient with the largest absolute value. For inferential statistics, we normalized each cross-correlation using the Fisher transformation (Fisher, 1921), and then we performed *t* tests on the mean cross-correlations across participants for each condition (untransformed means are reported in the text and figures).

The cross-correlation technique can reveal linear relations between time series. Recent research has revealed that movement in upright stance can contain significant nonlinearities (e.g., Balasubramaniam, Riley, & Turvey, 2000; Duarte & Zatsiorsky, 2000). The complexity of postural activity led us to consider nonlinear dependencies in coupling between the room motion and head movements. To estimate nonlinear coupling, we analyzed the average mutual information, or AMI, between the time series of head and room motion (Boker, Schreiber, Pompe, & Bertenthal, 1998). This analysis consists of assessing the uncertainty in the prediction of a given measurement according to a preceding measurement. The AMI, $I(\tau)$, for the measurement x_{t+} at time t is

$$I(\tau) = \frac{1}{N-\tau}\sum_{t}^{N-\tau} p(x_t, x_{t+\tau})\log_2\left[\frac{p(x_t, x_{t+\tau})}{p(x_t)p(x_{t+\tau})}\right],$$

where N is the number of measurements, τ is the time delay, $p(x_t, x_{t+})$ the joint probability density for x_t and x_{t+}, and $p(x_t)$ and $p(x_t, x_{t+})$ are the individual probability densities for x_t and x_{t+}.

To estimate the nonlinear dependencies between two time series, X and Y, the AMI at a time delay τ is

$$I_{XY}(\tau) = \frac{1}{N-\tau}\sum_{t}^{N-\tau} p(x_t, y_{t+\tau})\log_2\left[\frac{p(x_t, y_{t+\tau})}{p(x_t)p(y_{t+\tau})}\right].$$

We again analyzed 201 time lags around 0, from –100 to +100, and from these we selected the maximum of AMI. Figure 2A shows an example of AMI between the room movement and head movement. The figure clearly shows peaks at lags of about –10 and about +90. These peaks describe the time delays at

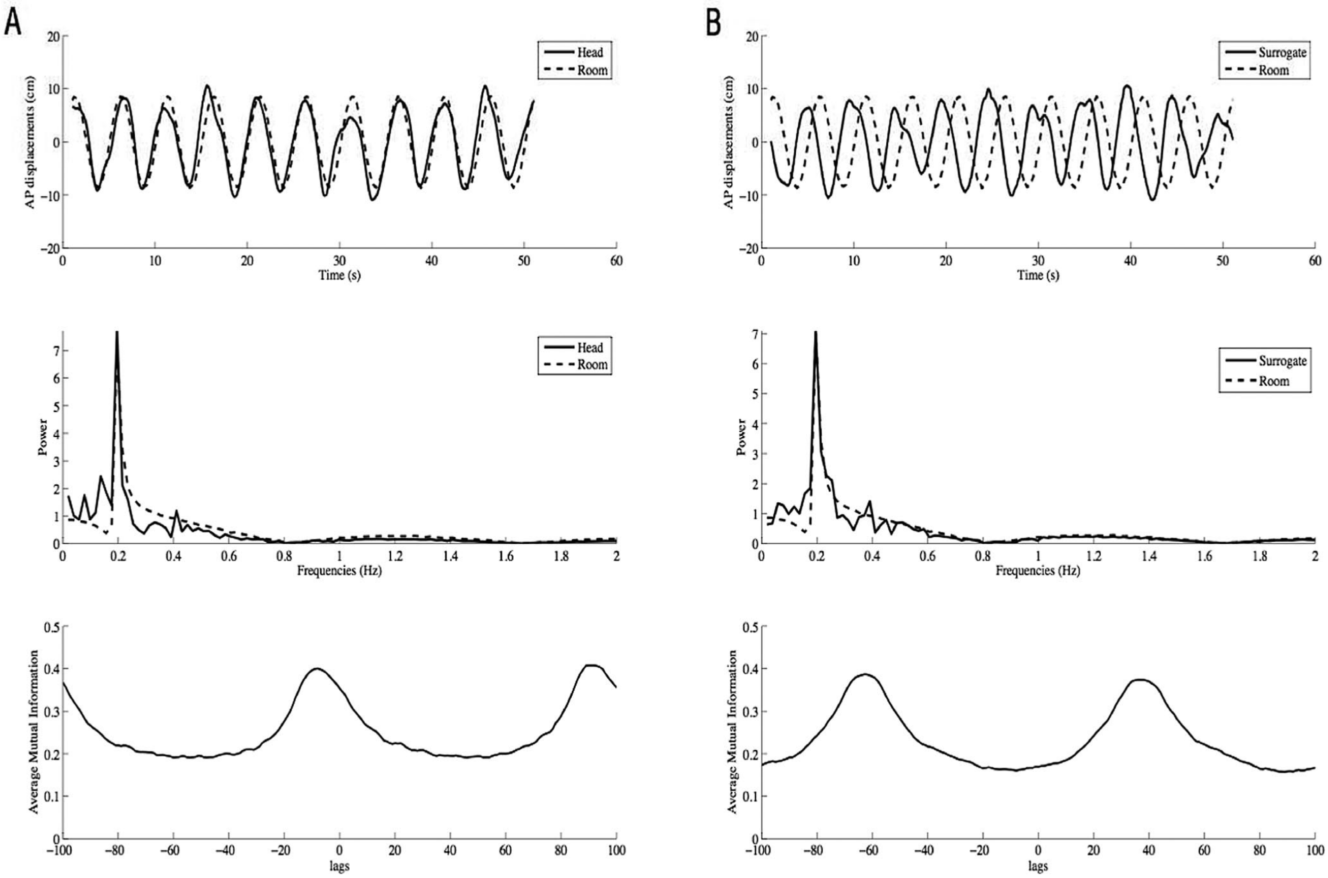

Figure 2. (A) Movement of the head and room (top), frequency spectrum of the head and room (middle), and their average mutual information (bottom) for a typical participant in Experiment 1. (B) Movement of the room and a surrogate data set (top), frequency spectra of the surrogate and the room (middle), and their average mutual information (bottom). AP = anterior–posterior.

which the room and the head shared a relatively large amount of information.

It is not known whether the mean maximum AMI exhibits a Gaussian distribution. For this reason, we used a Wilcoxon signed rank test to compare the rank of the mean maximum AMI to zero and a Mann–Whitney *U* test to compare the rank of the mean maximum AMI across experiments.

The AMI method is useful (relative to cross-correlation) only if the time series data exhibit nonlinearities. To test the nonlinearity of head–room coupling, we used the method of phase randomized surrogate data (Theiler, Eubank, Longtin, Galdrikian, & Farmer, 1992). This method consists of generating linear stochastic process data with the same statistical distribution, the same frequency, and then the same autocorrelation function than a given time series (in this case, the head movement data). Thus, we can discriminate the actual time series from a linear stochastic process (for an example in the context of postural data, see Mégrot & Bardy, 2006). We used an integrated amplitude-adjusted Fourier transform algorithm to generate the surrogate data from the time series of actual head movement data. Figure 2B shows one of the surrogate time series that we used. Comparison of Figures 2A and 2B reveals that the time series for real head movement and for the surrogate data set have the same shape, with similar amplitude and frequency.

In this study, the coupling between the room and the head was asymmetrical, in the sense that participants could adjust their behavior based on the activity of the room, but not vice versa. Thus, we considered the head movements as the only time series able to create nonlinear dependencies between the room and the subject. For each trial, we compared the maximum AMI between the room and the head with the maximum AMI between the room and a surrogate data set. Because we did not know whether the room–head maximum AMI followed a Gaussian distribution, we used a rank-based test to discriminate the room–head maximum AMI from the room–surrogate maximum AMI. Considering α as the probability of rejecting the null hypothesis if it were true, we needed $1/\alpha - 1$ surrogate data sets and one set of actual head data to test whether the maximum AMI for the room–head interaction was smaller than for the maximum AMI of the room–surrogate interactions. For a two-tailed inferential test, $2/\alpha - 1$ surrogate data sets are required, where α is the criterion for determining statistical significance (Schreiber & Schmitz, 2000). Accordingly, we generated 39 surrogate data sets.

In computing average mutual information, we used all trials in a given experiment, that is, we included trials in which head movements exhibited nonlinear relations with room motion, and trials in which head–room relations appeared to be linear. Similarly, we included all trials when computing cross-correlations (as well as in all other analyses). Conducting the AMI and cross-correlation analyses on identical data sets permitted us to compare the two types of analysis to each other and to relevant previous research (e.g., Boker et al., 1998).

Experiment 1

In this experiment, we aimed to determine whether blindfolded sighted participants could use dynamic acoustic stimulation to guide head movements. Using an auditory version of the tracking task developed by Bardy et al. (1999), we asked participants to move their head forward and backward so as to maintain a constant distance between their head and the audible position of the room. The acoustic flow produced by room motion had direct and indirect components.

Method

Participants. The participants were six men and six women ranging from 18 to 42 years of age ($M = 23.8$ years). Their heights ranged from 1.60 to 1.83 m ($M = 1.74$ m).

Apparatus. One speaker was attached at each interior corner of the room, 1.7 m above the floor, facing toward the center of the room (Figure 1A). Because they were attached to the room, the speakers moved when the room moved. Thus, participants were exposed to motion in sound arriving directly from the speakers and also in sound that arrived after reflecting from the interior walls of the room.

Results and Discussion

The results are summarized in Table 1. In the frequency spectra, the peak frequencies for both the head and the moving room were at 0.2 Hz. The mean value of gain at this peak frequency was 1.10, which did not differ from 1.0, $t(11) = -1.58$, $p = .143$. The robust gain between head and room motion indicates that participants accurately detected the amplitude of room motion and were able to match their own motion to that amplitude. The mean room–head relative phase was 8.2°. The 95% confidence interval for relative phase was $-9.0° < \text{mean} < 35.2°$, which included 0°. The small relative phase indicates strong temporal synchrony between room motion and head movements. Because the only stimulation for the tracking task was the audible motion of the room, the relationship between room position and head position as a function of time indicates participants' capability of perceiving and using acoustic information to track the room motion with their head. The values of phase and gain are similar to those reported by Bardy et al. (1999) for the visual version of the tracking task.

Table 1
Head–Room Coupling for Each Experiment

Variable	Experiment 1	Experiment 2	Experiment 3
Mean (*SD*) maximum cross-correlation	0.78 (0.24)	0.95 (0.02)	0.92 (0.07)
Mean (*SD*) maximum AMI	0.34 (0.12)	0.44 (0.05)	0.42 (0.06)
Mean (*SD*) $\text{RPh}_{\text{Room-Head}}$	8.2° (69.8)	6.3° (65.9)	17.8° (13.8)
Mean (*SD*) $\text{Gain}_{\text{Head-Room}}$	1.10 (0.19)	1.39 (0.13)	1.27 (0.19)

Note. AMI = average mutual information; $\text{RPh}_{\text{Room-Head}}$ = relative phase between room and head; $\text{Gain}_{\text{Head-Room}}$ = gain between head and room.

The mean maximum head–room cross-correlation, $r = .78$, was greater than 0, $t(11) = 7.8$, $p < .05$. The cross-correlation is slightly lower than those reported by Bardy et al. (1999), who observed mean maximum head–target cross-correlations of approximately .90.

The surrogate analysis showed that 6 of the 48 trials contained significant nonlinearities and, thus, violated the assumptions of the cross-correlation analysis. The mean maximum AMI, $v = 0.34$, was greater than 0, $z = -3.059$, $p < .05$.

Experiment 1 demonstrated that healthy adults, while wearing a blindfold, could couple their actions to audible motion. In Experiment 1, information about participants' motion relative to the moving room was available in reflected sound (i.e., in acoustic flow), but was also available in direct sound. Thus, it is unclear, on the basis of Experiment 1, what type of acoustic information was used in the tracking task. We addressed this issue in Experiments 2 and 3.

Experiment 2

In Experiment 1, the speakers faced the interior of the room. Thus, motion of the room structured acoustic flow (reflected sound) but also structured sound that arrived at the ears directly from the speakers. Participants might have detected room motion and controlled their stance relative to direct sound, reflected sound, or both.

In Experiment 2, we sought to create a situation in which information about room motion was available solely in the reflected components of acoustic flow but not in the direct sound coming from the speakers. To do this, we removed the speakers from the interior walls of the moving room and mounted them on stationary stands within the room. To succeed at the tracking task in this situation, participants could use motion information in reflected sound. To minimize possible effects of direct sound, which contained no motion information, the speakers were positioned so that they faced away from the participant and toward the walls. This meant that, in principle, there was no direct sound; all of the sound emitted by the speakers should have reached the participant's ears only after reflecting off the walls, ceiling, and floor.[1] We predicted that coupling between head movements and room motion would again be significant.

In Experiment 1, the gain between head movements and room motion indicated that, on average, participants moved their heads 22 cm in the tracking task, which strongly suggests that head movements were supplemented by body movements. In Experi-

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[1] A small amount of sound may have emanated from the back of the speakers. Sound arriving at the ears directly from the back of the speakers would have contained no information about room motion.

ment 2, we assessed the contribution of body movements to the tracking task by collecting data about rotation of the hip and ankle joints. We also sought to determine whether whole-body movements used in the acoustic tracking task were similar to movements used in the comparable visual tracking task (Bardy et al., 1999). Bardy et al. (1999) found that participants tend to exhibit an antiphase coordination between rotations around the hips and ankles during performance of the visual tracking task when the amplitude of target motion was large (18 or 35 cm). A similar finding was reported by Oullier et al., (2002), using the visual tracking task in the same moving room that was used in the present study. Because the amplitude of room motion was 22 cm, we expected that participants would exhibit antiphase hip–ankle coordination (i.e., hip–ankle relative phase ~ 180°) in executing the acoustic tracking task.

Method

Participants. Three men and nine women participated, ranging in age from 18 to 31 years, with a mean of 21.5 years. Their heights ranged from 1.55 to 1.93 m, with mean of 1.70 m.

Apparatus. The moving room was the same as in Experiment 1, only the placement of the speakers was different. Rather than being attached to the moving room, the four speakers were mounted on poles that stood on the floor of the laboratory within the moving room such that the speakers did not move with the room. The speakers were mounted at a height of 1.7 m. One pole was placed in each corner of the room, positioned so that it would almost be bumped when the room was at the extreme of its travel. Thus, the speaker positions were very similar to what they were in Experiment 1. Each speaker faced the nearest corner of the room. That is, each speaker faced away from the participant, such that very little sound energy reached the ears directly from the speakers. Except for sound reflected from the floor (which was stationary) and generated by rolling of the wheels (which arrived directly at the ears but also reflected off the walls), the acoustic stimulus at the participant's ears was almost exclusively reflected components of acoustic flow.

We measured rotation of the hips and ankles using electrogoniometers (Biopac Inc., Goleta, CA). Ankle rotation was measured by a goniometer attached to the skin of the lower left leg and foot, using cloth medical tape. Hip rotation was measured by a goniometer attached to a Velcro harness that cinched tightly about the waist and the upper left thigh. Each goniometer was sampled at 200 Hz.

Procedure. The procedure from Experiment 1 was repeated. The only differences were the placement of the speakers and the use of electrogoniometers.

Data analyses. Analyses of head and room motion were the same as in Experiment 1. To assess coordination of the hips and ankles, we computed the relative phase of hip and ankle rotations and hip–ankle gain (amplitude$_{\text{Hip}}$/amplitude$_{\text{Ankle}}$).

Results and Discussion

Head–room coupling. The results are summarized in Table 1. In the frequency spectra, the peak frequency for both the head and the moving room were again at 0.2 Hz. The mean value of gain at this peak frequency was 1.39, which differed from 1.0, $t(11) = -7.55$, $p < .05$, indicating that the amplitude of head movements was greater than the amplitude of room oscillations. The mean gain in Experiment 2 differed from the mean gain in Experiment 1, which was 1.10, $t(22) = 2.97$, $p < .05$.

As in Experiment 1, the mean relative phase, 6.3°, did not differ from 0° (–14.7° < mean < 27.3°). The small mean room–head relative phase indicates strong temporal synchrony between room motion and head movements. The mean maximum head–room cross-correlation, $r = .95$, was greater than 0, $t(11) = 35.68$, $p < .05$. The mean maximum cross-correlation in Experiment 2 was greater than the mean maximum cross-correlation in Experiment 1 (mean $r = .78$), $t(22) = -2.23$, $p < .05$. In Experiment 2, the values of phase, gain, and cross-correlation were similar to those observed with the visual version of the tracking task (Bardy et al., 1999).

The surrogate analysis showed that 4 of the 48 trials exhibited nonlinear dependencies between room and head movements. The mean maximum AMI, $v = 0.44$, was greater than 0, $z = -3.059$, $p < .05$, and was greater than the mean maximum AMI for Experiment 1, which was $v = 0.34$, $U = 33$, $p < .05$.

Coupling between head movements and room motion in Experiment 2 was again robust, confirming our prediction. In terms of cross-correlation and AMI, coupling was stronger in Experiment 2 than in Experiment 1. These results suggest that reflected sound (i.e., acoustic flow) may have played a greater role than direct sound in perceptual–motor coupling between the head and the moving room. The performance of the tracking task indicates that participants could hear the frequency and timing of room motion on the basis of acoustic flow. When there is relative motion between an observer and surroundings, flow is created, which provides information about the nature of the relative motion. Experiment 2 demonstrates that this information was sufficient for successful performance of the tracking task.

Although head–room coupling was robust overall, coupling in Experiment 2 was not identical to what we observed in Experiment 1. Our analysis of head–room gain revealed that in Experiment 2 the amplitude of participants' head movements exceeded the amplitude of room motion. The fact that head movements were greater than room motion may reflect exploratory attempts to obtain (or generate) information about how far the room was moving. Alternatively, it may have been more difficult to detect the amplitude of room motion from reflected sound (in Experiment 2) than from both reflected and direct sound (as in Experiment 1).

In addition to the above considerations, the results of Experiment 2 are important for methodological reasons. In principle, participants' behavior might have been influenced by uncontrolled aspects of the situation, such as sound generated by the motor or the moving wheels or vibrations transmitted through the floor. However, the difference in coupling between Experiments 1 and 2 indicates that participants were responding to some aspect of the experimental acoustic stimulus.

Hip–ankle coordination. The results for hip–ankle coordination are summarized in Table 2. A typical example of hip and ankle activity is illustrated in Figure 3. The mean relative phase between hip and ankle joints was 151.1° ($SD = 39.9$). The 95% confidence interval of the mean contained 180° (121.9° < mean < 180.3°), indicating that in performing the tracking task hip–ankle coordination was close to an antiphase mode (Figure 3b). The relative phase data indicate that there was rotation about the hips. The

Table 2
Hip–Ankle Coordination for Experiments 2 and 3

Variable	Experiment 2	Experiment 3
Mean (*SD*) Amp_{Hip}	2.5° (1.8)	3.0° (1.9)
Mean (*SD*) $\text{Amp}_{\text{Ankle}}$	1.1° (1.0)	1.0° (0.7)
Mean (*SD*) $\text{RPh}_{\text{Hip-Ankle}}$	151° (39.93)	159° (36.05)

Note. Amp = amplitude; $\text{RPh}_{\text{Hip-Ankle}}$ = relative phase between hip and ankle.

confidence intervals indicate that there was little variability in relative phase. Overall, the data on hip–ankle relative phase closely resemble those observed in studies using the visual version of the tracking task (Bardy et al., 1999; Marin, Bardy, Baumberger, Flückiger, & Stoffregen, 1999; Oullier et al., 2002; Faugloire et al., in press), confirming that antiphase coordination of the hips and ankles was used in the acoustic tracking task. The mean hip–ankle gain was 3.2, indicating that hip rotation was greater than ankle rotation. This value is larger than those observed during performance of the visual version of the tracking task. Bardy et al. (1999) and Oullier et al. (2002) observed hip–ankle gain values of approximately 2.0. However, the data on hip–ankle relative phase confirm that body movements were used in performance of the tracking task.

Experiment 3

Experiment 2 revealed that robust coupling of head and body movements with oscillations of the moving room could be achieved solely on the basis of reflected sound. Comparison of Experiments 1 and 2 suggested that direct sound might hamper perceptual–motor coupling with the room, even though the direct sound also provided information about room motion. In Experiment 3, we sought to create a situation in which information about room motion was available in reflected acoustic flow but not in the direct sound coming from the speakers. To do this, we again placed the speakers on stationary stands within the moving room, but in Experiment 3 we oriented the speakers toward the interior of the moving room, exposing participants to direct sound from

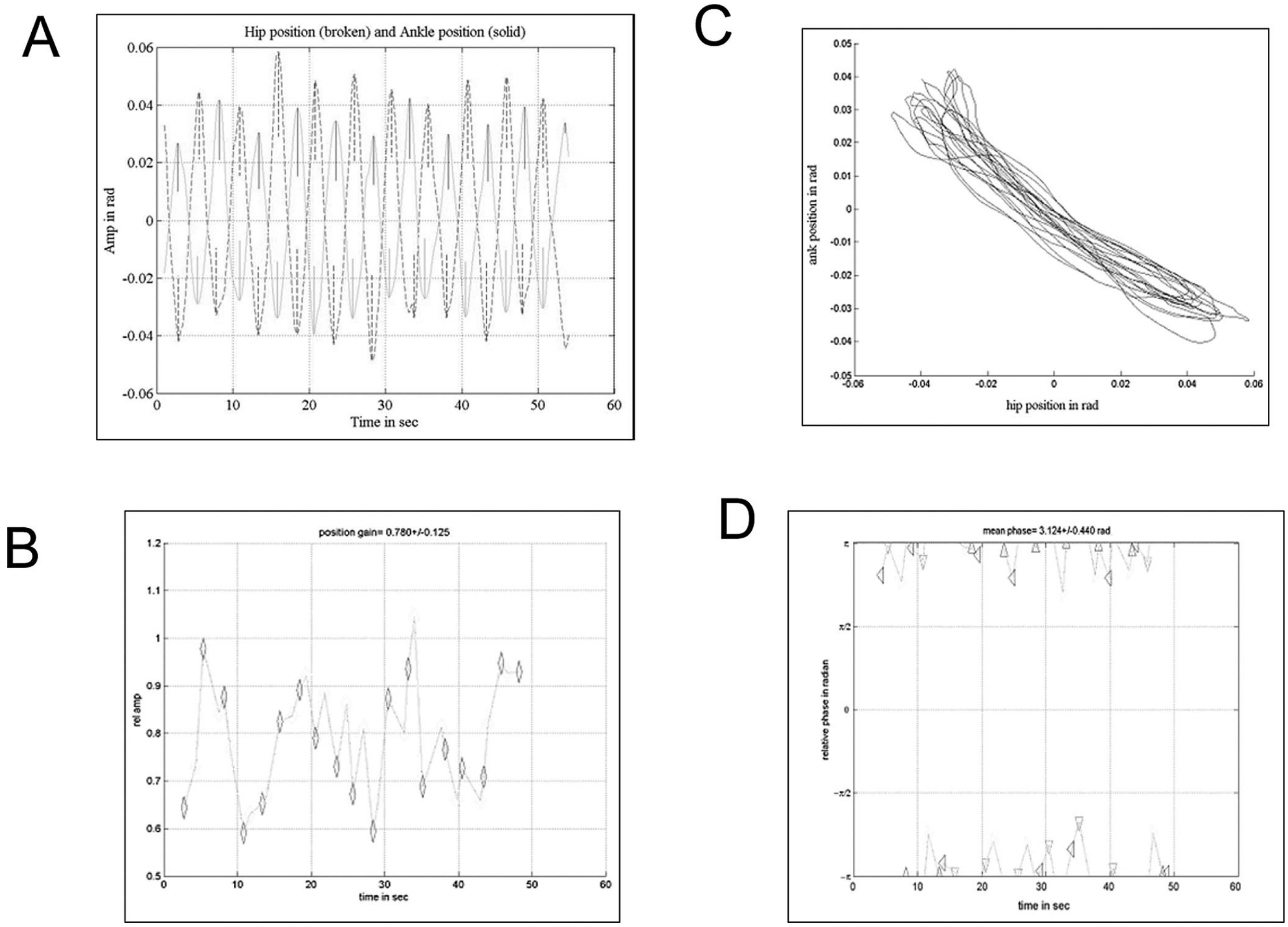

Figure 3. Rotation of the hips and ankles, Experiment 2. (A) hip and ankle angular displacement in radians, (B) angle–angle plot of hip and ankle, (C) hip–ankle gain, and (D) the relative phase of angular displacement of ankle joint angles to that of the hip joint angles (the mean relative phase in this trial = 3.1 radians, or 177.6°). The mean relative ankle joint displacement to hip joint displacement in this trial is 0.78.

stationary speakers. In this situation, the reflected sound coming from the walls of the moving room was overlaid by a much louder direct sound coming from the stationary speakers. We predicted that head–room coupling would be reduced, relative to Experiments 1 and 2.[2]

Method

Participants. Four men and eight women participated, ranging in age from 19 to 23 years, with a mean of 20.8 years. Their heights ranged from 1.58 to 1.75 m, with mean 1.67 m.

Apparatus. The equipment used in Experiment 3 was the same as in Experiment 2. The location of the four speakers was the same as in the Experiment 2, but in Experiment 3 the speakers faced to the interior of the moving room rather than facing the walls. Thus, the majority of sound available to participants was direct sound arriving from the stationary speakers. Sound also reflected from the moving walls, creating acoustic flow, but this sound was lower in intensity than the direct sound and was masked by the direct sound. As in Experiment 2, electrogoniometers were attached to the participants' left hip and ankle.

Procedure. The procedure from Experiment 2 was repeated. The only difference was the placement of the speakers.

Results and Discussion

Head–room coupling. The results are summarized in Table 1. The mean gain at the 0.2 Hz peak frequency was 1.27. As in Experiment 2, the mean gain differed from 1.0, $t(11) = -3.74$, $p < .05$. The mean gain in Experiment 3 did not differ from the mean gain in Experiment 1, which was 1.10, $t(22) = 1.56$, $p = .133$, or from the mean gain in Experiment 2, which was 1.39, $t(22) = -1.12$, $p = .274$.

The mean relative phase, 17.8°, differed from 0° ($10.8° < \text{mean} < 24.8°$), indicating that movement of the head tended to anticipate motion of the room. The mean head–room cross-correlation, $r = .92$, was greater than 0, $t(11) = 19.41$, $p < .05$. In Experiment 3, the mean maximum cross-correlation (mean $r = .92$) did not differ from the mean maximum cross-correlation in Experiment 1 (mean $r = .78$), $t(22) = -2.06$, $p = .051$ (see Table 1). Experiment 3 also did not differ from Experiment 2 ($r = .95$), $t(22) = 1.52$, $p = .143$.

The surrogate analysis showed that 2 of the 48 trials exhibited nonlinear dependencies between room and head movements. The mean maximum AMI was $v = 0.42$, which differed from 0, $z = -3.059$, $p < .05$. The mean maximum AMI for Experiment 3 did not differ from Experiment 1 ($v_{\text{Exp. 1}} = 0.34$, and $v_{\text{Exp. 3}} = 0.42$, $U = 44$, $p = .106$) or from Experiment 2 ($v_{\text{Exp. 2}} = 0.44$, $U = 58$, $p = .419$).

The results indicate that participants were able to track audible motion of the room despite the presence of much louder direct sound that, by itself, provided no information about room motion. One interpretation of the robust head–room coupling in Experiment 3 is that participants had refined skills of selective listening that permitted them to differentiate those portions of the acoustic waveform corresponding to room motion from the remainder of the waveform. Alternatively, participants may have attended to the ratio of sound intensity between direct and reflected sound. As the room moved away from the participant, the ratio of direct to indirect sound increased, whereas that ratio decreased when the room moved toward the participant. In either case, the masking stationary sound did have some effect on coupling: Head movements tended to anticipate room motion, as indicated by the data on room–head relative phase. It may be that this anticipatory movement reflected participants' exploratory attempt to disambiguate information about room motion (in reflected sound) from the louder sounds arriving directly from the stationary speakers.

Hip–ankle coordination. Two of the participants were not tested on electrogoniometer hip and ankle angle measurements. Therefore, a total of 10 participants were tested on electrogoniometer measurements. As predicted, the mean relative phase between hip and ankle angles, 159.0°, did not differ from 180° ($130.8° < \text{mean} < 187.3°$), indicating that participants used an antiphase mode of hip–ankle coordination in performing the tracking task. The mean hip–ankle gain was 4.0. These results confirm our finding, in Experiment 2, that hip and ankle rotations were organized in an antiphase pattern in support of the auditory tracking task.

General Discussion

In each experiment, head movement was coupled to room motion. We observed some variations across experiments, but overall coupling was robust. The results indicate that, in the absence of practice or prior experience, blindfolded sighted participants were able to detect relative motion between the moving room and themselves, and to use acoustic information to control whole-body motion so as to match their motion to that of the room. Experiment 2 suggested that reflected acoustic flow may have been sufficient for performance of the tracking task, and Experiment 3 indicated a robust ability to differentiate indirect information in acoustic flow from direct noise that provided no information about room motion.

Coupling of Head Movements With Motion of the Audible Environment

In each experiment, we observed strong coupling of head movements to room motion. This finding is perhaps the most robust, quantitative demonstration to date that intentional whole-body coordinated movement in humans can be organized and executed relative to motion in the audible environment.

Coupling of head movements with audible room motion was similar to coupling that has been reported when the tracking task has been performed with a visual target (e.g., Bardy et al., 1999, 2002). The similarity in coupling strength across visual and auditory versions of the tracking tasks suggests that sighted persons, without prior training or experience, are able to couple their actions to the audible environment with remarkable facility.

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[2] Mershon et al. (1989) asked seated participants to judge the distance of auditory targets. They manipulated the intensity of background noise and found that higher noise levels (65 dBA) were associated with greater estimated distances, whereas lower noise levels (45 dBA) were associated with reduced distance estimates. Mershon et al. did not ask participants to use perceived sound to control any action and did not collect data on any aspect of participants' movements. Accordingly, it is not clear how their findings relate to Experiment 3.

Many studies have examined the dynamics of coupling between human action and audible signals (see Kelso, 1995, for a review). In most cases, the audible signals varied only temporally (e.g., clicks from a metronome) and did not exhibit spatiotemporal variation of the kind that characterizes acoustic flow. Many studies have examined manual or digital actions, such as swinging a pendulum or tapping a finger. To our knowledge, ours is the first study to document dynamics of coordination between whole-body movement and acoustic flow.

Role of Acoustic Flow

We presented pink noise, and we manipulated aspects of this pink noise that provided information about motion of the room. Our experiments demonstrate that coupling of head and body movement with room motion was influenced by the dynamic structure of reflected sound (i.e., by reflected components of acoustic flow). However, we cannot conclude that reflected components of acoustic flow were the only source of information that participants used in detecting and controlling their movements relative to motion of the room. This is because sound arrived at the ears directly from the rolling wheels (sound from the wheels also reflected off the interior walls of the room, becoming part of the acoustic flow). The existence of direct sound from the wheels meant that we could not exclude all information about room motion in direct sound. It is important to note that in, Experiment 3, the pink noise arriving at the ears direct from the stationary speakers would have masked the sound of wheel movement, as well as masking pink noise reflected off the moving room. A pure test of the role of acoustic flow, that is, acoustic flow in the absence of any form of direct sound, might be achieved using a virtual acoustic environment (e.g., Shilling & Shinn-Cunningham, 2002). However, it might be difficult to create a virtual environment in which sound arrived at the ears from all directions, as is the case with natural acoustic flow. An alternative might be to build a moving room that was suspended from a height on ropes, such that its motion could be silent (Lee & Aronson, 1974).

We did not evaluate the hypothesis that direct sound would be sufficient for coupling of head and body movements relative to movement in the audible environment. Evaluation of this hypothesis would require the elimination of all reflected sound, which might be achieved in an anechoic chamber.

Hip–Ankle Coordination

Experiments 2 and 3 demonstrated that the tracking task was characterized by antiphase coordination of the hips and ankles, indicating that stable patterns of hip–ankle coordination were assembled in support of the auditory tracking task. This finding closely resembles hip–ankle coordination in visually guided versions of the tracking task (Bardy et al., 1999, 2002; Marin et al., 1999; Oullier et al., 2002), and suggests that coordination of the hips and ankles in support of deliberate head movements is similar when the head movements are controlled relative to the visible and audible environments.

The amplitude of target motion is known to act as a control parameter in the emergence of hip–ankle coordination modes in visual versions of the postural tracking task (e.g., Bardy et al., 1999). Similarly, the frequency of target motion is known to influence the dynamics of coupling in visual versions of the postural tracking task (Bardy et al., 2002; Oullier et al., 2002). In the present study, we used only one frequency and one amplitude of room motion. Future research should investigate the possibility that the amplitude and frequency of target motion may act as control parameters in the emergence of hip–ankle coordination modes in the acoustic postural tracking task.

Conclusion

In three experiments, we found that blindfolded sighted adults could perceive and control movements of their head and body relative to motion of the audible environment. Performance in the tracking task was robust despite the fact that sighted participants presumably had little experience controlling movements relative to motion of the audible environment, and despite the fact that participants presumably had little experience at deliberately moving their head back and forth relative to motion of any external target, audible or visible. Our results indicate that performance of the tracking task and the use of acoustic information in performing the tracking task were robust without practice. The strength of coupling, both between the head and the moving room, and between the hips and ankles, was very similar to studies in which participants have performed a visual version of the tracking task (Bardy et al., 1999; Oullier et al., 2002). This finding further emphasizes the robust ability of our participants to control their movements relative to the audible environment.

We found that coupling of movements to audible room motion was robust even in the presence of much louder stationary masking sounds. Our manipulations of the sound stimuli suggest that participants used acoustic flow in perceiving relative motion between themselves and the moving room. However, whereas tracking performance might have been mediated by acoustic flow, it might also have been mediated by direct sound arriving from the wheels. Future research will be needed to determine whether acoustic flow is sufficient for performance of the tracking task.

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Received January 10, 2008
Revision received July 7, 2008
Accepted July 25, 2008 ■