Postural coordination in looking and tracking tasks

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Abstract

Participants stood in a moving room and looked at a target that was attached to the front wall of the room. They were instructed either to look at the target or to track it, that is, to move so as to maintain a constant distance between the target and their head. Previous research (e.g. Bardy, Oullier, Bootsma, & Stoffregen, *Journal of Experimental Psychology: Human Perception and Performance*, 2002) has documented stable modes of coordination of the hip and ankle joints that emerge during the tracking task. In the present study our main goal was to determine the effects of task variation (tracking versus looking) on these postural coordination modes. Within trials, we varied the frequency of room motion between 0.10 and 0.75 Hz. The results revealed that in both the tracking and looking tasks, posture was characterized by the emergence of *in-phase* and *anti-phase* modes, although the modes were more prominent in the tracking task. For both tasks the coordination mode adopted depended on the frequency of motion of the moving room. Coupling between motion of the room and motion of the head was stronger in the tracking task than in the looking task. Overall, the dynamics of hip–ankle coordination were qualitatively similar during the looking and tracking tasks. This similarity has consequences for the development of a general theory of the visual regulation of stance. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Early studies of standing posture (e.g., Edwards, 1946; Travis, 1945) documented the role of visual information in the control of upright stance by showing that the amplitude of postural sway increases when the eyes are closed. Detailed analysis of coupling of body sway with optic flow was made possible by the introduction of the so-called moving room paradigm (Lee & Aronson, 1974), in which optic flow is created by the displacement (real or simulated) of an illuminated environment around an otherwise-stationary observer. Using this paradigm, researchers have consistently found that motion of the visual environment gives rise to motion of the body, and that body sway tends to minimize radial expansion and contraction at the eyes by oscillating with the moving environment. For imposed optical oscillations that resemble the spatio-temporal characteristics of natural body sway, a strong visual influence was found during upright stance (e.g., Lee & Lishman, 1975; Lestienne, Soechting, & Berthoz, 1977; Stoffregen, 1985, 1986; Stoffregen & Smart, 1998) as well as during walking (e.g., Bardy, Warren, & Kay, 1996; Warren, Kay, & Yilmaz, 1996). Further analyses have demonstrated influences of characteristics such as the frequency of the imposed optical motion (e.g., Dijkstra, Schöner, Giese, & Gielen, 1994) and the distance to the moving scene (Dijkstra, Schöner, & Gielen, 1994; van Asten, Gielen, & Denier van der Gon, 1988a).

In order to characterize the functional organization of postural control, an experimental paradigm using imposed motion of the surface of support was introduced by Nashner (1976). In this moving-platform paradigm, mechanical perturbations of the support surface are followed by postural adjustments. Research focusing on reveal the neuro-muscular basis of postural control has relied primarily on discrete perturbations of the support surface (e.g., Horak & Moore, 1993; Horak & Nashner, 1986; McCollum & Leen, 1989; Nashner & McCollum, 1985), but continuous oscillations have been used more recently (Buchanan & Horak, 1999). Studies using the moving-platform paradigm typically have been interpreted in terms of two distinct types of postural control, the ankle strategy and the hip strategy. These strategies are commonly assumed to arise from situation-specific neuro-muscular synergies selected by the central nervous system (e.g., Horak & Moore, 1993).

Recently, Bardy and colleagues (Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002; Marin, Bardy, & Bootsma, 1999; Marin, Bardy, Baumberger, Flückiger, & Stoffregen, 1999; Oullier, Bardy, Bootsma, & Stoffregen, 1999) have introduced an alternative paradigm for studying postural organization in which participants are asked to move the head so as to track the motion of a visual target. Participants are not given any instructions about posture;

rather, postural control emerges as a means to achieve the supra-postural tracking task. [1] The motion of different body segments underlying the movement of the head has been analyzed by focusing on the relative phase ϕ_{rel} of rotations around the ankles and hips. When tracking a target that oscillates at low frequencies, participants were found spontaneously to adopt an in-phase mode of coordination ($\phi_{rel} = \phi_{ankle–hip} = \phi_{ankle} - \phi_{hip} \approx 20°$), while tracking at higher frequencies of target motion leads to the adoption of an anti-phase mode of coordination ($\phi_{rel} \approx 180°$). Interestingly, transitions from one mode of postural coordination to the other, evoked by a gradual change in target frequency, exhibited typical hallmarks of non-equilibrium phase transitions, including (i) multi-stability, (ii) critical fluctuations and critical slowing down, (iii) a sudden switch from one mode to the other, and (iv) hysteresis (Bardy et al., 2002; Oullier et al., 1999). The studies of Bardy and colleagues provide support for an alternative view of the nature and origins of postural coordination, in which inter-segmental coordination is an emergent property of constraints in the animal–environment system, rather than arising from centrally organised neuro-muscular strategies. The aim of the present study was to assess whether the emergence of postural coordination modes observed in the studies of Bardy and colleagues are specific to the tracking task, that is, to the case in which postural control must support a deliberate movement of the head. We measured hip–ankle coordination in the context of two tasks; the tracking task used in our previous research, and a simple looking task. Almost invariably, when researchers study stance with the eyes open, participants are instructed to look at some target or display. Importantly, this looking instruction is universal in research examining the coupling of body sway with imposed optical flow (e.g., Dijkstra et al., 1994; Dijkstra, Schöner, Giese, et al., 1994; Lee & Lishman, 1975; Stoffregen, 1985; Warren et al., 1996). In these studies, attention has focused on coupling between motion of the visual environment and motion of the head, assuming (often implicitly) that body sway results primarily from motion around the ankles (cf. Schöner, 1991), even in studies that have simulated large displacements of the body (e.g., van Asten et al., 1988a).

Participants stood in a moving room while the frequency of room motion was increased or decreased, and were asked to execute one of two tasks. In the tracking task, participants were asked to move the head so as to follow the motion of a visual target in the antero-posterior plane, maintaining a constant distance between target and head. In the looking task, participants were asked simply to look at the target as it moved. In research on the coupling between imposed optical flow and body sway,

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[1] According to Gibson (1966): "the maintenance of stable posture (including upright stance) is a fundamental requirement for behavioral success: behavior depends on posture and is inseperable from it". Thus, postural stabilization is not an end in itself, but is valuable primarily to the extent that it facilitates the achievement of other goals (Riccio & Stoffregen, 1988). Stoffregen, Smart, Bardy, and Pagulayan (1999) refer to tasks or behavioral goals that are super-ordinate to the control of posture as supra-postural tasks. The latter differ from postural control in that they are defined and evaluated in different terms. Postural oscillations can influence performance at supra postural tasks, but this performance is not measured in terms of postural coordination or stability of balance (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000).

the instructions provided closely resemble those given in our looking task (e.g., Dijkstra et al., 1994; Dijkstra, Schöner, Giese, et al., 1994; Stoffregen, 1985). For this reason, we expected a significant degree of coupling between motion of the room and motion of the head, especially for the frequencies close to the natural frequency range. Nevertheless, given the instructions to follow the motion of the room in the tracking task, we expected this coupling to be stronger in the latter task.

2. Method

2.1. Participants

The experimental protocol was approved by the Institutional Review Board of the University of Cincinnati. Twenty-six undergraduate students, 15 males and 11 females ranging in age from 18 to 23 years ($M = 19.2$, SD $= 1.7$), participated. Their mean height was 1.71 m (SD $= 0.09$) and their mean weight was 69.5 kg (SD $= 8.2$). All participants had normal or corrected-to-normal vision, and reported no history of dizziness, recurrent falls, or vestibular (inner ear) dysfunction. They received course credit for their participation. Participants were randomly assigned to either the looking group or the tracking group.

2.2. Apparatus

The moving room consisted of a cubical metal frame, 2.4 m on a side, mounted on four wheels, which could be moved along one horizontal axis by a computer-controlled 4 kW electric torque motor (Westamp, Inc.). The frame was covered with rigid foam-plastic sheeting, with a marble-pattern adhesive paper covering the inside surfaces (all four walls and ceiling). Access into the room was provided through an opening in the rear of the right wall, 0.5 m wide, which was not visible by participants during experimental trials. A black target (55 by 55 cm square) was attached to the centre of the front wall of the room. The centre of the target was adjusted to each participant's eye level. Lighting inside the room was provided by a fluorescent tube attached rigidly to the centre of the ceiling. The motor had a positioning accuracy of 1.0 mm.

2.3. Task and instructions

Participants stood barefooted inside the room, on the concrete laboratory floor at a distance of 1.5 m from the target, with their arms comfortably folded across the chest and their feet parallel (see Fig. 1A and B). They faced the target, so that room motion occurred along the anterior–posterior (AP) axis of the body. Contact of the toes with the floor was monitored via a customized detector informing the experimenter when contact with the floor was lost. If the contact was lost more than five times during a trial, the experimental trial was reinitiated. Movements of the neck and the knees were constrained by elastic bands, allowing participants to notice
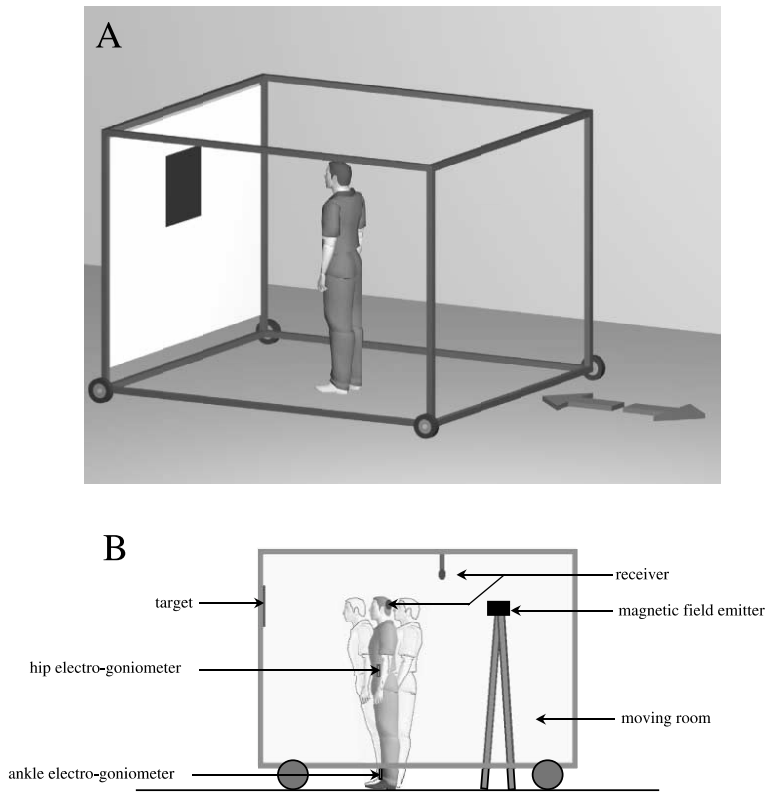
Fig. 1. Experimental set-up. (A) Three-dimensional view of the moving room. (B) Data acquisition hardware.

when they were using motion of the knees and/or neck to a (too) large extent. The bands restricted motion in a 2° range (Bardy et al., 2002; Oullier et al., 1999).

Thirteen participants were tested in the looking task. They were asked to look at the target attached to the front wall while the room was oscillating. They were instructed not to resist if they felt their body was moving, but were given no other instructions regarding stance or posture. The thirteen remaining participants were tested in the tracking task. They were asked to move with the oscillation of the target attached to the front wall so as to maintain a constant distance between their head and the target.

2.4. Design and procedure

In all conditions, the room oscillated with a constant peak-to-peak displacement of 4 cm. This amplitude was chosen to match the amplitude of head motion during quiet stance (Bensel & Dzendolet, 1968). In both the looking and tracking tasks, we varied the *stimulus frequency*, i.e. the frequency of moving room oscillations, in a

step-wise manner. In the up condition, frequency increased in 0.05 Hz steps from 0.10 to 0.75 Hz. In the down condition, frequency decreased, also in 0.05 Hz steps, from 0.75 to 0.10 Hz. We presented two directions (up and down) to counter hysteresis and/or order or fatigue effects (cf. Bardy et al., 2002). Each frequency segment lasted 10 cycles, yielding a total of 140 cycles per trial. A trial lasted 8 min. Trial order was balanced over participants, who were given a 5 min rest period between trials.

2.5. Data collection

Postural sway was recorded in the moving room using a magnetic motion tracking system (flock of birds; Ascension, Inc.). Only linear motion in the antero-posterior direction was retained for data analysis. A magnetic emitter was fixed at the top of a stand (1.65 m high) placed within the room behind the participant. It created a low-intensity magnetic field in which the receivers (birds) moved, thus allowing for their tracking. One receiver was attached to the room while another was attached to the back of a bicycle helmet worn by the participant. During data collection, the two receivers remained within 50 cm of the emitter, in the area where the greatest amount of spatial resolution was achieved.

Angular displacements of the right ankle and right hip were recorded using two electro-goniometers (Biopac Systems, Inc.), providing a 1° accuracy in measuring fore/aft motion. One electro-goniometer was attached to the lateral side of the right hip (from the greater trochanter to the iliac crest) and the other one to the anterior side of the right ankle (from the scaphoïd to the inferior third of the tibia). Both electro-goniometers were connected to a Biopac MP-100 A/D converter, controlled by an Apple Power Macintosh using the AcqKnowledge v 3.0 software. The electro-goniometers and the flock of birds were sampled at 50 Hz, and the data stored on disk for later analysis.

2.6. Data analysis and variables

Time series from the birds and the electro-goniometers were synchronized by a trigger sent by the computer controlling the moving room 30 s after initiation of room motion. Time series typically exhibited low frequency drift and high frequency noise. Inspection of the power spectra obtained using a fast Fourier transform (FFT) indicated that the drift was due to frequencies below 0.08 Hz. Data were therefore processed using a customized FFT-based decomposition and re-construction method. After decomposition, the signal was reconstructed in the 0.08–3 Hz frequency range (see Fig. 2). Because 0.08 Hz was close to the value of the first frequency segment (0.1 Hz), we decided to exclude the 0.10 Hz frequency level from our analysis.

After computing dependent variables (relative phase, power spectrum overlap, cross-correlation, amplitude and frequency of movement), data from up and down conditions were collapsed across frequency segments (for data on hysteresis in multi-segmental postural control, see Bardy et al., 2002; Oullier et al., 1999). As is often the case (e.g., Dijkstra et al., 1994; Stoffregen, 1985), the identification of cycles
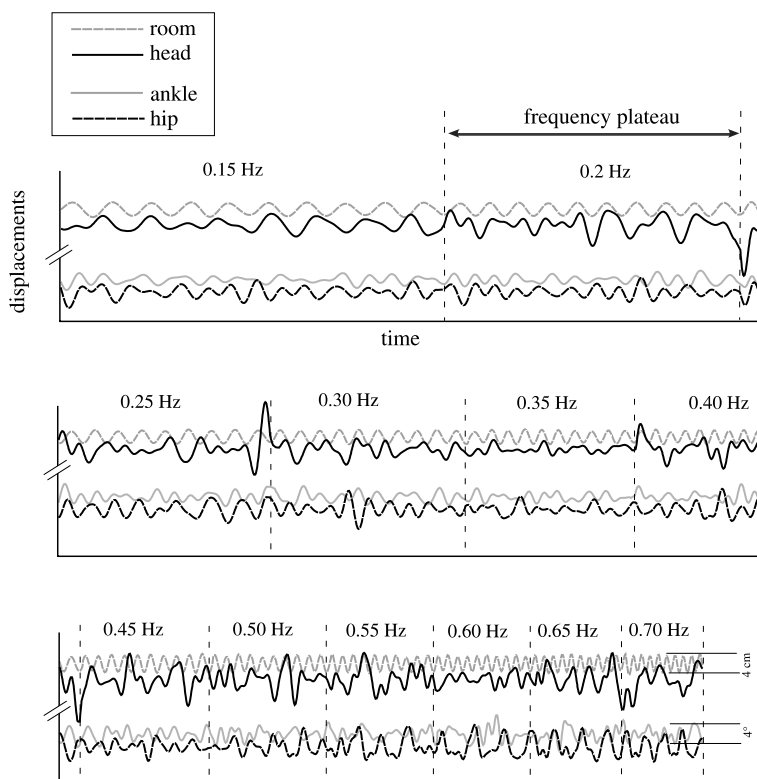
Fig. 2. An example of typical data in the looking condition. Filtered time series of the displacements of the moving room, head, ankle and hip over time. The frequency of the moving room is increasing from 0.15 to 0.70 Hz (12 frequency plateau); 8 cycles out of 10 are analyzed for each plateau (the first and the last cycles of each plateau are excluded).

was sometimes problematic and it was often difficult to calculate movement amplitude. For this reason, we calculated (1) *amplitude*, the 95% confidence interval $(2 \times 1.96 \times \text{SD})$ of the amplitude at each frequency segment of motion of the head A_{head}, the ankle A_{ankle}, and the hip A_{hip}. In order to evaluate the strength of the coupling between components, we determined (2) the *maximum cross-correlation* between movements of the room and head $R_{\text{room–head}}$, and between movements of the ankle and hip $R_{\text{ankle–hip}}$ (see Amblard, Assaiante, Lekhel, & Marchand, 1994). We also computed (3) the mean FFT *power spectrum overlap* between movements of the room and head, $\text{PSO}_{\text{room–head}}$, and between movements of the ankle and hip, $\text{PSO}_{\text{ankle–hip}}$. The power spectrum overlap enabled us to evaluate the frequency coupling between room and head, on the one hand, and ankle and hip, on the other. After plotting the head (or ankle) and room (or hip) FFT power spectra, the areas under the curves were calculated and normalized to 100%. The percentage of common surface covered by the head (or ankle) and the room (or hip) was identified as an index of their frequency coupling. Low values of coupling between the room

and the head, observed in the $R_{room–head}$ and $PSO_{room–head}$ variables, suggested that the head did not always oscillate at the frequency of room motion, especially at high frequencies when performing the looking task (Fig. 2). For this reason, we computed (4) the *mean head frequency*, $Freq_{head}$, for each frequency level of the stimulus. We also computed (5) the *mean relative phase* of room and head motion, $\phi_{room–head}$, and the mean relative phase of ankle and hip motion, ϕ_{rel}, using the point-estimate method (Zanone & Kelso, 1997). [2] Given the cycle identification problem noted above, we decided to retain the mean value of the relative phase for a given frequency of stimulus motion only if there was a minimum of four unambiguously identified values (out 10 target cycles). If not, the frequency plateau was excluded from the analysis. Since relative phase is a circular variable, we used standard circular statistics to compute the measures of central tendency and variability, as well as relevant inferential statistics (cf., Batschelet, 1981).

3. Results

We begin with an analysis of the visual coupling (i.e., coupling between the head and the moving room), followed by an analysis of postural coordination (i.e., coupling between ankle and hip).

3.1. Room–head coupling

3.1.1. Amplitude of head motion

The mean amplitude of head motion A_{head} was 3.34 cm (SD = 3.10) in the looking task, and 7.78 cm (SD = 2.69) in the tracking task. A two-way (task × frequency) repeated measures analysis of variance (ANOVA) revealed a significant main effect for task $F(1, 24) = 20.96$, $p < 0.05$, Effect intensity (i.e., percentage of variance accounted for) EI = 39.91%, indicating that on average A_{head} was higher in the tracking task than in the looking task. A significant main effect was also found for frequency, $F(12, 288) = 1.90$, $p < 0.05$, EI = 1.27%, and for the interaction between task and frequency, $F(12, 288) = 2.4$, $p < 0.05$, EI = 1.64%. Linear regression of A_{head} onto frequency indicated no changes in the looking task ($R^2 = 0.0262$, $F(1, 12) = 1.32$, $p = 0.2725$ ns) and an increase of A_{head} with increasing frequency in the tracking task ($R^2 = 0.656$, $F(1, 12) = 23.91$, $p < 0.05$, Fig. 3A).

3.1.2. Maximal room–head cross-correlation and power spectrum overlap

Mean $R_{room–head}$ was 0.26 (SD = 0.13) in the looking task and 0.63 (SD = 0.34) in the tracking task. An ANOVA performed on the (Fisher-transformed) values of $R_{room–head}$ revealed a significant main effect of task, $F(1, 24) = 35.6$, $p < 0.05$,

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[2] We repeated the data analysis using standard linear system analysis tools (i.e., magnitude square coherence MSC, gain and phase). Differences appeared when multiple peaks were observed: in multi-peak situations, the MSC values were not interpretable.
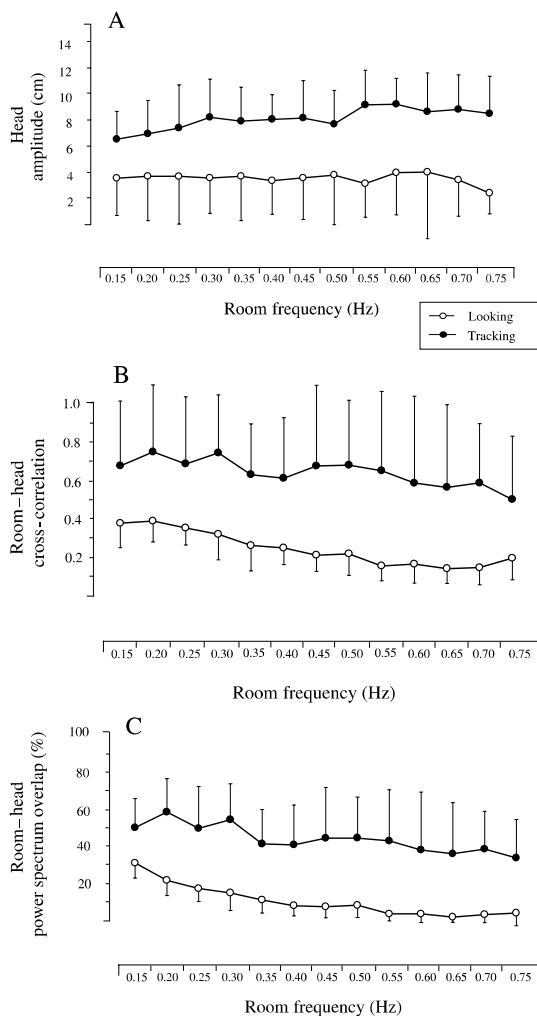
Fig. 3. Room–head coupling. Relations between movement of the head and room as a function of the room motion frequency, in both the looking and tracking tasks. (A) Means (and SDs) of amplitude of head motion A_{head}. (B) Means (and SDs) of the maximal room–head cross-correlation $R_{room–head}$. (C) Means (and SDs) of the room–head power spectrum overlap $PSO_{room–head}$. (D) Circular means (and SDs) of the room–head relative phase $\phi_{room–head}$. (E) Means (and SDs) of the frequency of head movement $Freq_{head}$.

$EI = 45.29\%$, confirming that values of $R_{room–head}$ were significantly higher in the tracking task than in the looking task. A significant effect was also found for frequency, $F(12, 288) = 8.51$, $p < 0.05$, $EI = 6.29\%$, indicating a decrease in coupling as room frequency increased (Fig. 3B). This was the case for both the looking and tracking tasks, as indicated by the non-significant interaction between the two factors, $F(12, 288) = 1.47$ ns, $EI = 1.05\%$. At the 0.15 Hz stimulus frequency, the mean
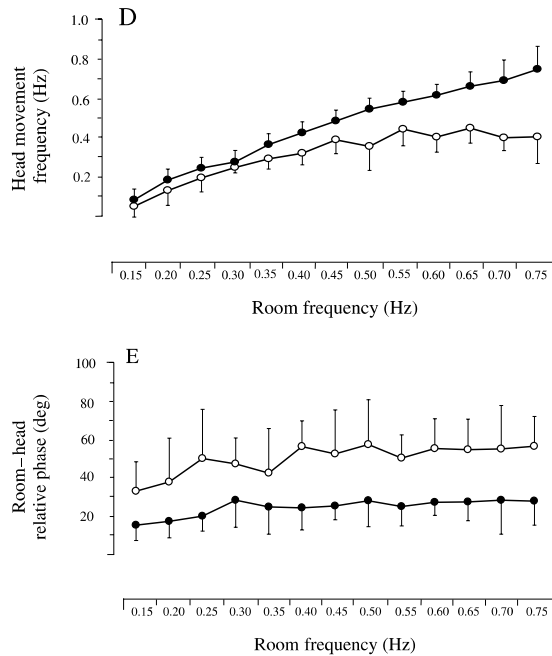
Fig. 3 (*continued*)

$R_{\text{room–head}}$ for the looking task was 0.38. This is comparable to values observed in previous research with similar stimulus frequency and a similar looking task (e.g., 0.49, Stoffregen, 1985; 0.40, Stoffregen, 1986).

The analysis of $\text{PSO}_{\text{room–head}}$ yielded similar results, confirming that the frequency coupling between room and head movement decreased as room frequency increased. Mean $\text{PSO}_{\text{room–head}}$ was 13.44% (SD = 9.4) in the looking task and 43.99% (SD = 21.36) in the tracking task. Significant main effects were found for task, $F(1, 24) = 41.00$, $p < 0.05$, EI = 18.74%, and frequency, $F(12, 288) = 11.80$, $p < 0.05$, EI = 3.37%. The task $\times$ frequency interaction also reached significance, $F(12, 288) = 1.91$, $p < 0.05$, EI = 0.55%, due to a marginal increase in $\text{PSO}_{\text{room–head}}$ in the low frequencies of the room while performing the tracking task (Fig. 3C).

3.1.3. Frequency of head movement

Since analyses of $R_{\text{room–head}}$ and $\text{PSO}_{\text{room–head}}$ revealed an effect of stimulus frequency on visual coupling, we examined the frequency of head motion for each level of stimulus frequency. An ANOVA revealed a significant main effect of task, $F(1, 24) = 57.19$, $p < 0.05$, EI = 12.05%, indicating higher values of $\text{Freq}_{\text{head}}$ in the tracking task. Not surprisingly, a significant main effect was found for frequency, $F(12, 288) = 199.35$, $p < 0.05$, EI = 61.84%. However, the task $\times$ frequency interaction was also significant, $F(12, 288) = 18.96$, $p < 0.05$, EI = 5.88%, indicating differ-

ences between the looking and tracking tasks for the higher frequencies of the room motion (Fig. 3D).

3.1.4. Room–head relative phase

For each task, head movement lagged behind room motion. For each task, the relative phase values were clustered around a mean (significant Raleigh test for non-homogeneity, $p < 0.05$), indicating a preferred phase angle. The mean value of $\phi_{\text{room–head}}$, was 49.4° (SD = 19.3) for looking task and 24.2° (SD = 11.5) for tracking (see Fig. 3E); the difference was significant, $F_{\text{Watson–Williams}}(1, 124) = 80.44$, $p < 0.05$. In addition, $\phi_{\text{room–head}}$ differed significantly from 0° in both tasks, as indicated by the 95% confidence interval for $\phi_{\text{room–head}}$, which did not contain 0° neither when looking (44.30° $< \phi_{\text{room–head}} <$ 54.58°) nor when tracking (21.55° $<$ $\phi_{\text{room–head}} <$ 26.86°) task.

Taken together, these results suggest that participants followed the oscillations of the room, rather than anticipating them. A systematic effect of the type of task was found on the visual coupling between the room and the head, showing that the instruction to track the target significantly increased coupling between room and head movements. In both tasks, the strength of visual coupling decreased with increasing room frequency (Fig. 3B and C). It is noteworthy that in the looking task the frequency of head movement increased with frequency of the moving room only up to room frequency of 0.50 Hz, that is, the frequency of head movements never exceeded 0.50 Hz. However, the effect intensity results indicate that relative to stimulus frequency the nature of the task had an overwhelming effect on the coupling between the room and the head.

3.2. Intrinsic coordination

We now describe coordination between ankle and hip motion that emerged from the interplay between task and frequency constraints. We present data on ankle and hip amplitudes, cross-correlations, power spectrum overlap, and relative phase between the two joints.

3.2.1. Angular amplitude of ankle motion

The average value of A_{ankle} was 3.1° (SD = 2.8) in the looking task, and 4.8° (SD = 3.3) in the tracking task. An ANOVA revealed a significant main effect of frequency, $F(12, 288) = 2.10$, $p < 0.05$, EI = 1.07%, but no significant effect of task, $F(1, 24) = 1.9$ ns. Similarly, the task × frequency interaction failed to reach significance, $F(12, 288) = 1.61$ ns. Fig. 4A shows that in both tasks ankle amplitude decreased slightly as room frequency increased.

3.2.2. Angular amplitude of the hip motion

The mean value of A_{hip} was 5.1° (SD = 4.4) in the looking task, and 9.9° (SD = 8.6) in the tracking task. An ANOVA yielded a significant main effect of frequency, $F(12, 288) = 1.83$, $p < 0.05$, EI = 1.16%, and non-significant effects of task, $F(1, 24) = 1.83$ ns, as well as task × frequency interaction, $F < 1$ ns. Fig. 4B

illustrates the small frequency effect for both looking and tracking. It should be noted that, while the increase in room frequency produced a decrease in ankle amplitude, it produced an opposite effect (i.e., an increase) on hip amplitude.

3.2.3. Maximal ankle–hip cross-correlation $R_{ankle–hip}$ and power spectrum overlap $PSO_{ankle–hip}$

Mean $R_{ankle–hip}$ was 0.40 (SD = 0.22) in the looking task, and 0.62 (SD = 0.29) in the tracking task. An ANOVA revealed a significant main effect of task, $F(1, 24) = 33.89$, $p < 0.05$, EI = 33.43%. A significant main effect was also found for fre-
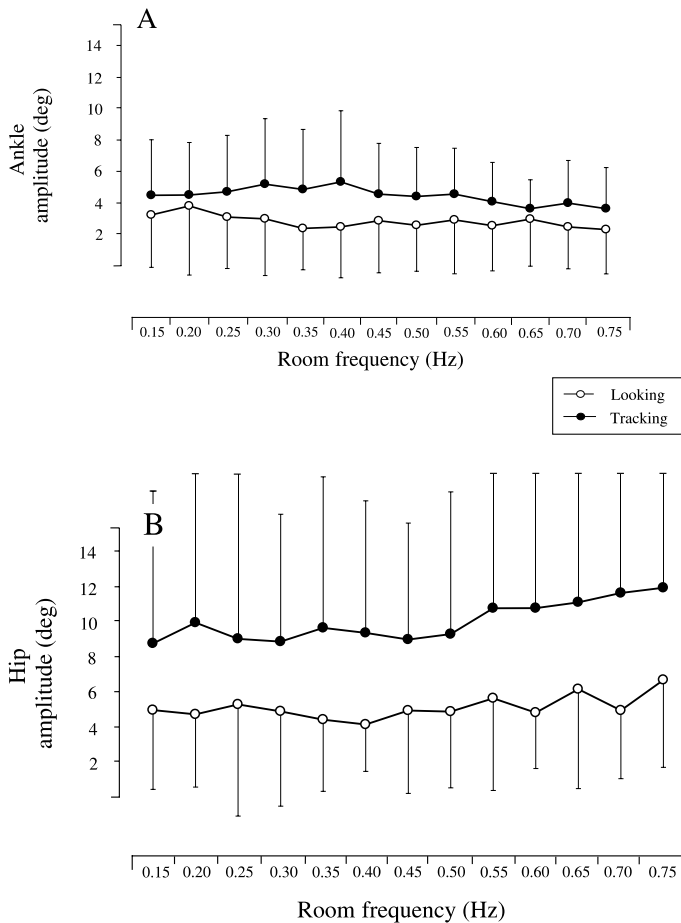

Fig. 4. Ankle–hip coordination: relations between movement of the ankle and movement of the hip as a function of room motion frequency, in both looking and tracking. (A) Means (and SDs) of the angular amplitude the ankle, A_{ankle}. (B) Means (and SDs) of the angular amplitude of the hip, A_{hip}. (C) Means (and SDs) of the maximal room–head cross-correlation, $R_{ankle–hip}$. (D) Means (and SDs) of the ankle–hip power spectrum overlap $PSO_{ankle–hip}$.
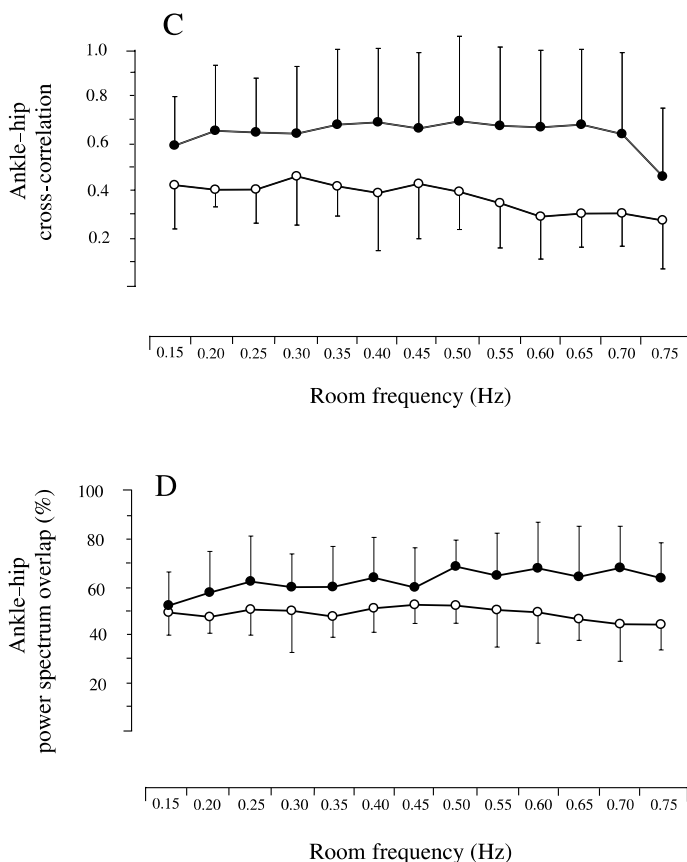
C

D

Fig. 4 (*continued*)

quency, $F(12, 288) = 2.68$, $p < 0.05$, EI = 3.91%, indicating a slight decrease of the ankle–hip coupling with the increase of the room frequency. The interaction between task and frequency was not significant, $F(12, 288) = 1.4$ ns, suggesting that these two effects were independent (Fig. 4C).

The power spectrum overlap (PSO$_{ankle–hip}$) exhibited similar results. Effects of task, $F(1, 24) = 15.80$, $p < 0.05$, EI = 15.61%, and frequency, $F(12, 288) = 1.97$, $p < 0.05$, EI = 4.15%, were found to be significant, but the task × frequency interaction was not, $F(12, 288) = 1.29$ ns. Fig. 4D illustrates the task and frequency effects.

Both the ankle–hip cross-correlation and power spectrum overlap results indicate significant differences in the strength of ankle–hip coupling between the looking and the tracking task. These measures inform us about the strength of coupling between movements of the two joints, but they do not specify how these two movements were coupled, that is, the coordinative state between ankle and hip that underlies

the coupling between motion of the room and head. An analysis of the relative phase between ankle and hip is required for this purpose, and we proceed with this analysis in the next section.

3.2.4. Ankle–hip relative phase

On the basis of earlier research on postural coordination modes (Bardy et al., 2002; Oullier et al., 1999) we assumed that different coordination modes could co-exist for a given frequency of motion of the room. Thus, before proceeding with descriptive circular statistics, we categorized all individual ϕ_{rel} values, in 20° bins, in order to analyse the frequency distribution of these relative phase values as a function of task and room frequency. Fig. 5 indicates a clearly bi-modal distribution of relative phase values. Computing means for each frequency step, as we did for other dependent variables, would thus not be appropriate for this kind of distribution. We therefore decided to separate the distribution into two regions of analysis: ϕ_{rel} values around 0° (from −80° to 100°), which we designate as low values, LV, and high values of ϕ_{rel}, HV (from 100° to 280°). In the looking task, 20° was the modal value that appeared in the LV region. In the HV region, the modal value was 180°. Results for the tracking task were similar since, in the LV region the modal value was 20° and 180° in the HV region.

Results of circular statistics applied to ϕ_{rel} in the two regions LV and HV separately are reported in Table 1. For both the looking and the tracking tasks, the in-phase (close to 20°) and the anti-phase (close to 180°) postural coordination modes were adopted for high and low frequencies of the moving room, respectively. This finding suggests that postural coordination was similar in the looking and the tracking tasks. As can be seen in Fig. 5, the number of ϕ_{rel} values retained for analysis was higher in the tracking task, while the standard deviations reported in Table 1 suggest that this task also led to somewhat more stable patterns. This observation is confirmed for LV by Watson–Williams tests performed on the circular standard deviation of ϕ_{rel} values reported in Table 2. We found a significant effect of task when comparing variance of LV in the tracking task to LV in the looking task, $F_{\mathrm{Watson–Williams}}(1,22) = 4.14$, $p < 0.05$, but not when comparing HV, $F_{\mathrm{Watson–Williams}}(1,20) = 2.59$ ns. In order to interpret the data presented in Tables 1 and 2 and Fig. 5 it is important to bear in mind that frequency of head movement did not follow the frequency of the room movement for the higher frequencies in the looking task.

4. Discussion

The results obtained in the present experiment illustrate the role of supra-postural tasks in modulating motion of the body, as indicated by the effects of the type of task on a number of dependent variables. Tracking the target induced larger amplitudes of movement of the head (Fig. 3A) than merely looking at it. Consistent with this, both room–head (see Fig. 3B and C) and ankle–hip couplings (see Fig. 4C and D) were stronger in the tracking task. Changes in ankle–hip and room–head coupling
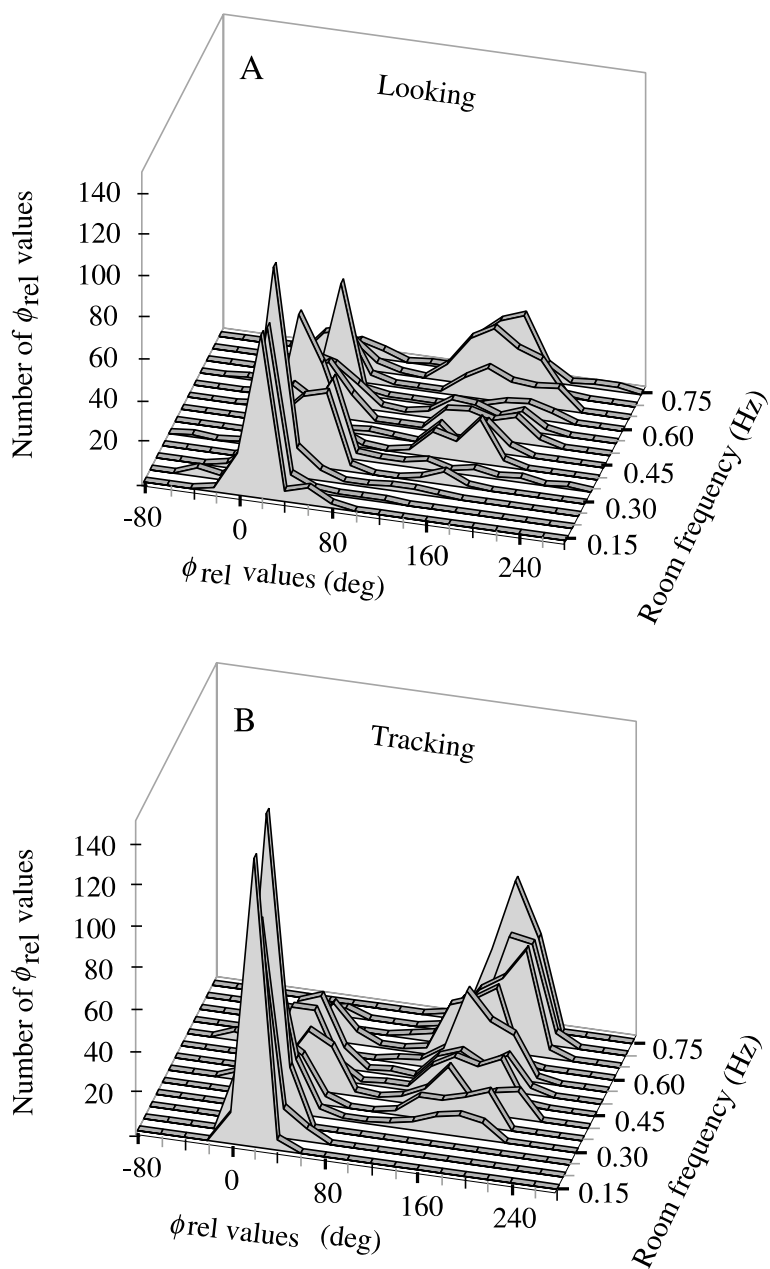
Fig. 5. Distribution of ankle–hip relative phase values (in 20° frequency bins) as a function of room motion frequency for looking (A) and tracking (B).

were observed as a function of the type of task and the oscillating frequency of the room. Increasing room frequency was accompanied by decreasing visual coupling,

Table 1
Circular statistics for ankle–hip relative phase ϕ_{rel} values

| | ϕ_{rel} (deg) | | | |
| | LV | | HV | |
	Looking	Tracking	Looking	Tracking
Mean	17.72	20.65	178.5	180.22
Standard deviation	20.22	14.84	30.04	24.15

LV: low values ($-80° < \phi_{rel} < 100°$) and HV: high values ($100° < \phi_{rel} < 280°$).

Table 2
Standard deviation for ankle–hip relative phase ϕ_{rel} values

| Room frequency (Hz) | Standard deviation of ϕ_{rel} (deg) | | | |
| | LV | | HV | |
	Looking	Tracking	Looking	Tracking
0.15	10.25	9.33	–	–
0.20	19.36	8.53	21.62	–
0.25	36.23	14.23	22.33	–
0.30	31.06	18.84	34.55	21.20
0.35	17.52	19.41	26.57	45.32
0.40	17.18	19.81	36.57	33.65
0.45	21.01	14.35	28.85	32.56
0.50	21.11	13.01	40.61	21.25
0.55	19.20	17.41	23.89	16.25
0.60	10.47	15.61	24.60	18.25
0.65	12.06	–	36.62	15.32
0.70	17.31	12.72	41.62	18.30
0.75	30.06	–	22.63	19.25

LV: low values ($-80° < \phi_{rel} < 100°$) and HV: high values ($100° < \phi_{rel} < 280°$) as a function of room frequency.

during both looking and tracking tasks, although coupling remained stronger during tracking. The looking task was associated with reductions in both room–head and ankle–hip coupling (see Fig. 4C and D).

4.1. Visual coupling

The visually based coupling between motion of the head and room was influenced by the frequency of room motion, and by the nature of the visual task (looking versus tracking). Frequency and task influenced each of the five dependent variables that were used to assess head–room coupling. For the amplitude (A_{head}), cross-correlation ($R_{room–head}$), and power spectral overlap ($PSO_{room–head}$) variables, the influence of task was dramatically greater than the influence of frequency. This is indicated by the data on effect intensity, where the effect of task exceeded the effect of frequency by at least a factor of 5. The tracking task could be considered to establish an upper

limit on the strength of coupling, and on the availability of visual information to support coupling. In this context, we regard the differences in effect intensity as illustrating the weakness of coupling in the looking task. This may have relevance for theories in which imposed optical flow is interpreted as a "driver" of postural control actions (e.g., Schöner, 1991).

When analyzing the relative phase distribution illustrated in Fig. 5, we should bear in mind the results for frequency of head movement (Fig. 3E). In the tracking task, head frequency followed room frequency from low to high stimulus frequencies, but this was not the case in the looking task, where frequency of head movement never exceeded 0.5 Hz. This finding is in line with the idea that the postural control system can play the role of a linear-second order low-pass system with a cut-off frequency around 0.5 Hz (van Asten, Gielen, & Denier van der Gon, 1988b).

Some of our results relating to room–head coupling differ from previous research relating vision and stance. Several studies have reported phase-lead at low driving frequencies and phase-lag at higher ones (e.g. Dijkstra, 2000; Lestienne et al., 1977) when performing tasks similar to our looking task. By contrast, our results indicate phase-lag at all stimulus frequencies. One difference between our study and many previous studies is in the amplitude of stimulus motion. Most studies have used relatively large amplitudes (e.g. Lee & Aronson, 1974; van Asten et al., 1988a,b). Large amplitude motions are easily noticed by experimental participants, but they are not representative of natural oscillations of the body. In our study the amplitude of room motion closely approximated the amplitude of ordinary body sway.

The tracking task used in the present study closely resembled one used by Bardy et al. (1999) and Bardy et al. (2002). However, in the present study the stimulus–head coupling was stronger and the relative phase between the room and the head was lower than the values reported by Bardy et al. The differences across studies might arise from a difference in the means used to generate optical flow. Here we used a moving room to generate flow, while Bardy et al. generate flow using computer graphics and video projection. The difference in results is consistent with the hypothesis of Stoffregen, Bardy, Merhi, and Oullier (2002) that coupling of body sway with experimenter-imposed optical flow may vary with the technology used to generate the flow. This methodological difference may also explain differences between our results and previous studies in the looking task.

4.2. Postural coordination modes

Bardy et al. (1999) and Bardy et al. (2002) documented the emergence of two preferred modes of postural coordination when participants used voluntary movements of the head to track motion of a target in the antero-posterior axis. The present results suggest that similar modes emerge whether participants track the target, or merely look at it. Thus, ankle–hip coordination underlying the maintenance of upright stance appears similar when performing a looking or tracking task. This is demonstrated by the emergence of in-phase and anti-phase modes of postural coordination (Bardy et al., 1999), as illustrated in Fig. 5 by the bi-modal distribution

of ankle–hip relative phase values in each task. These results have clear implications for research on the visual control of stance. The vision-and-posture literature has repeatedly demonstrated the importance of visual coupling for the maintenance of stance (e.g., Dijkstra, Schöner, Giese, et al., 1994; Schöner, 1991), but there have been almost no studies reporting the underlying intersegmental coupling. Implicitly or explicitly, the body is often considered as a simple inverted pendulum oscillating about the ankles and actively matching (Schöner, 1991), or passively driven by, the optical flow created by body sway. Results of the present study indicate that the inverted pendulum analogy may not be correct, for adaptive patterns of postural coordination underlie the simple act of looking. Whether changes in coordination mode have consequences for the coupling of head movement to the visual environment remains an open question. The fact that in-phase coordination between ankle and hip emerged under conditions of slow motion of the visual surrounds and antiphase coordination under conditions of rapid motion may or may not be related to the finding, reported here and in earlier studies (e.g., Dijkstra, Gielen, & Melis, 1992; Dijkstra et al., 1994; Lestienne et al., 1977; van Asten et al., 1988a) that the strength of coupling between motion of the room and motion of the head decreases with increasing frequency.

An important aspect of the data presented in Fig. 5 is the deep valley between the two distribution peaks, that is, the absence of transient modes of coordination. This valley (visible separately in Fig. 5A and B) suggests that there must have been a sudden change in coordination mode in each of the tasks. The present set-up did not allow us to determine whether this transition in postural coordination was preceded by an increase in fluctuations, and whether it was accompanied by an hysteresis effect (for a direct test, see Bardy et al., 2002). However, it is clear from Fig. 5 that the observed bi-modal distribution of relative phase values is congruent with a bifurcation between postural patterns. Interestingly, the looking and tracking tasks seemed to exhibit differences in stability, as suggested by the smaller number of in-phase peaks and the systematically larger standard deviation of relative phase. This suggests that the intention to look or track might be considered as modulating the intrinsic dynamics of the postural system (Kelso, 1995).

5. Coordination subserving supra-postural performance

In this study, participants were asked to stand comfortably, but were given no other instructions about how to control their posture. Two patterns of intersegmental coordination emerged. These patterns were qualitatively similar in the looking and tracking tasks, but not identical. The coupling of head movements to room motion was weaker during the looking task, and the in-phase postural coordination mode was less stable during the looking task than during the tracking task. We interpret these findings as indicating that the looking task imposed weaker constraints than the tracking tasks on posture. Future research will be needed to understand the nature of the differing task constraints. In particular, it would be informative to use visual tasks for which visual performance could be measured independent of posture

(e.g., visual search; Stoffregen et al., 2000). This would permit direct assessment of the extent to which a particular level of visual performance influenced postural coordination, and vice versa.

The coordination modes observed in our study subserved performance of the supra-postural looking and tracking tasks. In essence, postural coordination and supra-postural performance existed in an hierarchical relation to one another, with postural coordination serving as a means (lower level) to achieve the ends of the supra-postural tasks (higher level). This hierarchical relation can be understood as an example of the affordance hierarchy discussed by Vicente and Rasmussen (1990).

6. Conclusion

The in-phase and anti-phase modes of coordination emerged when tracking the visual target and when simply looking at it. Thus these modes of coordination are not particular to the tracking task. Interestingly the tracking task amplified the motion of the body and strengthened both coordination modes, thus indicating its usefulness for the study of postural coordination in general. Our results, obtained when tracking a target in a moving room, confirm those obtained when tracking the simulated motion of a target on a screen (Bardy et al., 2002), and extend the earlier findings to a simple looking task.

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