Visual information and body sway coupling in infants during sitting acquisition

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Abstract

The purpose of this study was to examine if there is any developmental change in the coupling between visual information and trunk sway in infants as they acquire the sitting position. Twenty-four infants distributed in four groups (6-, 7-, 8-, and 9-month-old) were sat inside a moving room that oscillated back and forward at frequencies of 0.2 and 0.5 Hz. The results revealed that trunk sway matched to the moving room at both frequencies but did not differ among the four age groups. Coherence and gain revealed that the coupling was weaker at 0.2 than at 0.5 Hz. Relative phase showed that at 0.2 Hz, infants were swaying with no lag but at 0.5 Hz they were lagging the room. These results showed that the coupling between visual information and trunk sway in infants varies with the visual stimulus but does not change as infants acquire the sitting position. © 2000 Elsevier Science Inc. All rights reserved.

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1. Introduction

For most children and adults, sitting is a daily motor task easily performed. However, watching a young infant’s first attempts at sitting, one sees the struggle of maintaining the huge trunk and head mass in the upright position. Indeed, it is only after a great deal of effort that infants master independent sitting, usually after the sixth month of age (Capute et al., 1985). To achieve a stable sitting posture, the infant must have the motor and sensory
systems working together to stabilize the trunk in the erect position and the head aligned on the trunk. In this paper, we investigate the development of this relationship between the motor and sensory system, that is the perception-action coupling, as infants acquire the sitting position. Specifically, we examine the relationship between body sway and an oscillatory visual flow provided by a moving room in infants aging from 6 to 9 months of age.

To solve the puzzling problem of achieving a stable sitting posture, infants must solve two sensorimotor challenges. First, infants must maintain the trunk in an erect position over a base of support composed of the pelvis and legs. Second, infants must keep the disproportionately heavy head aligned with the trunk. These are not simple tasks for the young infants. While the trunk must be kept aligned with a relatively stable base of support, the pelvis and the legs, the head must be kept aligned with a moving base of support, the trunk. Thus, infants are faced with a complex task that involves muscle activation around both trunk and neck coherent with the position of the trunk and head. In other words, infants must produce muscle activation based on the sensory signals indicating the position of both body components in space.

The mastering of the sitting position has been characterized by an increase in the coordination and control of the musculature responsible for supporting the trunk and head (Harbourne et al., 1993) and by more organized and more frequent automatic postural muscle responses around the neck and trunk when the sitting position is disturbed (Woollacott et al., 1987). These results would suggest that changes in the control of the musculature responsible for supporting the trunk and the head occur as the infant acquires the ability to sit independently. Moreover, the development of muscle activation would occur progressively as the infants have more experience in the sitting position. Although these findings reveal the course of sitting acquisition, developmentally a main question remains to be answered: What is developing? Do changes occur due to improvement in the motor or sensory system?

We have suggested and shown empirically that one of the mechanisms underlying developmental changes in postural control during the acquisition of upright stance is the acquisition of a coherent and stable relationship between sensory information and body control (Barela et al., 1999). Control of posture is a function of the dynamic interaction between sensory information about the body relative to the environment and the production of appropriate motor responses for managing postural equilibrium and orientation (Horak & Macpherson, 1996). Our view reflects a bi-directional relationship between perception and action that can be characterized by examining the temporal relationship between sensory information and body sway.

Many studies have investigated the influences of visual information on postural control in adults, children, and infants using the “moving room” paradigm. Lishman and Lee (1973) were the first to show that upright stance in adults could be disrupted by moving the surrounding visual environment with discrete and abrupt movements of the walls and ceiling. Shortly, this paradigm was also employed to examine developmental changes in the coupling between sensory information and postural control in infants standing (Lee & Aronson, 1974) and sitting (Butterworth & Hicks, 1977). Studies have also examined the relationship between sensory information and postural control by oscillating the visual environment continuously. Delorme, Frigon and Lagacé (1989) showed that oscillatory movements of a
moving room produce correspondent body sway oscillation in infants as young as 7 months of age. Likewise, Bertenthal and colleagues demonstrated that infants during the acquisition of independent sitting not only became more influenced by the visual information but also could scale their postural responses to the visual information (Bertenthal et al., 1997). Moreover, infant’s postural responses to the visual flow showed considerable developmental improvement as infants learn to sit. Postural responses to moving room oscillation are also present in children maintaining upright stance. Schmuckler (1997) showed that 3- and 5-year-old children not only respond coherently to the moving room oscillations but also that their responses are similar in temporal pattern to those observed in adults.

Overall, developmental studies using the moving room paradigm have shown that visual information is an important part of postural control in infants and children. However, researchers have only recently tried to uncover some of the characteristics of the relationship between the visual information and postural control (e.g., Bertenthal et al., 1997; Schmuckler, 1997) but many questions are still be answered: How stable is the relationship between sensory information and postural control in infants? Are there any developmental changes in this relationship? In the present study, we intend to extend our knowledge in examining the stability of the coupling between visual information and body sway and examining if any developmental change takes place in this coupling as infants acquire the sitting position.

Our approach is based on Schöner’s (Schöner, 1991) conceptual framework in which postural control was characterized as a second-order dynamical system coupled to visual inputs captured through the eyes. The basic idea is that visual information and postural control are coupled together into a perception-action cycle. In addition, the temporal stability of this perception-action relationship is a function of the coupling strength between postural sway and the sensory information. This conceptual framework has empirically been applied to identify that body sway is sensitive to the velocity of visual stimulus (Dijkstra et al., 1994a; Dijkstra et al., 1994b) and to the position and velocity of somatosensory stimulus (Jeka et al., 1997; Jeka et al., 1998).

In this experiment, we employ a moving room to examine how 6-, 7-, 8-, and 9-month-old infants couple their body sway to visual information. Specifically, we examined the temporal relationship between visual information provided by a moving room and body sway in infants. In addition, we examined if this temporal relationship changed as infants acquired the sitting position. Our hypothesis is that infants couple to the visual stimulus and that the strength and, therefore, the stability of this coupling between visual information and body sway will increase as infants have more experience in maintaining the independent sitting position.

2. Methods

2.1. Participants

Twenty-four infants, thirteen males and eleven females, participated in this study. Four groups of 6 participants each were formed: 6- (M = 6.0 and SD = 0.4); 7- (M = 7.1 and SD = 0.4); 8- (M = 8.5 and SD = 0.3); and 9-month-olds (M = 9.4 and SD = 0.2). The infants were recruited through personal contact with colleagues, friends, and neighbors. Each
infant’s parent gave written informed consent prior to his or her participation. Based on parental reports, no infant had any musculoskeletal injuries or neurological disorders that might have affected his or her ability to maintain the sitting position. In addition, the parents were questioned when the infants started to maintain the sitting position independently. Based on their information, the mean of independent sitting for each group was 0.5, 1.1, 2.0, and 2.8 months.

2.2. Procedures

The infants were brought to the Laboratório para Estudos do Movimento (LEM) - UNESP/RC and after a brief period of adaptation they were prepared for the experimental session, being sat inside a moving room. This moving room, which measured $2.1 \times 1.2 \times 1.2$ m (long, wide, and height), consisted of three walls and a ceiling mounted on wheels such that could be moved back and forth on top of a stationary basis. The moving room walls were covered inside by white and black contact paper displaying a pattern of vertical stripes of 40 and 20 cm, respectively. In addition, each wall was ornamented with an animal drawing and at the end part of the ceiling a 15 W light was placed to keep the lightness inside the room constant across all trials.

The moving room movement was produced and controlled by a servo-motor mechanism. This servo-motor mechanism was constituted by a controller (Compumotor - Mod APEX 6151), a controlled stepper motor (Compumotor - Mod. N0992GR0NMSN), an electrical cylinder (COMPUMOTOR Mod. EC3-X3xxN-10004a-MS1-MT1M), which connected the servo-motor to the structure of the moving room, and a software (Compumotor - Motion Architect for Windows). This servo-motor mechanism was used to move the moving room sinusoidally in the participant’s anterior-posterior plane at frequencies of 0.2 and 0.5 Hz. Peak velocity at both frequencies was kept constant at 3.5 cm/s by varying moving room displacement with frequency. The peak-to-peak displacement of the moving room was 5.65 and 2.26 cm at 0.2 and 0.5 Hz, respectively.

Body sway and moving room displacement were obtained through two active markers (OPTOTRAK 3020–3D Motion Measurement System, NDI) positioned on the infant’s back (the level of the 5th thoracic vertebra) and on the edge of moving room’s front wall, respectively. Information about these markers positioning was collected at 60 Hz and provided information about body sway and moving room displacement in the anterior-posterior, medial-lateral, and vertical directions.

For each infant at least three trials in each frequency were collected. Each trial lasted 60 s. The frequency of the first trial was defined randomly and then the frequency of the following trials was alternated. The trials began when the infant was sitting quietly and looking to the front wall. In order to infants to accomplish the task throughout the trial, an experimenter stayed inside of the moving room showing pictures and drawings in an attempt to capture the infant’s attention. These pictures and drawings were taped, one each time, on the front wall and away from the person in an attempt to prevent the infant from looking at the experimenter.
2.3. Data reduction

Data from one of the 6-month-old infant were not analyzed since the infant was not able to maintain the sitting position independently when the moving room was oscillated and had to be helped during the experimental procedures. In addition, although the goal was to collect three trials of each infant in each frequency, in some cases this was not possible. Trials were not considered for analyses in those cases when infants did not cooperate, produced undesirable movements not related to postural oscillation or did not keep looking forward to the front wall. Following these criteria, from a total of 138 possible trials, 24 trials (17.3% of the total) were not considered for analyses. In addition, of the 114 trials analyzed 30 trials had to be shorter than the 60 s initially suggested in order to accomplish the criteria stipulated. Twelve trials were 50–55 s, 14 trials were 40–49 s, and 4 trials were 35 s long. All the trials not considered for analyses or the shortened ones were evenly distributed across the four age groups and all the infants had at least one trial in each frequency.

Since the moving room’s movement was in the anterior-posterior direction relative to participants, analyses of the relationship between the moving room displacement and body sway focused only on the anterior-posterior direction. Four measures were used to examine the relationship between moving room displacement (MR\textsubscript{AP}) and anterior-posterior body sway (BS\textsubscript{AP}): the magnitude squared coherence; gain; relative phase; and angular deviation of relative phase. Coherence measures the strength of relationship between the body sway and the oscillatory movement of the moving room, that is, how strongly body sway is coupled with the visual stimulus. Magnitude squared coherence (MSC) is defined as:

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MSC = \frac{|P_{xy}(\omega)|^2}{P_{xx}(\omega) P_{yy}(\omega)}
\]

where \(P_{xy}(\omega)\) is the cross-spectrum of two signals \(x(t)\) and \(y(t)\), \(P_{xx}(\omega)\) and \(P_{yy}(\omega)\) are the auto-spectra of \(x(t)\) and \(y(t)\), respectively, calculated at a particular frequency, \(\omega\). Gain was calculated as the ratio between the body sway amplitude spectrum and the moving room amplitude spectrum. Gain values close to 1 indicate that body sway is the same as the amplitude of the driving signal. Both MSC and gain were calculated at the driving frequency (0.2 or 0.5 Hz). This procedure was adopted because, as in previous studies (i.e., Barela, 1997; Dijkstra et al., 1994b), inspection of the spectra indicated systematic peaks at the driving frequency.

Discrete time series of relative phase were also calculated between body sway and moving room movement. This calculation employed a peak-picking technique (Dijkstra et al., 1994b) that involved the identification of significant extrema of the position and velocity of moving room and body sway cycles. The definition of an extremum was based upon the difference between maximum and minimum in a segment of one cycle before and one cycle after the extremum. For example, an extremum was accepted when it differed more than 20% from the neighboring extrema. Relative phase was calculated by taking the time difference between an extremum of the body sway signal and an extremum of moving room movement and dividing this difference by the driving stimulus period. From this procedure, four time series of relative phase were available: maxima and minima of position and velocity. These
four time series were combined in one overall time series and the mean and standard deviation of relative phase were calculated. The relative phase mean provided information about the time relationship between the moving room movement and the body sway response. The angular deviation of the relative phase provided information about the stability of coupling between body sway and the moving room. In addition, mean body sway frequency was also calculated by averaging the individual cycle periods defined by peak-picking within a trial. Mean body sway frequency corresponded to the inverse of the cycle period of body sway.

2.4. Statistical analysis

Two statistical analyses were employed. The first statistical analysis was a 4 × 2 (Age x Frequency) MANOVA, with repeated measures on the last factor, conducted to evaluate the effects of age (6-, 7-, 8-, and 9-month-olds) and the two moving room frequencies (0.2 and 0.5 Hz). The dependent measures were the coherence, gain, relative phase, and angular deviation calculated between the moving room and postural sway displacement in the anterior-posterior direction. Appropriate follow-up univariate tests were performed, when they were applicable, and the overall alpha level was kept at .05.

The second statistical analysis was a 4 × 2 (Age x Frequency) ANOVA, with repeated measures on the last factor, conducted to evaluate the effects of age (6-, 7-, 8-, and 9-month-olds) and the two moving room frequencies (0.2 and 0.5 Hz) in body sway displayed by the infants. The dependent measure was the infant’s mean body sway frequency in the anterior-posterior direction.

3. Results

Visual information from a moving room induced postural sway in all infants at both frequencies. Fig. 1 depicts exemplar time series, spectra, and relative phase between body sway (BS\textsubscript{AP}) and moving room displacement (MR\textsubscript{AP}) for a 6-month-old at 0.2 (Fig. 1a-c) and 0.5 Hz (Fig. 1d-f). The overlaid time series for the frequency of 0.2 (Fig. 1a) and 0.5 Hz (Fig. 1d) show that BS\textsubscript{AP} entrains to the movement of the moving room. Spectral plots in Fig. 1c and 1f show a defined peak in the BS\textsubscript{ML} signal at the moving room frequency of 0.2 and 0.5 Hz, respectively. The relative phase time series plots (Fig. 1b and 1e) show a phase relationship between the body sway and moving room displacement around 0° at frequency of 0.2 Hz (Fig. 1b) and a phase lag around −70° at frequency of 0.5 Hz (Fig. 1e).

3.1. Mean sway frequency

Fig. 2 depicts the mean body sway frequency in the anterior-posterior direction at the two driving frequencies. Clearly, body sway frequency of all age groups matches the moving room frequency. Univariate analysis of variance revealed only a significant frequency effect for body sway mean frequency: $F(1, 19) = 519.54, p < .001$. 
Fig. 1. Overlaid time series of body sway (BS\textsubscript{AP}) and moving room (MR\textsubscript{AP}) displacement, relative phase time series of body sway versus moving room displacement, and amplitude spectra of body sway and moving room displacement in the anterior-posterior direction of a 6-month-old infant. The three top panels (a-c) are from a frequency of 0.2 Hz and the three bottom panels (d-f) are from a frequency of 0.5 Hz.
3.2. Moving room and body sway relationship

Since the moving room movement influenced the infant body sway, we report below the temporal relationship between visual information and body sway. Results of the MANOVA revealed no significant age effect (Wilks’ Lambda = 0.68, F(12,42) = 0.54, p > .05) and interaction between age and frequency (Wilks’ Lambda = 0.48, F(12,42) = 1.13, p > .05) but a significant effect for frequency (Wilks’ Lambda = 0.23, F(4,16) = 12.69, p < .001). Therefore, we report the results of the frequency follow-up univariate analyses on all four variables employed to examine the relationship between the moving room movement and body sway.

3.2.1. Mean squared coherence

The coupling between the moving room and body sway was not different among the children’s age groups but it was higher for the frequency of 0.5 than 0.2 Hz. Fig. 3 depicts the $\text{MR}_{\text{AP}}-\text{BS}_{\text{AP}}$ mean coherence values for all the age groups in the two driving frequencies. Follow up univariate analyses showed a significant frequency effect for $\text{MR}_{\text{AP}}-\text{BS}_{\text{AP}}$ coherence, $F(1,19) = 5.72, p < .05$.

3.2.2. Gain

Body sway response to the moving room movement was not different among the children’s age groups but it was higher for the frequency of 0.5 than at 0.2 Hz, as shown in Fig. 4. Univariate analyses showed a significant frequency effect for $\text{MR}_{\text{AP}}-\text{BS}_{\text{ML}}$ gain, $F(1,19) = 17.84, p < .001$.

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**Fig. 2.** Mean body sway frequency of the body sway for all age groups in the anterior-posterior direction across the two driving frequencies.
3.2.3. Relative phase

Body sway was slightly ahead of the moving room at frequency of 0.2 Hz and then body sway lagged behind of the moving room to approximately −70° at frequency of 0.5 Hz (Fig. 5). Univariate analysis showed a significant frequency effect for MR<sub>AP</sub>-BS<sub>AP</sub> relative phase, $F(1,19) = 28.44$, $p < .001$.

Fig. 3. Mean coherence values between body sway and moving room displacement for all age groups in the anterior-posterior direction across the two driving frequencies.

Fig. 4. Mean gain values between body sway and moving room displacement for all age groups in the anterior-posterior direction across the two driving frequencies.
3.2.4. Angular deviation

The temporal stability between MR AP - BS AP, as shown by the angular deviation of relative phase in Fig. 6, was similar across the age groups and frequencies. Univariate analyses did not reveal any significant age or frequency effect in phase angular deviation for MR AP - BS AP relationship.

Fig. 5. Mean relative phase values between body sway and moving room displacement for all age groups in the anterior-posterior direction across the two driving frequencies.

Fig. 6. Mean angular deviation values between body sway and moving room displacement for all age groups in the anterior-posterior direction across the two driving frequencies.
4. Discussion

Visual information provided by an oscillatory moving room produces corresponding oscillatory postural sway in infants in the sitting position. Indeed our results demonstrate that perception-action coupling is well-developed in infants as young as six-month-old. This finding confirms results from previous studies that have indicated that infants entrained to an oscillatory visual information during sitting (Bertenthal et al., 1997) and standing (Delorme et al., 1989). The present study, however, extends our knowledge in the way that some of the characteristics of this coupling are revealed. First, infants as young as six months show many of the adultlike temporal parameters when they couple to a sensory stimulus. Second, there is empirical evidence that infants couple differently to different frequencies of an oscillatory visual information. Finally, this coupling does not seem to developmentally change as infants refine the maintenance of independent sitting.

The results revealed that even young infants couple to an oscillatory visual information with similar temporal parameters of the postural control system observed in adults. Relative phase values between the moving room displacement and body sway indicated that at frequency of 0.2 Hz infants oscillated together with the moving room. As the frequency increased, however, they lagged the oscillation of the moving room. Schmuckler (1997) observed similar postural sway responses also to a moving room in children 3- and 5-year-olds, that is, these children also increased time lag responding to visual information as frequency of moving room was increased. This temporal relationship observed when visual information is manipulated has also been observed when such manipulation involves the somatosensory information in adults (e.g., Jeka et al., 1998) and in children (Barela, 1997). It appears, therefore, that postural control is temporally constrained by visual and somatosensory information in the same fashion and that this temporal relationship does not differ among infants, children, and adults.

Although infants entrained to both moving room frequencies (0.2 and 0.5 Hz), difference in the coupling strength was observed. Coherence and gain values were significantly higher when the moving room was oscillated at 0.5 than at 0.2 Hz, indicating that not only the coupling was stronger at 0.5 than at 0.2 but also that the postural response to the visual stimulus at 0.5 was larger than at 0.2 Hz. The difference in coupling strength between these two frequencies is surprising and provocative. From previous work, we know that children respond to sensory information manipulation across a range of frequencies. For instance, correspondent postural responses in children have been observed when visual (Schmuckler, 1997) or somatosensory (Barela, 1997) information has been manipulated across a range of frequencies (from 0.2 to 0.8 Hz). However, no response magnification or strengthening of the coupling between the stimulus and the response was observed. Dijkstra et al. (1994b) have suggested that postural sway couples to the velocity of a visual stimulus and since the moving room velocity was kept constant across both frequencies, we would not expect any difference in the coupling between the frequencies of 0.2 and 0.5 Hz. Therefore, the difference between 0.2 and 0.5 Hz frequencies observed in our results indicate that infant’s postural sway may not only be coupling to the velocity of the visual stimulus but also to other characteristics of the visual stimulus. One possibility would be the position of the moving room, but this still waits for empirical verification.
Finally, no developmental change was observed in the coupling between visual information and body sway as infants acquire and refine the maintenance of independent sitting. At first glance, this finding is somewhat surprising since many studies have shown developmental effects in infant’s postural response to visual manipulation (e.g., Bertenthal & Bai, 1989; Bertenthal et al., 1997). However, recent empirical evidences have revealed the lack of developmental differences in postural sway across ages when vision (Schmuckler, 1997) or somatosensory (Barela, 1997) information was manipulated. Recently we have shown that even though 4-, 6-, and 8-year-old children did not differ among them, they have not matured to adultlike stability in the coupling between somatosensory information and body sway in maintaining the upright position (Barela, 1997). In the present experiment, angular deviation values, which indicate the stability of the perception-action coupling, are similar to those verified for children in the stance position. Thus, it seems that the perception-action coupling in infants and children is characterized by less stability than observed in adults. Moreover, this stability does not developmentally change with experience and with improvement in performance. The question is, then, to identify what is the source of this lack of stability in infants and children and to identify what developmentally changes in the perception-action coupling that supports improvement in performance.

In summary, we have observed that during the acquisition of independent sitting infants couple to visual information provided by a moving room. This coupling between visual information and body sway can be characterized by adultlike properties. Moreover, the stronger coupling observed for frequency of 0.5 compared to 0.2 indicates that infants may not be coupling only to the velocity of the visual stimulus. This finding differs from what has been observed for adults. Finally, no developmental changes were found among the four age groups, indicating no change in the coupling between visual information and body sway as infants acquire and refine the independent sitting position.

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