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Development of adaptive sensorimotor control in infant sitting posture

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ABSTRACT

A reliable and adaptive relationship between action and perception is necessary for postural control. Our understanding of how this adaptive sensorimotor control develops during infancy is very limited. This study examines the dynamic visual–postural relationship during early development. Twenty healthy infants were divided into 4 developmental groups (each $n = 5$): sitting onset, standing alone, walking onset, and 1-year post-walking. During the experiment, the infant sat independently in a virtual moving-room in which anterior-posterior oscillations of visual motion were presented using a sum-of-sines technique with five input frequencies (from 0.12 to 1.24 Hz). Infants were tested in five conditions that varied in the amplitude of visual motion (from 0 to 8.64 cm). Gain and phase responses of infants' postural sway were analyzed. Our results showed that infants, from a few months post-sitting to 1 year post-walking, were able to control their sitting posture in response to various frequency and amplitude properties of the visual motion. Infants showed an adult-like inverted-U pattern for the frequency response to visual inputs with the highest gain at 0.52 and 0.76 Hz. As the visual motion amplitude increased, the gain response decreased. For the phase response, an adult-like frequency-dependent pattern was observed in all amplitude conditions for the experienced walkers. Newly sitting infants, however, showed variable postural behavior and did not systemically respond to the visual stimulus. Our results suggest that visual–postural entrainment and sensory re-weighting are fundamental processes that are present after a few months post sitting. Sensorimotor refinement during early postural development may result from the interactions of improved self-motion control and enhanced perceptual abilities.

1. Introduction

Postural control is an important motor skill acquired during early development. To control the multi-segmented body in various conditions, a reliable and adaptive relationship between action and perception is necessary. Evidence of adaptive sensorimotor control in posture has been shown in adults [1,2] and in children [3–5]. Little is known about how this type of control develops during infancy.

Young adults entrain their standing posture to the frequency properties of vision and somatosensory information [1,6,7]. The frequency response of this sensory-postural relationship demonstrates an inverted-U pattern with the greatest in-phase entrainment near 0.2 Hz and weaker and out-of-phase entrainment as the stimulus frequency decreases or increases [6,7]. Furthermore, adults' postural sway is proportional to the stimulus amplitude within a range. When the amplitude exceeds a certain value, postural response decreases [2,8]. This change in the postural response to a change in the sensory stimuli indicates sensory re-weighting, a critical component of the adaptive sensorimotor control [1,2,9]. When a source of sensory information is unreliable, the postural system needs to attenuate this source of information and increase reliance on another modality. This sensory re-weighting process has been shown in children as young as 4 years of age [3] but has not been investigated in very young children or infants.

Newborn infants show directionally appropriate and velocity-scaled head response to visual flow information [10], suggesting

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that the visual–postural relationship may be a fundamental component of the sensorimotor system. A few studies have investigated infants' postural responses to changes in the frequency of visual stimuli [11–13]. However, the results were conflicting. While some studies showed that infants' postural entrainment increased as the frequency of the visual motion increased [11,12], one study reported a linear decline in sway coherence as a function of stimulus frequency [13]. Furthermore, the developmental changes in infants' visual–postural coupling were inconsistent between the studies [11,12]. These conflicting results may be due to differences in the postural measures as well as the range of sensory properties employed in the studies. Since children were shown to respond to a wider frequency range of visual stimuli compared to adults [5], a sufficient range of sensory properties is required to better characterize the sensorimotor relationships in infants' postural control.

In the present study, we sought to systematically examine the dynamic visual–postural relationship in infants as they develop postural control. Specifically, we examined infants' ability to adapt their sitting posture to different properties of the visual signal, i.e., frequency and amplitude. Incorporating a wide range of input frequency and amplitude, we addressed the following research questions: (1) does the adult patter (inverted-U) of visual–postural coupling exist in early infancy? (2) is sensory re-weighting a fundamental process of postural control present in young infants? Using a cross-sectional design, we also examined how the adaptive visual–postural relationship may differ by infants' advances and experience in postural development from sitting to standing and finally to walking.

2. Method

2.1. Participants

Twenty healthy infants (13 boys) composed four groups (each $n = 5$): (1) sitting onset (SO; aged 6.7 ± 1.1 months; 6.0 ± 5.1 days after sitting onset), (2) standing alone (ST; aged 10.6 ± 1.2 months; 28.8 ± 11.9 days before walking onset), (3) walking onset (WO; aged 11.7 ± 1.4 months; 8.8 ± 8.1 days after walking onset), and (4) 1-year post-walking (W12; aged 23.5 ± 1.2 months; 11.7 ± 1.0 months after walking onset). Sitting onset was when the infant could sit without support for 10 s. Standing alone was when the infant first able to stand without support for 5 s. Walking onset was when the infant started to walk independently for three continuous steps. Although no formal developmental assessment was done, the first author, a pediatric physical therapist, screened all infants to assure age-appropriate development. All experimental procedures were approved by the Institutional Review Board of the University. Parents gave written informed consent before participation.

2.2. Apparatus and measures

Fig. 1 illustrates the experimental set-up in which the infant sat on a customized chair that was fixed on a 45 cm high pedestal and placed 100 cm from the front wall. The chair had a small back support and a safety belt loosely across the infant's hip.

The visual stimulus was created in a Fakespace Systems CAVE Automatic Virtual Environment^{TM} that is a rear-projected 3-screen display (each 2.5 m × 3.0 m) with 1280 × 1024 pixels spatial resolution and 60 Hz framing rate. The visual display was specified by white triangles (0.2° × 0.3° × 0.2°) randomly projected on a black background, excluding the foveal region (15 cm diameter circle) on the front screen. To attract the infant's attention to the front screen, a cartoon video was projected onto the foveal region with auditory outputs behind the front screen.

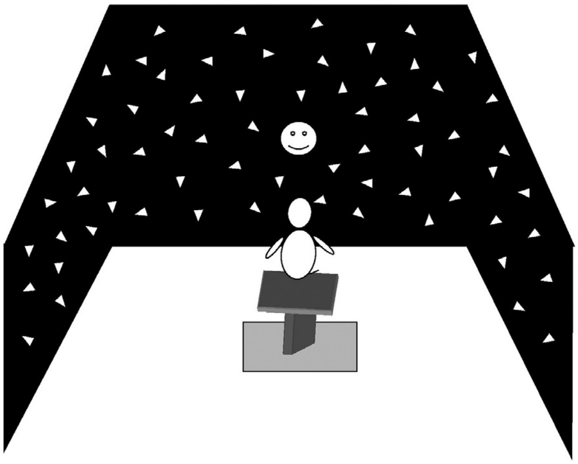

Fig. 1. An infant sits independently on a chair in a 3-wall room. The smiley face represents the location of the cartoon video.

Infants' postural sway was measured using an active infrared position tracking system (Optotrak, Northern Digital Inc.). Three small infrared LEDs were affixed to the infant's occipital prominence, upper and middle trunk. A bank of three cameras was positioned parallel to the front screen and 2 m behind the infant. In addition, the testing session was videotaped for later coding of the infant's sitting behavior.

2.3. Experimental design and procedures

The visual stimulus was created by anterior–posterior (AP) oscillations of the animated display using a sum-of-sines technique [14] that allowed us to examine infants' visual–postural coupling over a large range of frequency and amplitude variations without increasing the testing burden. The sum-of-sines consisted of a summation of 5 sinusoids at frequencies 0.12, 0.28, 0.52, 0.76, and 1.24 Hz with baseline amplitudes of 0.417, 0.179, 0.096, 0.065, and 0.040 cm, respectively. Five amplitude conditions were tested:

A0: The visual display was stationary.
A1: The visual display oscillated with the baseline amplitudes as described above. Peak-to-peak amplitude was 1.44 cm.
A2: The amplitudes were twice of those in A1 condition.
A4: The amplitudes were four times of those in A1 condition.
A12: The amplitudes were twelve times of those in A1 condition.

During the experiment, one experimenter and the parent stayed near the infant but not within his/her sight to provide help when needed. Data were collected in 3 randomized blocks, each with one 60-s trial for each amplitude condition.

2.4. Data reduction and analysis

Videos of all sitting trials were coded for usable time segments. In this study, the shortest period required to characterize all sum-of-sines components is 8.33 s (for the lowest frequency 0.12 Hz). For comparison with previous studies [15,16] and for coding convenience, we decided the minimal duration for sitting time segments as 10 s. The coding criterion was that the infant maintained quiet posture and continuous visual engagement to the front screen for at least 10 s. Only those time segments were used for subsequent data analysis. Mean segment time (MST) was computed across all segments of each infant in each amplitude condition to represent the infant's engagement in the sitting task.