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Variable coordination of eye and head movements during the early development of attention: A longitudinal study of infants aged 12–36 months

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ABSTRACT

This longitudinal study investigated the effects of attentional development on peripheral stimulus localization by analyzing the eye and head movements of toddlers as they matured from 12 to 36 months. On each trial of an experiment, a central fixation point and a 30° peripheral stimulus were presented, such that in the gap condition the fixation disappeared 300 ms before the peripheral stimulus, whereas in the no-overlap condition it disappeared simultaneously as the peripheral stimulus, and in the overlap condition the fixation remained present when the peripheral target occurred. Results showed that eye and head movement latencies were highly correlated in all conditions and ages. However, at 12 months, head movements were as fast as eye movements, whereas during the subsequent development, eye movements became increasingly faster than head movements. These findings are indicative of a transition between 12 and 36 months due either to a change in attentional control, or to changes in the size of the visual field in which only eye movements occur.

Gaze shifts can occur with or without head movement. In adults, head movements seldom occur in response to target stimuli located less than 20° of eccentricity (Bahill, Adler, & Stark, 1975; Tomlinson & Bahra, 1986). By contrast, gaze shifts to targets of larger eccentricities almost always involve head movement (Bartz, 1966; Fuller, 1992). In a typical adult pattern of combined eye and head movements, a gaze shift begins when the rapid eye movement changes the positions of the eyes relative to the head. Once gaze shift reaches its target, it is stabilized in space, in spite of continuing head motion. During movement of the head toward a target, the eyes make a compensatory movement in the opposite direction, which cancels the effect of head rotation thereby allowing the participant to maintain fixation of the target.

However, electromyographic records reveal that the orienting neural command issued to the head usually precedes that issued to the eyes (Bizzi, Kalil, & Tagliasco, 1971; Corneil, 2011). In other words, the overt onset sequence of eye and head movements does not reflect the order of neural commands. In the case of infants, the temporal order of these two movements has been documented as head movements first followed by eye movements (Tronick & Clanton, 1971). The contribution of head movement during gaze shifts emerges around two months and it gradually increases with age; saccadic eye movements show continued refinement with maturation into adolescence (Goodkin, 1980; Proudlock & Gottlob, 2007; Regal, Ashmead, & Salapatek, 1983; Roucoux, Culee, & Roucoux, 1983; Tronick & Clanton, 1971). Thus, the early pattern of temporal ordering of eye and head movements gradually shift from head first to eye first. The time course of decreasing contributions of

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head movements conforms to maturational changes in the frontal cortical region; hence it may be associated with complex cognitive functions (Proudlock & Gottlob, 2007).

Head and eye movements to visual targets as well as covert shifts of attention are controlled by an orienting neural network that involves the frontal eye fields, and areas of the inferior and superior parietal lobe (Corbetta & Shulman, 2002). However, a recent neurodevelopmental model (Posner, Rothbart, Sheese, & Voelker, 2012) proposes a developmental shift that occurs between 1.5 and 3–4 years of age in which dominant control shifts from the orienting network to the executive network. The executive attention network includes the anterior cingulate, left anterior insula and parts of the basal ganglia and prefrontal cortex. The executive network forms the basis for voluntary control in older children and adults.

Adult head and eye movements are closely correlated and both seem to be facilitated by cues that occur at the target location (Khan, Blohm, McPeek, & Lefèvre, 2009). However, unlike adults, infants frequently show head movements that precede eye movements, as well as a lack of coordination between the two (Regal et al., 1983; Richards & Hunter, 1997).

This study examined the transition from the orienting to the executive network by testing 12–36 month old infants. This age range represents an important transitional period for control by attention. However, very little is known about the development of eye and head movements of children in their second and third years (Murray, Lillakas, Weber, Moore, & Irving, 2007). In addition to assessing eye and head movements of toddlers, we also obtained metrics for assessing each toddler's control of executive attention using a parent-report questionnaire for assessing temperament. The higher-order factor of Effortful Control of this questionnaire was used to score a toddler's major form of self-regulation (Rothbart & Rueda, 2005). Effortful Control is defined as the ability to inhibit a dominant response to perform a subdominant response, to detect errors, and to engage in planning. In toddlers, the development of attentional orienting can be demonstrated by a marker task that measures an infant's ability to disengage attention from a particular spatial location (Johnson, Posner, & Rothbart, 1991). Accordingly, we examined the effect of attention on eye and head movements using the gap–overlap paradigm. This paradigm comprises three conditions. In the overlap condition, a central fixation point is not turned off when a peripheral target appears. Consequently this condition requires an active process of disengagement of attention from the initial fixation point, prior to a gaze shift toward a target. Arguably, this should entail a degree of higher-level control of attention by a toddler. By contrast, in the gap condition, a central fixation stimulus disappears after presentation, thereby allowing attention to automatically disengage, hence enabling saccadic eye movements to occur more rapidly. Suzuki and Hirai (1998) measuring reaction times indicted that the head and eye motor systems are controlled by separate neural mechanisms in the gap condition generating express saccades. We examined in infants, whether a decrease of saccade latency under the gap condition was more pronounced than that of head movement reaction time.

In the present study, we described longitudinal developmental changes in the ability of toddlers (over the 12–36 month age period) to localize eye and head movements in response to peripheral targets. Nakagawa and Sukigara (2007) have described the method for the quantitative analysis of infants' eye and head movements. In this method, eye and head movements are recorded using the corneal reflection method. We compared the onset latencies between eye and head for each trial. We also administered the Early Childhood Behavior Questionnaire (ECBQ; Sukigara, Nakagawa, & Mizuno, 2007) to assess the development of executive control network in our participants.

Two hypotheses were tested. The fist was that the attention control system changes between 12 and 36 months. Eye movements to targets remain under the control of the orienting system and improve in speed as that system matures. Head movements, however, begin as an automatic feature of orienting, but later become part of voluntary control exercised by the executive system due to maturation. The second and alternative hypothesis was that the size of the functional visual field increases with age. Thus, a 30° movements begin as combined head and eye movements, but with age, head movements become limited to targets further in the periphery and eye movements become more frequent for targets in the near periphery.

1. Methods

1.1. Participants

Toddlers ($N = 26$, mean age 12 months) were recruited through local maternity groups. All parents gave written informed consent before the experiments. The Ethics Committee of Nagoya City University (No. 7007) approved the study in accordance with the ethical standards of the 1964 Helsinki Declaration. Criteria for admission into the study were having no known birth defects or other complications, full term (more than 37 weeks gestation), and normal birth weight (2500–4000 g). One participant at 18 months, four at 24 months, and one at 36 months could not participate in the experiments for personal reasons.

1.2. Recording of eye and head movements

The toddler sat in an experimental chair 65 cm away from the color monitor of an AV tachistoscope (IS-702). The experimenter monitored the participant's eye and head movements from the outside through a low-angle CCD near-infrared video camera (ELMO CN43H) located in front of the toddler, and controlled the stimulus presentation through a microcomputer (FMV-S167). We recorded two types of data using two cameras and recorders. First, the stimuli presented