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Developmental trends in infant temporal processing speed

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ABSTRACT

Processing speed, which can be measured behaviorally in various sensory domains, has been shown to be a strong marker of central nervous system health and functioning in adults. Visual temporal processing speed (measured via critical flicker fusion [CFF] thresholds) represents the maximum speed at which the visual system can detect changes. Previous studies of infant CFF development have been limited and inconsistent. The present study sought to characterize the development of CFF thresholds in the first year of life using a larger sample than previous studies and a repeated measures design (in Experiment 2) to control for individual differences. Experiment 1 ($n = 44$ infants and $n = 24$ adults) used a cross-sectional design aimed at examining age-related changes that exist in CFF thresholds across infants during the first year of life. Adult data were collected to give context to infant CFF thresholds obtained under our specific stimulus conditions. Experiment 2 ($N = 28$) used a repeated-measures design to characterize the developmental trajectory of infant CFF thresholds between three and six months of age, based on the results of Experiment 1. Our results reveal a general increase in CFF from three to four and one-half months of age, with a high degree of variability within each age group. Infant CFF thresholds at 4.5 months of age were not significantly different from the adult average, though a regression analysis of the data from Experiment 2 predicted that infants would reach the adult average closer to 6 months of age. Developmental and clinical implications of these data are discussed.

1. Developmental trends in infant temporal processing speed

Visual temporal processing speed can be quantified by an individual's critical flicker fusion (CFF) threshold, which refers to the highest frequency of a square-wave function that the visual system can discriminate. Unlike other psychophysical thresholds, higher CFF thresholds are indicative of faster processing and therefore better functioning. CFF thresholds decline with age (Wooten, Renzi, Moore, & Hammond, 2010), correlate positively with cognitive functions (e.g., Mewborn, Renzi, Hammond, & Miller, 2015), and declining thresholds can even signal age-related pathology in adults (Curran & Wattis, 1998). For this reason, CFF has been used as a biomarker of central nervous system (CNS) functioning in studies ranging from pharmacology (Smith & Misiak, 1976) to monitoring clinical interventions (Achinivu, Staufenberg, Cull, Cavanna, & Ring, 2012; Balestra, Lafère, & Germonpré, 2012) to disease states as diverse as schizophrenia (Parsons et al., 2013) and liver cirrhosis (Gencdal et al., 2014). The common thread that ties together findings from such wide-ranging fields of study is the apparent difficulty in compensating for losses in temporal processing speed (as opposed to more static visual characteristics; Salthouse, 2011). If CFF does, in fact, represent a cognitive fundamental, it likely develops early and individual differences could be a powerful predictor of later development. These assessments also have the potential to be clinically useful in detecting processing speed deficits early in life, which may allow for early implementation of interventions to mitigate these deficits before they have a chance to significantly impact higher-level developmental processes. For these reasons it would be valuable to develop efficient methods for the measurement of CFF in infants.

Research investigating the developmental time course of CFF in infants has been limited and contradictory. Regal (1981) measured CFF thresholds behaviorally in one-, two-, and three-month-old infants using a forced-choice preferential-looking paradigm (FPL; Teller, 1979) and a projector beam with a rotating sectored disk to create various frequencies of flickering stimuli. Infants were centered in front of two stimuli (one flickering, one solid) while an experimenter who was naïve to the true location of the flickering stimulus monitored the infant's face. The percent of trials that the experimenter judged correctly at each flicker frequency was plotted to a psychometric curve,

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and the point at which the experimenter was able to judge at 75% or higher accuracy was taken to be the infant's CFF threshold. Using this method, Regal (1981) estimated that infant CFF thresholds reach adult levels by roughly three months of age. In a later study, Mercer and Adams (1989) investigated the impact of wavelength on infant CFF thresholds using a similar method to Regal (1981) and found that cone immaturity in the first few months of life leads to lower CFF thresholds for chromatic (vs. achromatic) stimuli. In addition, three-month-old infant CFF thresholds were significantly lower than adult values in their study, which likely reflects the immaturity of the color vision system at that age. Similarly, Hartmann and Banks (1992) used a FPL paradigm to estimate CFF thresholds from a temporal contrast sensitivity function (TCSF) and found 3 month olds infants' CFF thresholds to be far lower than those of the 3 month old infants in Regal's (1981) study. Rasengane, Allen, and Manny (1997) also contradicted the findings of Regal (1981); infants in their study exhibited CFF thresholds that were still immature at four months of age in relation to adults tested on the same device.

Disagreement within the literature about the developmental trajectory of CFF thresholds in early life may stem from differences in the psychophysical properties of the stimuli used, low sample sizes, and imprecision associated with the estimation of CFF thresholds from TCSFs that measure contrast sensitivity at a very limited number of temporal frequencies. First, CFF thresholds are strongly influenced by the amount of light that reaches the retina at low luminance levels; brighter stimuli yield higher CFF thresholds. This effect eventually plateaus as the luminance level of the stimulus increases (characterized by the Ferry-Porter Law), but can be a major source of variability between studies that utilize dim stimuli. In addition, CFF thresholds increase with stimulus size (characterized by the Granit-Harper Law). There has been significant variability in stimuli luminance and size across studies, as well as how the stimuli were presented (e.g., CRT monitor in Rasengane et al., 1997 vs. a projector beam with rotating sectored disc in Regal, 1981). In addition, when adults were tested to determine when CFF thresholds (or TCSFs) reach or approach maturity, the number of adults tested has been very small (e.g., $n = 4$ in Regal, 1981; $n = 3$ in Hartmann & Banks, 1992; $n = 3$ in Rasengane et al., 1997). Given that adult CFF threhsolds vary widely (e.g., range of 8.3–30 Hz in Renzi & Hammond, 2010), a sample of three or four adults is insufficient to determine "adult-like" performance for a particular set of testing conditions. Further, in cross-sectional studies, the number of infants tested at each age were sometimes as low as five or six, yielding overall sample sizes as low as 12 or 15 infants (Regal, 1981; Hartmann & Banks, 1992, respectively). Finally, in both Hartmann and Banks (1992) and Rasengane et al. (1997), CFF was extrapolated from a temporal contrast sensitivity function (with only 3–6 points) instead of being measured directly, which limits the precision of their findings.

The present study sought to characterize the development of CFF thresholds in the first year of life using a larger sample and a repeated measures design (in Experiment 2) to control for individual differences. Experiment 1 used a cross-sectional design aimed at examining age-related changes that exist in CFF thresholds during the first year of life using our specific set of stimulus characteristics. Experiment 2 replicated Experiment 1 using a longitudinal design to gather more detailed information about how infant CFF thresholds develop between three and six months of age. Because of the positive relation between CFF and age that has been found in previous infant CFF literature and the fact that other aspects of visual development improve with age in infancy (e.g., acuity; Fantz, Ordy, & Udelf, 1962; Teller, Morse, Borton, & Regal, 1974), it was hypothesized that CFF would be positively correlated with infant age in both experiments.

2. General method

2.1. CFF assessment

2.1.1. Overview

Critical flicker fusion (CFF) thresholds were measured in infants using the classic two-alternative forced choice preferential looking (FPL) technique, wherein an observer who is naïve to the side on which the stimulus is being presented makes a judgment as to the location of the stimulus based on the infant's behavioral cues (Teller, 1979). Participants sat with their parent in the testing room for three minutes before testing began so that their eyes could adjust to the dimmer lighting of the room (1.51 cd/m^2, measured at infant eye-level with a SpectraScan PR-650 spectroradiometer, Photo Research, Inc., Chatsworth, CA, USA). During this time, adult participants and parents of infants completed the consent forms, received information regarding the task procedure, and were aligned with the stimulus (stimulus at eye-level, 60 cm away from participant's eyes). Infants sat in their parent's lap, and parents were instructed to look down at their baby's head so that they would not look at the stimuli (all parents complied with this request). Once testing was complete, demographic questionnaires were completed.

2.1.2. Apparatus

Infant CFF thresholds were measured using a custom-built device (see Fig. 1). The light source for this device was two clusters of cool-white LEDs (Cree™C503C, Cree Inc., Durham, NC, USA). The intensity of these LEDs was electronically controlled using high frequency (~3.9 kHz) pulse-width modulation and the light was rear projected onto two custom acrylic diffusers (resulting in the presentation of two stimuli that were each 8° in size, separated by 22° at 60 cm). The luminance of the two stimuli was held constant (153 cd/m^2), but two size-matched insets were used to vary the shape of the stimuli (stars or hearts) across trials, as needed. Each infant experimental session began with the pair of star insets in the device, which were switched to the heart insets if necessary to maintain infant interest in the task. The flickering stimuli were presented at 100% depth of modulation (stimulus completely on then completely off) for various frequencies. The entire optical apparatus was light baffled and a high-resolution video camcorder was mounted directly above the central fixation point to provide a video feed that a trained observer could view from a separate area of the testing room.

2.1.3. Infant CFF threshold assessment

A two-alternative forced choice preferential looking (FPL) technique was used to estimate infant CFF thresholds (Teller, 1979). One of the authors (JF), who is an experienced infant behavioral coder, was the primary observer for this study (JF observed 84% and 87% of the babies that were included in analyses in Experiments 1 and 2, respectively). If the primary observer was not available, one of three backup observers was utilized. All backup observers used for this study obtained a Cohen's Kappa coefficient of 0.8 or higher (signifying "almost perfect agreement"; Landis & Koch, 1977) with the primary observer, as well as with one another, when tested for reliability using videotaped footage of three infants who had previously participated in the task. After positioning the infant in the parent's lap, two easily visible trials (20 Hz on one side and then the other) were performed to help the observer become familiar with each infant's demeanor during the task. Once these initial trials were completed and the observer felt comfortable proceeding, threshold estimation trials began at 40 Hz. On each trial, the observer – naïve to both the frequency being tested and the side of the flickering stimulus – estimated