Development of Multimodal Attention in Young Infants: Modification of the Startle Reflex by Attention

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Running head: Auditory-visual foregrounds and reflex blinks

ABSTRACT

This study examined the effect of attention engagement to compound auditory-visual stimuli on the modification of the startle blink reflex in infants. Infants at 8, 14, 20, or 26 weeks of age were presented with interesting audio-visual stimuli. After stimulus onset, at delays defined by heart rate changes known to be associated with sustained attention or attention disengagement, blink reflexes were elicited by visual or auditory stimuli. Blink amplitude to either visual or auditory stimuli was enhanced when the infants were engaged in attention to the foreground auditory-visual stimuli relative to control trials with no foreground patterns. This enhancement of the blink amplitude increased from 8 to 26 weeks of age. In distinction to selective modality enhancement for single modality foreground stimuli, these results show that multimodal stimuli engage both visual and auditory attention systems in this age range.

Descriptors: Infants, attention, heart rate, blink reflex, multimodal stimuli

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INTRODUCTION

Directing attention to one modality affects the blink reflex to stimuli in that modality and other modalities. Several studies have shown that the blink reflex to a stimulus is enhanced when there is a match between the modality of the blink stimulus and the modality of the foreground stimulus to which attention is directed (Anthony & Graham, 1983, 1985; Balaban, Anthony & Graham, 1989; Hackley & Graham, 1983; Haerich, 1994; Richards, 1998). Alternatively, when the modality of the blink stimulus and the modality of the foreground stimulus to which attention is directed are different, the blink reflex may be attenuated or may be the same as when attention is not engaged. This attentional modulation of the blink reflex shows that attention may be selective towards specific modalities and implies that there may be modality-specific attention systems in the brain. This study shows that attention to "multi-modal" auditory-visual foreground stimuli may engage both visual and auditory attention systems in the young infant and that blink reflexes to auditory and visual stimuli are affected by attention.

The modality-selective effect of attention on the blink reflex implies that the visual and auditory attention systems are "selective" and is consistent with the existence of separate attention systems in the brain for these modalities. Attention systems in the brain have been hypothesized to include a system of general arousal / alertness as well as specific sensory attentional systems (Heilman, Watson, Valenstein, & Goldberg, 1987; Mesulam, 1983; Posner, 1995; Robbins & Everitt, 1995). Prima facie evidence for separate visual and auditory systems comes from their different pathways and attention-effects at different cortical levels. The visual system pathways, from the retina through the lateral geniculate nucleus to the visual cortical areas in the occipital cortex (areas 17, 18, 19), show enhanced effects of attention in areas 18 and 19 (Desimone & Duncan, 1995). The auditory system pathways, from the auditory nerves through the cochlear nerve to the inferior colliculus to the auditory cortical areas in the temporal cortex (41, 42, and 22), show attention enhancement effects in area 22. The existence of these separate pathways suggests that the brain may support separate attention systems for the auditory sensory modality and the visual sensory modality. The modality-selective effect of attention on the blink reflex is consistent with a model that the foreground stimulus engages the appropriate cortical attention system and that this system enhances complementary cortical and subcortical systems, resulting in a facilitation of the subcortically-mediated blink reflex in the same modality. Alternatively, attention may act to inhibit competing responses, such as sensor redirection (Richards, 1987, 1997) or blink reflexes in unattended modalities (Anthony, 1991; Richards, 1998).

The modality-selective effect of attention on the reflex blink has been shown in young infants (Anthony & Graham, 1983; Balaban et al., 1989; Richards, 1998). For example, Anthony and Graham (1983) presented “interesting” or “dull”, visual or auditory stimuli to 16-week-old infants. They found that blink reflexes were enhanced in magnitude when attention was the greatest (interesting vs. dull stimuli) and when the blink probe and the foreground stimulus were in the same modality (match vs. mismatch). A study by Richards (1998) extended the Anthony and Graham (1983) results to younger and older ages (8 to 26 weeks). Richards (1998) found that blink reflexes, and the selective modality effect, were the greatest during periods when the heart rate responses to the foreground stimuli were decelerated (attention engagement) than when the heart rate level had returned to its prestimulus level to the same foreground stimuli (attention was disengaged). The selective modality effects, and the enhancement of blink reflexes during attention, also increased over the age range from 8 to 26 weeks (testing ages of 8, 14, 20, and 26 weeks). These results imply that the selective attention effects found in young infants show a developmental change in the early part of infancy. This developmental change found in selective attention parallels the increase in attention to visual and auditory stimuli over the age range from 2 to 6 months found in other paradigms (Berg & Richards, 1997; Richards, 1987, 1997; Richards & Hunter, 1998).

In contrast to unimodal stimuli, and separable sensory systems, there is evidence that multimodal or non-specific attentional systems may exist. For example, in the brain there are specific pathways and functions that control general arousal and alertness (Heilman et al., 1987; Mesulam, 1983; Posner, 1995; Robbins & Everitt, 1995). For example, the mesencephalic reticular formation via its noradrenergic projections has widespread influence on the thalamus and cortex and is thought to represent a general arousal system that invigorates a number of specific attentional systems (Heilman et al., 1987; Robbins & Everitt, 1995). These general systems may act to invigorate specific sensory systems, or may invigorate multiple sensory systems simultaneously. There also are multimodal centers in the brain. These include the superior colliculus at the subcortical level, which responds to a number of multimodal combinations of auditory, visual, and somatosensory information (Stein & Meredith, 1993; Stein, Meredith, & Wallace, 1994). There also are polysensory areas in the cortex, including the parietal cortex which integrates information from auditory, visual, and somatosensory cortical areas and which is heavily involved in attention (Posner, 1995). It is possible that attention per se operates in an amodal fashion, affecting individual sensory systems when those systems are engaged in stimulus processing. The modality-selective effects of attention may be the interaction between amodal attention engagement and the testing conditions using unimodal stimuli. This study examined the effects of compound auditory-visual stimuli as foreground stimuli on blink reflexes to auditory or visual blink stimuli.

Many of the stimuli the infant faces in its everyday world are multimodal, and a substantial number of studies of perceptual development have investigated infants' responses to multimodal stimulation (e.g., Lewkowicz & Lickliter, 1994). One question posed by this research has been if infants responded more to one stimulus modality over another when presented with multimodal stimuli.Lewkowicz (1988a, 1988b) presented infants with a simultaneously presented flashing checkerboard and a pulsing tone and then tested for responsiveness to changes in either the auditory, visual, or both stimuli. The 6-month-old infants responded only to the auditory and combined changes, whereas the 10-month-old infants responded to all three types of changes. These findings were interpreted as suggesting that the auditory modality dominated the attention of young infants who were presented with concurrent, auditory-visual information. Subsequent studies have shown, however, that intersensory dominance relationships are dependent on the specific nature of the information presented. Thus, when infants were habituated to a bouncing/sounding object, they responded to changes in the auditory, visual, and combined auditory-visual changes at 4, 6, and 8 months of age (Lewkowicz, 1992), and even as young as 2 months of age (Lewkowicz, 1994). Moreover, response to the visual changes was greater than to the auditory changes. This finding suggests that when the visual information is spatially dynamic, the visual information and the auditory information of the multimodal stimuli were encoded and processing of information occurred in both modalities.

The research on the effects of attention on the blink reflex only has examined blink reflexes in the presence of unimodal foreground stimuli. Given that infants' responsiveness to bimodal stimuli is greater than to unimodal stimuli, one of the goals of this study was to examine the developmental changes in blink reflex modulation during attention to compound auditory-visual stimuli. In this study infants were tested at 8, 14, 20, and 26 weeks of age. This age range was chosen to match that used by Richards (1998), and because across this age range there is an increase in attention to visual and auditory stimuli (Berg & Richards, 1997; Richards, 1987, 1997; Richards & Hunter, 1998). This is particularly true of the development of sustained heart rate responses during visual attention, reflecting an increase in sustained attention. In this study attention was elicited by presenting the participants with stimuli that consisted of combined audio and visual components. These components have been shown to elicit large heart rate changes in infants in this age range, presented separately (Richards, 1998) or in combination (Richards & Gibson, 1997). In young infants, these heart rate changes have been used to distinguish attention phases labeled stimulus orienting, sustained attention, and attention termination (Berg & Richards, 1997; Graham, 1979; Graham, Anthony, & Zeigler, 1983; Richards & Casey, 1992; Richards & Hunter, 1998). Heart rate changes also have been used with unimodal foreground stimuli in young infants and resulted in blink reflex modification in infants (Anthony & Graham, 1983; Richards, 1998). The effects in infant participants were similar to those found with experimental manipulations of attention used in adults (Hackley & Graham, 1983; Haerich, 1994). In this study the blink reflex was elicited with stimuli known to elicit a startle blink reflex in infants. It was expected that the blink reflex would be enhanced during attention to the auditory-visual stimuli, and would be attenuated (or not be enhanced) when the infant was not engaged in attention.

The second goal of the study was to determine if there was a different modulation of the blink reflex for the auditory and visual blink stimuli, and if this differential modulation changed over these testing ages. When a young infant’s attention is engaged with a unimodal stimulus, there is a selective enhancement/attenuation of the blink reflex depending on the match between the blink stimulus and the foreground attention-eliciting stimulus (Anthony & Graham, 1983; Richards, 1998). If a compound auditory-visual stimulus elicits attention in both the visual and the auditory system, then there should be enhancement of reflex blinks from either visual or auditory blink stimuli. If only one or the other of the attention systems is engaged, then there should be differential enhancement/attenuation of reflex blinks elicited by the visual or auditory blink stimuli. The available research evidence does not suggest which of the possible outcomes for this study would occur, so specific predictions or expectations were not made for this goal.

METHOD

Participants

Participants were recruited from birth notices published in a Columbia, South Carolina newspaper. The infants were full term, defined as having birthweight greater than 2500 grams and gestational age of 38 weeks or greater based on the mother's report of her last menstrual cycle. The participants were tested at 8 (M = 58.0 days, S.D. = 4.09, N = 22, 10/12 female/male), 14 (M = 99.8 days, S.D. = 4.04, N = 21, 11/10 female/male), 20 (M = 142.7 days, S.D. = 4.06, N = 20, 11/9 female/male), or 26 (M = 184.0 days, S.D. = 4.38, N = 21, 9/12 female/male), weeks of age. The infants were assigned either to an auditory blink stimulus or visual blink stimulus condition (between-subjects conditions). There were at least 10 infants in each condition at each age. An additional twenty-eight children were tested but were eliminated from the study because they did not have at least two identifiable blinks in the blink reflex control condition or did not have at least one blink in each testing condition (N = 13) or did not complete the testing session due to fussiness or crying (N = 15).

Apparatus

The child was held on the parent's lap approximately 55 cm from a 49 cm (19 in) TV monitor. The TV subtended 44^{o} visual angle. Two Radio Shack “Realistic” audio speakers were placed above the TV for the audio portion of the foreground. A neutral color material covered the surrounding area. A video camera was above the TV, and in an adjacent room an observer judged the participant's fixations on a TV monitor. The session was recorded on videotape with a time code in order to synchronize fixation changes with heart rate and stimulus information for analysis.

The foreground stimuli were visual patterns shown on the TV accompanied by sounds. The stimuli were computer-generated auditory-visual stimuli, interspersed with segments selected from a Sesame Street movie (see Richards & Gibson, 1997; Richards & Cronise, in press). The computer-generated stimuli consisted of 16 visual patterns accompanied by 12 auditory stimulus patterns, randomly paired together for each presentation. The computer-generated visual patterns were dynamic (e.g., a series of concentric squares of varying size, a flashing checkerboard pattern, a small box shape moving across a diamond) and changed at approximately 4 Hz (foreground visual patterns in Richards, 1998). The computer-generated auditory patterns consisted of changing patterns of sound (e.g., a pulsed 1200 Hz tone, a pulsed 1400 Hz tone, a pulsed tone alternating 1200 Hz / 1400 Hz, a sliding frequency from 0 to 1200 Hz or from 400 to 1600 Hz, random frequencies across the range of 0 to 1600 Hz; foreground audio patterns in Richards, 1998). The audio stimuli were generated by Coulbourn Precision Signal Generator (S81-06) and Voltage Controlled Oscillator (S24-05) modules and were presented on two Radio Shack Realistic audio speakers located above the TV and amplified by two channels of a Yamaha Power Amplifier (MX-35, 4 channels in pairs of 2) , and were approximately 60 dB (A-scale) at the infants' ears. The dynamic changes in the audio and visual patterns were synchronized and occurred at approximately 4 Hz. The segments from the Sesame Street movie consisted of 12 scenes that contained two or more characters, and the scene continued without perspective shifts for at least 25 seconds. Two computer-generated stimuli and one Sesame Street segment were presented randomly in three-trial blocks. The auditory-visual patterns are known to elicit heart rate decelerations, typically result in first look durations of greater than 10 s, and are easily discriminable by each of the four age groups (Richards & Gibson, 1997).

The blink stimuli were either auditory or visual (between-subjects condition). The auditory blink stimulus was noise bursts that were presented binaurally on Radio Shack "Realistic" speakers that were placed at the edges of the TV. The noise bursts were presented at 100 dB (A-scale) at the infant's ear, with 5 ms rise/fall times, and 50 ms at the maximum level. The audio blink stimulus was generated by a Colbourn White Noise Generator (S81-02), shaped with a Colbourn (S84-04) rise/fall gate, and amplified by a Yamaha Power Amplifier (MX-35). The visual blink stimulus was produced by two

Vivitar photo flash units (Model 2800) that were placed in the same location as the speakers used for the auditory blink stimulus. They were approximately 60 cm from either side of the infant, and at approximately 22^o in the periphery.

Measurement and Quantification of Heart Rate Changes

The ECG was recorded with Ag-AgCl electrodes on the infant's chest and was digitized at 1000 Hz (each ms) with a microcomputer. An online computer algorithm identified the QRS complex in the ECG and inter-beat interval (IBI) was defined as the duration between successive R-waves in the ECG. This evaluation was made within 30-60 ms following the R-wave occurrence. This online evaluation was used to define two of the delay conditions. The “heart rate deceleration” condition was defined as 5 successive beats occurring with IBIs each longer than the median of the 5 prestimulus beats. The “return of heart rate to prestimulus level” was defined as occurring after a heart rate deceleration, and when 5 successive beats occurred each with IBIs shorter than the median of the 5 prestimulus beats (see Richards, 1997, 1998).

For offline analyses, IBIs were corrected for artifacts using the Cheung (1981) and Berntson, Quigley, Jang, & Boysen (1990) algorithms along with visual inspection of the ECG of suspect beats. The IBI was assigned to 0.5-s intervals by averaging the IBIs in each interval weighted by the proportion of the interval occupied by that beat. The inter-beat interval is the reciprocal of heart rate, so that lengthening of the IBI corresponds to heart rate deceleration and shortening of IBI corresponds to heart rate acceleration, or the return of heart rate to its prestimulus level. The IBI rather than heart rate was used in the analysis of the heart function changes since the IBI has characteristics suggesting it is more linearly related to neural control mechanisms (Berntson, Cacioppo, & Quigley, 1995).

Measurement and Quantification of Reflex Blinks

The electromyogram (EMG) of the obicularis oculi muscle was measured by placing two miniature (SensoriMedic, 3 mm contact, 11 mm collar) Ag/AgCl electrodes just below the lower right eyelid (11 mm center-to-center). The electrodes were affixed with adhesive collars, and SignaCreme electrode cream was used to complete the electrical contact. The EMG signal was amplified (20k), filtered (bandpass 10 Hz to 300 Hz) and digitized at 1 kHz.

The digitized values were used to quantify the reflex blinks. The digitized values were first converted to μV values, and then the root-mean-squared (rms) μV EMG was calculated on an ms basis. The EMG from each trial was displayed, and blinks were scored on each trial for latency to blink onset and latency and amplitude of maximum rms μV EMG for the blink (see Haerich, 1994). Blinks were included only if the onset of the EMG activity began within 350 ms of the blink stimulus onset. Trials without identifiable blinks were not included in the analyses. Each participant had identifiable blinks in two of the blink reflex control trials and at least 1 identifiable blink in a trial for each of the 4 delay conditions. In addition to the raw rms μV EMG values, a proportion change score was analyzed. The proportion change score was the score found in the experimental trials (foreground + blink stimulus) divided by the average blink amplitude from the no-foreground blink reflex control, separately for each participant. The latter dependent variable (proportion change) standardizes the blink amplitude between groups since a difference might occur in the blink amplitude for the visual and auditory modality stimuli.

Procedure

The parent sat in a chair in the viewing area with the infant on the parent's lap facing the TV monitor. There were four trials consisting of the alternating presentation of the foreground stimulus alone or the presentation of the blink stimulus alone (2 trials each). These trials were administered in order to familiarize the infant with the stimuli and testing situation, and the two blink stimulus trials were used as “blink reflex control” trials. These four trials were followed by the experimental trials. The experimental trials consisted of the presentation of an auditory-visual foreground stimulus followed by a delay, the presentation of the blink stimulus, and a minimum 5-s intertrial interval. One of four delays was used on each trial: a 2-s delay, a heart rate deceleration + 2-s delay, a delay until heart rate returned to its prestimulus level following a heart rate deceleration, and a delay of 5-s after heart rate returned to its prestimulus level. These conditions represent “stimulus orienting” (2-s), “sustained attention” engagement (heart rate deceleration + 2-s) and “attention termination” (return of heart rate to prestimulus level following sustained attention; see Richards, 1987, 1997, 1998). For some analyses, the return of heart rate + 5-s delay condition was separated into those trials in which the heart rate was still at or above prestimulus level and trials in which the heart rate had decelerated again. A second deceleration of heart rate indicated that attention was re-engaged, whereas if the heart rate was still near prestimulus level attention was still unengaged. In addition, during the experimental trials, trials in which the foreground stimulus was presented alone, or in which the blink stimulus was presented alone (blink reflex control), were interspersed with the experimental trials. These six trial types (four delay conditions, blink reflex control, foreground stimulus alone) were presented randomly without replacement in 6-trial blocks. Each participant received at least two 6-trial blocks and as many as three 6-trial blocks. The duration of the trials differed due to the delay condition. The 2-s trial was 2 s in duration. The average durations of the heart-rate-defined trials were 5.15 s, 10.44 s, and 16.36 s for the heart rate deceleration + 2 s, heart rate return to prestimulus level, heart rate return to prestimulus level + 5-s trials, respectively.

Experimental Design for Data Analysis

The results were analyzed with factorial designs. Testing age (4; 8, 14, 20, 26 weeks) and blink stimulus modality (2; auditory, visual) were between-subjects factors. The delay factor was a within-subjects factor in the design. For the raw rms μV EMG dependent variable, there were five levels of this delay factor: blink reflex control, 2-s, heart rate deceleration + 2 s, heart rate return to prestimulus level, heart rate return to prestimulus level + 5-s. For the proportion change score (experimental trial amplitude divided by amplitude on the blink reflex control trials) the delay factor only used the four experimental trials since the data were standardized on the blink reflex control trial. For the blink amplitude effects the mean values on the heart rate return to prestimulus level + 5-s trials were split into those trials where the heart rate had slowed down again indicating attention was reengaged, and those trials in which the heart rate remained at or above prestimulus level indicating attention was still unengaged. The interbeat intervals changes also included a within-subjects “beats” factor representing five beats before blink stimulus onset, the beat occurring at blink stimulus onset, and five beats following blink stimulus onset. The beats effects were adjusted by the Huynh-Feldt correction (Huynh & Feldt, 1970) for lack of homogeneity in the covariance matrices for repeated measures (Huynh & Feldt, 1970; Jennings & Wood, 1976; Keselman, 1998; Keselman & Keselman, 1988).

The ANOVAs for the analyses were done with a general linear models approach using non-orthogonal design because of the unequal distribution of trials across subjects and delay conditions. The sums of squares (hypothesis and error) for the nested effects in the design were estimated using "subjects" as a class and nesting repeated measures (e.g., delay condition) within this class variable. The "PROC GLM" of SAS was used for the computations.

RESULTS

Interbeat Interval Changes

The interbeat interval (IBI) changes were analyzed to determine if the experimental manipulations based on heart rate had their desired effect and to determine if the blink stimulus affected IBI changes. Five beats before the presentation of the blink stimulus, the beat at which the blink stimulus occurred, and five beats after the blink stimulus were analyzed as the difference in IBI and the mean IBI of the five prestimulus beats. This change score was analyzed with an age (4) X blink stimulus modality (2) X delay (5) X stimulus presence (present, control) X beats (11) ANOVA[1]. For this analysis, epochs were selected in which the delay criteria was reached but a blink stimulus was not presented in order to compare IBI changes to the blink stimuli with IBI changes that occurred due to the delay manipulations. Only the effects that interacted with the "beats" factor were examined.

There was the expected interaction between delay and beats, F (40, 3040, ε = .367) = 91.02, $p < .001$. This effect was due to the definition of the experimental manipulations (e.g., heart rate deceleration + 2 s; return of heart rate to prestimulus level). There were interactions between beats and stimulus presence, F (10, 760, ε = .467) = 2.30, $p = .058$, and a three-way interaction between beats, delay, and stimulus presence, F (90, 6350, ε = .440) = 49.79, $p < .001$. These effects are illustrated in Figure 1. The "All Conditions" figure shows the IBI changes for the trials on which the blink stimulus occurred and the epochs with no blink stimulus. There was an increase in IBI length of about 4 ms on the beat following the blink stimulus, compared to an increase in that beat of about 1 ms on the control epochs. The three-way interaction reflected a difference in the extent of the IBI change for the delay conditions. It can be seen in Figure 1 that for most of the delay conditions there was a significant increase of about 3 to 5 ms in the beat following the blink stimulus compared to the control epochs. Post hoc tests showed that the beats X stimulus presence interaction was significant for each delay condition (p's < .05) except the two second condition ($p = .098$). There were no significant interactions that included age or blink stimulus modality for the IBI changes[2].

Blink Latency

The latency to the onset of the blink, and the time from the onset to the peak of the blink, were analyzed. These latencies were analyzed with an age (4) X blink stimulus modality (2) X delay (5) ANOVA. Because of the possiblity that these latency scores were not normally distributed, the natural logarithms of the times were analyzed. There was a significant effect of blink stimulus modality on the blink onset latency, F (1, 76) =

50.52 p < .0001, and peak latency, F (1, 76) = 15.72, p = .0002. The onset and peak latencies were shorter for the auditory blink stimulus (M's = 114.0 and 48.0 ms, for onset and peak, respectively) than for the visual blink stimulus (M's = 163.9 and 65.1 ms). There were no significant effects on the onset-to-peak latency involving testing age. There were no effects of delay condition on either the onset or peak latencies.

There was a significant interaction of age and blink stimulus modality on the latency to the onset of the blink, F (3, 76) = 3.57, p = .0178. Post hoc Scheffe' tests showed that there was no age effect for the blink onset latency to the auditory blink stimulus and that there was a significant effect of age on the blink onset latency to the visual blink stimulus (p < .05). There was a decrease in the onset latency to the visual blink stimulus over the first three testing ages (M's = 201.3, 165.2, 135.1 ms for the 8, 14, 20 week olds), and the onset latency for the 26-week-old infants was not significantly different from the 20-week-old infants (M = 147.1 ms for the 26 week olds).

Blink Amplitude

Blink amplitude was analyzed as the peak of the rms μV value during the blink. The blink amplitude from the blink reflex control trials was first examined with an age (4) X blink stimulus modality (2) ANOVA. There was a significant effect of blink stimulus modality on blink amplitude, F (1, 75) = 7.06, p = .0096. The blinks to the visual blink stimulus were smaller than those to the auditory blink stimulus (M's = 22.74 rms μV and 37.0 rms μV, respectively). The amplitude of the blinks on the blink reflex control trials did not change significantly over the four testing ages. A "trials" factor also was tested, comparing the two pre-experimental blink reflex control trials and the blink reflex control trials interspersed in the experimental trials. Blink amplitude did not differ significantly between the pre-experimental and experimental trials, nor did it show habituation within the experimental trials.

Blink reflex amplitude for the experimental and control trials was analyzed. The peak of the rms μV value during the blink was examined with an age (4) X blink stimulus modality (2) X delay (5) ANOVA. There were significant main effects of blink stimulus modality, F (1, 76) = 7.63, p = .0072, and delay condition, F (4, 257) = 5.80, p = .0002. The effect of blink stimulus was similar to that found on the blink reflex control trials, where the auditory blink stimulus elicited larger amplitude blinks than did the visual blink stimulus. The delay condition effect is illustrated in Figure 2. This figure shows an effect of attention engagement on the blink amplitude. The blink amplitude on the trials representing the return of heart rate to prestimulus level + 5-s were split into those in which the heart rate responses was re-engaged and those in which the heart rate response remained at or above the prestimulus level. The blinks were enhanced in the delay conditions representing attention engagement (2-s, heart rate deceleration + 2-s, and return of heart rate to prestimulus level + 5-s when re-engaged). The delay conditions representing attention unengaged (return of heart rate to prestimulus level, return of heart rate to prestimulus level + 5-s when unengaged) did not show the facilitation of the reflex blink. Post hoc tests showed that blink amplitude in the three conditions representing attention engagement were not significantly different (p = .2265). The blink amplitude in the two delay conditions representing inattention and the blink reflex control trials were not significantly different (p = .1101). The blink amplitude in the three attention conditions was significantly larger than the conditions in which attention was unengaged (p < .05).

There was a significant interaction of age and delay condition on blink amplitude, F (12, 257) = 1.81, p = .0468. This effect is illustrated in Figure 3 which shows the peak rms μV amplitude, separately for the four testing ages, and combined across trials in which attention was engaged (2-s, heart rate deceleration + 2-s, and return of heart rate to prestimulus level + 5-s when re-engaged) and unengaged (return of heart rate to prestimulus level, return of heart rate to prestimulus level + 5-s when unengaged). The blink reflex amplitude for the four ages in the attention-engaged delay conditions was significantly different (p = .0002). There was an increase over the four testing ages in the enhancement of the blink reflex in the attention-engaged delay conditions. The difference in blink amplitude between the blink reflex control condition and the attention-engaged conditions was 1.77, 3.89, 10.25, and 11.14 rms μV for the 8, 14, 20, and 26 week old infants, respectively (Figure 3). The blink reflex amplitude for the four ages in the attention-unengaged delay conditions only showed a marginal statistically significant effect (p =.0862). The difference between the attention-unengaged and blink reflex control trials showed a smaller increase over age from 1.93 to 4.71 rms μV over the four testing ages. The blink amplitude in the blink reflex control condition did not change significantly with age ($F < 1.0$). It also can be seen in Figure 3 that the difference in blink amplitude between the atttention-engaged and attention-unengaged trials increased over ages, and was the largest in the 26-week-old infants.

There were no interactions that were significant that involved the modality of blink stimulus. The lack of a significant age by blink stimulus modality by delay interaction indicates that attention to the auditory-visual foreground had the same facilitatory effect on the blink amplitude to the auditory blink stimulus as it did to the visual blink stimulus. However, the data for the visual blink stimulus and the auditory stimulus were examined separately to determine if there were different age or attention effects on the two blink modalities. The blink reflex amplitude in response to the auditory blink stimulus was affected by the delay condition, F (4, 125) = 3.30, p = .0132, and the interaction between age and delay, F (12, 125) = 1.93, p = .0371. The blink reflex amplitude in response to the visual blink stimulus was affected by the delay condition, F (4, 132) = 2.78, p = .0296, but the age and delay interaction was not significant (p = 0.5872). Figure 4 illustrates the interaction between testing age and delay condition separately for the visual and auditory blink stimuli. There was an increase over age in the blink reflex to the auditory probe that only occurred on the trials on which attention was engaged. There was a significant and steady increase over age in the level of the blink reflex to the visual blink probe when attention was engaged or unengaged. This effect was larger for the trials on which attention was engaged, but the lack of a significant age by delay effect indicates this difference was not statistically significant. For the attention-engaged trials, there was a slightly larger blink reflex to the auditory blink stimulus than to the visual blink reflex, though the omnibus interaction testing such an effect was not statistically significant.

Since there were differences in the amplitude of the blink reflex to the auditory and visual stimuli on the blink reflex control trials, the proportion change from the blink reflex control trials to the experimental trials also was analyzed. This proportion score standardizes the scores across the two modalities for participants who were presented with the auditory blink stimulus and those presented with the visual blink stimulus. This proportion score was analyzed with an age (4) X blink stimulus modality (2) X delay (4; only experimental trials) ANOVA. The blink stimulus modality factor did not significantly affect the proportion score ($p = .4574$) indicating the proportion score equated the auditory and visual blink amplitudes. The interaction between age and delay condition approached statistical significance, F (9, 180) = 3.47, $p = .0591$. Similar to the raw rms μV amplitude, there was a significant increase over the four testing ages in this proportion score in the attention-engaged delay conditions (2-s, heart rate deceleration + 2-s, and return of heart rate to prestimulus level + 5-s when re-engaged; $p < .05$). The value of this score was 1.01, 1.24, 1.24, and 1.36 for the 8, 14, 20, and 26 week old infants, respectively. This indicates that during the attention-engaged trials the response of the 8-week-old infants was similar to the blink reflex control trials, whereas the oldest aged infants the blink reflex amplitude was 1.36 times larger during the attention-engaged trials than during the blink reflex control trials. The proportion score did not increase significantly over the four testing ages in the attention-unengaged conditions (return of heart rate to prestimulus level, return of heart rate to prestimulus level + 5-s when unengaged). The value of this score was 1.07, 1.15, 1.13, and 1.17 for the 8, 14, 20, and 26 week old infants, respectively. This pattern of change over testing age in the attention-engaged and attention-unengaged conditions parallels the findings with the raw EMG score (Figure 3). There were no interactions that were significant that involved the modality of blink stimulus.

DISCUSSION

This study showed that the blink reflex of young infants to auditory and visual stimuli was modulated by attention to foreground auditory-visual stimuli. Relative to control trials with no foreground stimulus, there was an enhancement of the blink reflex when the infants' heart rate changes showed that attention was directed toward the foreground auditory-visual stimulus. If the heart rate changes indicated that the infant was viewing but inattentive, there was a smaller enhancement of the blink reflex than when attention was engaged. The enhancement of the blink reflex during attention to the multimodal stimulus increased over the age range of 2 to 6 months. The blink reflex enhancement due to attention toward the multimodal foreground stimulus was similar for the auditory and visual blink stimuli.

The development of the blink reflex enhancement during attention replicates previous findings by Richards (1998) and was consistent with a study of 16-week-old infants by Anthony and Graham (1983). Richards (1998) reported an attention-related enhancement in auditory and visual blink reflexes when the infant was attending to a unimodal auditory or visual foreground that matched the modality of the blink-eliciting stimulus. This enhancement increased over 8 to 26 weeks, as in this study. Similarly, Anthony and Graham (1983) found with 16-week-old infants that reflex blinks were enhanced during an interesting foreground stimulus more than during a "dull" foreground stimulus. The developmental changes in this study and in Richards (1998) show an increase in this attention-enhancement effect from 8 to 26 weeks of age, with the 16-week-old infants in the Anthony and Graham study falling midway between the effects found in the 14 and 20 week olds of Richards' studies (Berg & Richards, 1997; Richards, 1998).

One goal of this study was to determine if infants' attention to a foreground multimodal stimulus differentially affected the blink reflex to auditory and visual blink stimuli. The studies of Richards (1998) and Anthony and Graham (1983) engaged infant attention to unimodal auditory or visual foreground stimuli. There was a selective enhancement/attenuation of the blink reflex during attention, depending on the match/mismatch between the foreground and blink stimuli. The facilitatory effects of attention on blink reflex amplitude presumably are due to enhancement of afferent sensory pathways that are complementary to the attention system that is engaged (Anthony & Graham, 1983, 1985; Graham, 1992; Richards, 1998). In this study, there was enhancement of the blink reflex to the auditory blink stimulus and the visual blink stimulus in the conditions in which attention was engaged relative to the conditions in which attention was hypothesized to be unengaged. Additionally, for the auditory blink stimulus this attention enhancement effect significantly increased over the four testing ages (Figure 4). For the visual blink stimulus the attention enhancement effect also increased over the four testing ages (Figure 4) though this effect was not statistically significant. The enhancement of the blink amplitude for both blink stimuli implies therefore that the auditory and visual attention systems were engaged by the compound auditory-visual stimuli used in this study.

There were two differences in the amplitude of the blink reflex modulation found in this study and in Richards (1998). First, the facilitation of the blink reflex during attention to the multimodal stimuli in this study was nearly twice the size as the facilitation to the unimodal stimuli used in Richards (1998). For example, the difference between the blink reflex control trials and the 2-s or heart rate deceleration + 2-s delay conditions was about 3 rms μV when the foreground and blink stimuli matched in Richards, 1998, but was about 6 – 7 rms μV in this study (cf. Figure 1 in Richards, 1998, with Figure 2 in this study). Similarly, the facilitation of the blink reflex amplitude for attention-engaged conditions (and match foreground-blink stimuli), changed from 8 to 26 weeks of age from about –1 to +5 rms μV for unimodal stimuli (Richards, 1998), compared to a change from +1 to +11 rms μV in this study (cf. Figure 2 in Richards, 1998 with Figure 3 in this study). The heart rate changes to the multimodal stimulus were larger than the heart rate changes to the unimodal stimuli (e.g., heart rate deceleration + 2-s delay), and attention seemed to be re-engaged more easily by the multimodal stimuli[2] (return of heart rate to prestimulus level + 5-s delay). The larger blink reflex facilitation during attention and the larger heart rate responses suggest that there was heightened attention to the multimodal stimulus in this study over the unimodal stimuli in Richards (1998). The heart rate changes in infants occurring during sustained attention have been interpreted as indexing a general arousal system (Richards & Casey, 1992; Richards & Hunter, 1998). Thus, the infants in this study were more "attentive" or more highly "aroused" for the multimodal stimulus than for the unimodal stimuli in Richards (1998). This finding is consistent with several reports by Lewkowicz that infants' visual fixation responses to combined auditory and visual changes in multimodal stimuli were larger than the responses to the changes in a single stimulus modality of multimodal stimuli, or to changes of a unimodal stimulus (Lewkowicz, 1988a, 1988b, 1992, 1996, 1998).

A second difference between the current study and Richards (1998) was the response of the blink reflex during inattentive periods. The return of heart rate to its prestimulus level following sustained attention represents a period in which attention is unengaged (Berg & Richards, 1997; Richards & Casey, 1991; Richards & Hunter, 1998), and may signal a refractory period for the re-engagement of attention (Casey & Richards, 1991; Richards & Casey, 1991). The blink reflex during this period was attenuated below the blink reflex control trials for both match/mismatch stimuli when the foreground stimulus was unimodal (Richards, 1998). In contrast in this study, the delay condition representing the return of heart rate to its prestimulus level had a blink reflex amplitude that was not different from the control trials (Figure 2, HR Return delay) or slightly enhanced above the blink reflex control trials (Figure 2, HR Return + 5-S Unengaged, or

Figure 3, Inattentive trials). Additionally, for the unimodal stimuli in Richards (1998), there was little difference between the reflex blink response immediately upon return of heart rate to its prestimulus level, and 5 seconds later (Richards, 1998, Figure 1). In this study, however, on about 50% of the trials there was a subsequent deceleration of heart rate, indicating a re-engagement of attention to the multimodal stimulus, and a corresponding facilitation of the blink reflex (Figure 2). Some studies examining the modality-selective effect of attention on the blink reflex have shown an attenuation of the blink reflex amplitude relative to control trials (e.g., Putnam, 1990), whereas others have not included an appropriate control condition with no foreground pattern (e.g., Anthony & Graham, 1983; Hackley & Graham, 1983). Thus, whereas the facilitation effects for the complementary foreground and blink reflex channels are well established, the inhibitory effects of the foreground attention system on the competing sensory systems are not.

The heart rate changes and blink reflex elicited by the auditory and blink stimuli were dissimilar to what had been expected. Graham (1992; also see Berg & Richards, 1997; Cook & Turpin, 1997; Graham, 1979; Graham et al., 1983) distinguished two types of physiological responses to short latency stimuli depending on the intensity of the stimulus. The “startle reflex” was hypothesized to be a response to high-intensity short duration stimuli, and included widespread flexor jerk (e.g., startle blink reflex) and transient heart rate acceleration. The startle reflex should habituate quickly. The “transient-detecting response” was hypothesized to be a response to low-intensity short duration stimuli, should show heart rate deceleration and body movements directing sensors to the stimulus, and should not habituate.

The stimuli in this study meet the high intensity criteria and the reflex blinks to both auditory and visual blink stimuli represent flexor movements characteristic of the startle reflex. The characteristics of the auditory blink stimulus (5 ms rise time, 60 ms total time, 100 dB (A) intensity) match what has been used in infant and adult research to elicit the startle reflex. The visual blink stimuli (photo flash units) may be less “intense” primarily because their total time is probably less than 10-20 msec, accounting for the smaller blink reflex amplitude and longer latencies (Anthony, Zeigler, & Graham, 1987). For both stimuli, however, reliable blink reflexes were elicited. Alternatively, the ubiquitous heart rate deceleration at blink stimulus onset (lengthening of interbeat intervals) found across delay conditions (Figure 1), and occurring in the presence of unimodal (Richards, 1998) and multimodal (this study) foreground stimuli, appear more like the transient-detecting response. The heart rate change to the blink stimuli occurred without foreground stimuli (blink reflex control trials), during attention to all three types of foreground stimuli (unimodal auditory, unimodal visual, multimodal auditory-visual), and during periods of “inattentive fixation” (e.g., return of heart rate to prestimulus level). The blink reflex amplitude and latency did not habituate during the course of the testing session. The blink stimuli also seemed to re-engage a heart rate deceleration after attention had waned. This can be seen in the delay conditions representing the return of heart rate to prestimulus level, and the return of heart rate to prestimulus level + 5-s (Figure 1). In these cases, the trials on which the blink stimulus occurred had a small heart rate deceleration due to the blink and then a more sustained heart rate deceleration to the foreground stimulus. These characteristics suggest that the response to the auditory and visual blink stimuli did involve the “startle reflex” system. Unlike the functions of the startle reflex system hypothesized by Graham, which should interrupt current processing, the response to the blink stimuli was more like the “transient-detection response” in that it involved primitive information processing (i.e., stimulus detection) and led to increased stimulus processing.

The changes across testing ages in the blink reflex modulation found in this study, and in Richards (1998), were not due to changes in the blink reflex itself. In neither study was there a significant effect of testing age on the blink amplitude to either the visual blink stimulus or the auditory blink stimulus. The decrease across ages in blink latency found in this study for the visual blink stimulus was not consistent with the pattern of reflex facilitation at the older two ages, and such an effect of age was not found in Richards (1998) with identical blink reflex control trials. This lack of effect of age on the blink reflex is consistent with its neurophysiological bases. The acoustic blink startle and the visual blink startle are based upon short-latency reflex pathways involving first-order neurons in the sensory pathways, the brainstem, and spinal motor neurons for the blink reflex (Balaban, 1996; Davis, 1997; Hackley & Boelhouwer, 1997). The spinal motor neurons controlling the blink muscles and the brainstem afferent pathways involved in these reflexes are relatively mature at birth. Thus, the reflex itself should show little developmental change over the testing ages such as those used in this study.

The pattern of results in this study, and in studies examining selective modality effects of attention (Anthony & Graham, 1983, 1985; Balaban, Anthony & Graham, 1989; Hackley & Graham, 1983; Haerich, 1994; Richards, 1998) suggest that a general arousal system and modality-specific systems are involved in attention. The heart rate changes in infants occurring during sustained attention have been interpreted (Richards & Casey, 1992; Richards & Hunter, 1998) as indexing a general arousal system (Heilman et al., 1987; Mesulam, 1983; Posner, 1994; Robbins & Everitt, 1995). The lack of selective modality effects on the heart rate response (Richards, 1998), the lack of attention effects on the heart rate increase at blink reflex onset (Figure 1), and the modulation of auditory and visual blink reflexes during heart-rate-defined attention engagement (e.g., Figure 2; Figure 1 in Richards, 1998; also Anthony & Graham, 1983) imply that the heart rate changes index a general arousal system rather than one tied to specific sensory modalities. This general arousal system invigorates specific attentional systems, such as the auditory or visual attention systems. On the other hand, blink reflex facilitation represents sensory-specific attention engagement. The blink reflex in infants is dependent upon the modality of the eliciting stimulus matching the specific cortical attention system that is engaged (Anthony & Graham, 1983; Richards, 1998). Blink reflex modulation by sustained attention in the same modality would imply that blink stimuli are processed as complementary to the cortical attention system. In this study, the blink reflex to either auditory or visual blink stimuli was facilitated by attention to the multimodal stimulus. This indicates that the multimodal stimulus engaged auditory and visual cortical attention systems, which enhanced the afferent sensory pathways for both modalities.

The pattern of results in this study, and in Richards (1998), provide information about the development of attention in young infants. In this study, the multimodal stimuli elicited auditory and visual attention systems, shown in the facilitation of the blink reflex to both visual and auditory stimuli. This change in attention also was indexed by heart rate. The developmental changes in this study were in the general arousal system (“sustained attention”) rather than in the specific systems underlying auditory or visual attention. The developmental change in sustained attention found in this study was similar to increases in sustained attention found in other paradigms (Berg & Richards, 1997; Richards, 1987, 1997; Richards & Hunter, 1998). This change in sustained attention from 2 to 6 months of age in the human infant seems to be characterized by an increase in cortically-mediated behavior and an increasing influence of cortically-mediated functions over subcortically-mediated behavior (Johnson, 1990, 1995; Johnson et al., 1998; Richards & Casey, 1992; Richards & Hunter, 1998).

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FOOTNOTES

[1]The analysis of IBI changes that is reported used data from all trials. I also compared the IBI changes on trials with and without identifiable blinks, and found no difference between the IBI response to the blink stimulus on those trials.

[2]The interbeat intervals (IBI) changes were compared with data from Richards (1998). In Richards (1998), infants at the same ages as this study were tested, auditory and visual blink stimuli were used as in this study, but the foreground stimuli were presented in a single modality (auditory or visual in Richards, 1998) rather than as a combined auditory-visual stimulus (this study). The IBI changes from Richards, 1998 and this study were analyzed with an age (4) X blink stimulus modality (2; auditory, visual) X delay (5) X stimulus presence (2) X beats (11) X foreground stimulus (3; visual, auditory, auditory-visual) ANOVA. The effects found for this study were nearly identical for the combined data (e.g., delay X beats, stimulus presence X beats, and delay X stimulus presence X beats interactions). A graph of the means from that study (not presented in Richards, 1998) were nearly identical to this study. In each of the conditions, there was a 4 or 5 ms increase in the IBI of the beat following the blink stimulus compared to the control epochs when no beat occurred, and as much as a 7-8 ms IBI increase over all affected beats. There were no significant interactions with the beats factor involving age or blink stimulus modality, and no interactions involving the foreground stimulus type (visual, auditory, or combined auditory-visual stimulus) that showed a difference in the IBI change for the different foreground stimuli.

There were some statistically significant differences between the IBI level for the three foreground stimulus types for the delay conditions representing the heart rate deceleration + 2-s, and return of heart rate to prestimulus level + 5-s. The IBI change at the heart rate deceleration + 2-s delay was 19, 23, and 26 ms for the visual, auditory, and visual-auditory stimuli, respectively, and the peak of the average responses for these stimuli was 22, 26, and 29 ms. The IBI change at the return of heart rate to prestimulus level + 5-s delay was 6, 3, and 10 ms for the visual, auditory, and auditory-visual stimuli. These two findings suggest a larger deceleration for the multimodal stimulus than the unimodal stimuli, and a greater tendency for heart rate to decelerate a second time after inattention, indicating a re-engagement of attention for the multimodal stimulus.

FIGURES

Figure 1. Beat-to-beat interbeat interval (IBI) change at the blink stimulus onset as a function of delay types. The blink stimulus was presented at "beat 0". The solid line represents the IBI changes on blink stimulus present trials, and the dotted line represents the IBI changes occurring on control epochs in which the appropriate delay was met but did not have a blink stimulus presented.

Figure 2. Reflex blink amplitude (rms μV) as a function of the delay types. The bars in this figure represent the rms μV blink amplitude in the auditory-visual foreground + blink stimulus experimental trials, and the dark solid line represents the mean rms μV blink amplitude on the reflex blink control trials along with the standard error (dotted lines). The heart rate return to prestimulus level + 5-s delay condition was separated into trials in which the heart rate was still at or above prestimulus level (attention unengaged) and in which a second heart rate deceleration had occurred (attention re-engaged).

Figure 3. Reflex blink amplitude (rms μV) as a function of testing age separately for the delay conditions hypothesized to have attention engaged and attention unengaged at blink stimulus onset. The solid bars represent blink reflex control trials, the dotted bars represent trials on which attention is engaged, and the gray bars represent trials on which attention was unengaged.

Figure 4. Reflex blink amplitude (rms μV) in response to the visual and auditory blink stimuli. This figure shows the difference in blink amplitude (peak rms μV) between the experimental trials and the blink reflex control trials as a function of testing age separately for the delay conditions hypothesized to have attention engaged and attention unengaged at blink stimulus onset. The dotted bars represent trials with the visual blink stimulus and the gray bars represent trials with the auditory blink stimulus.