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Audiovisual Integration in Noise by Children and Adults

Short Title: Audiovisual Integration in Noise

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Abstract

The aim of this study was to investigate the development of multisensory facilitation in primary school age children under conditions of auditory noise. Motor reaction times and accuracy were recorded from 8-year-olds, 10-year-olds and adults during an auditory, a visual, and an audiovisual detection task. Auditory signal-to-noise ratios (SNRs) of 30, 22, 12 and 9 dB across the different age groups were compared. Multisensory facilitation was greater in adults than in children, though performance for all age-groups was affected by the presence of background noise. It is posited that changes in multisensory facilitation with increased auditory noise may be due to changes in attention bias.

Key Words: Multisensory, Facilitation, Vision, Audition, Development, Children.

Audiovisual Integration in Noise by Children and Adults

Information from multiple sensory systems is readily combined to form a coherent representation of the environment. Multisensory integration can enhance the perception of sensory stimuli (e.g., Gillmeister & Eimer, 2007; Lovelace, Stein, & Wallace, 2003; Stein, London, Wilkinson, & Price, 1996) and enables the association and organization of information between the senses. These integrative processes are useful in noisy situations. For example, the sight of a car and the sound of its horn in traffic may facilitate an individual's motor actions to move out of the way of the oncoming vehicle. It is generally accepted that multisensory integration is guided by the spatial and temporal coincidence of sensory cues (see Stein & Meredith, 1993 for review), however little is known about multisensory facilitation in the presence of either auditory or visual noise. This paper focuses on the effects of auditory background noise on multisensory facilitation in primary school age children and adults.

Under unisensory conditions, noise degrades the perception of auditory signals (e.g., Gockel, Moore, Plack, & Carlyon, 2006) and the intelligibility of speech (e.g., Kobayashi, Morimoto, & Sato, 2007). The greatest interference is observed when the auditory signal and noise originate from the same temporal (e.g., Zwicker, 1965; Zwislocki, Buining, & Glantz, 1968) and spatial location (e.g., Gilkey & Good, 1995; Saberi, Dostal, Sadralodabai, Bull, & Perrott, 1991). Recent studies have shown that even if the accuracy of detecting an auditory signal in noise is high, motor responses are delayed (Kaplan-Neeman, Kishon-Rabin, Henkin, & Muchnik, 2006). In addition, electrophysiological studies in adults have shown that in noisy environments the N1 component of the auditory event-related-potential (ERP) is also delayed during the discrimination of speech stimuli (e.g., Kaplan-Neeman et al., 2006; Martin, Sigal,

Kurtzberg, & Stapells, 1997) and amplitude-modulated complex tones (Okamoto, Stracke, Ross, Kakigi, & Pantev, 2007). Furthermore, speech perception studies indicate that the interference of auditory noise is greater in children than adults (e.g., Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Fallon, Trehub, & Schneider, 2000; Papso & Blood, 1989; Talarico et al., 2007). Developmental improvements in the ability to detect speech in noise have been observed between the ages of 5 and early adolescence (e.g., Elliott, 1979; Johnson, 2000). However, to our knowledge the effect of auditory background noise on the detection of simple auditory stimuli unrelated to speech in children has not been reported.

Auditory perception can be altered by multisensory integration. For example, in the McGurk effect, the phoneme /b/ dubbed over the visual articulation of /g/ leads to the auditory perception of /d/ (McGurk & MacDonald, 1976). Multisensory integration can also improve speech perception in noise in both adults (e.g., Binnie, Montgomery, & Jackson, 1974; Erber, 1969; Grant & Seitz, 2000; Sumbly & Pollack, 1954) and children (Erber, 1971; also see Woodhouse, Hickson, & Dodd, 2008 for a review of the development of audiovisual speech perception). The degree of improvement has been explained by the inverse effectiveness hypothesis, where the effect of seeing a speaker's lip movements increases with decreased signal-to-noise ratio (SNR). The inverse effectiveness hypothesis was initially proposed after intracranial recordings in animals showed that neural firing is most enhanced by multisensory integration when stimuli are close to perceptual thresholds (Stein & Meredith, 1993). The facilitating effect of audiovisual speech perception was recently shown to be greatest at intermediate auditory signal-to-noise ratios (Ma, Zhou, Ross, Foxe, & Parra, 2009; Ross, Saint-Amour, Leavitt,

Javitt, & Foxe, 2007), suggesting that multisensory facilitation of speech intelligibility in noise may not strictly follow the trend predicted by the inverse effectiveness hypothesis.

Multisensory integration also facilitates motor responses, which tend to be faster to multisensory stimuli than to unisensory stimuli (e.g., Miller, 1982; Todd, 1912). It was initially proposed that multisensory facilitation arises from a race between the senses, such that motor responses are initiated by the faster sense (Raab, 1962). However, Miller (1982) later pointed out the race-model's '*prediction of inequality*'; motor responses to multisensory stimuli cannot be faster than those possible under either unisensory condition alone:

$$\text{CDF}_{\text{AVS}}(t) \leq \text{CDF}_{\text{AS}}(t) + \text{CDF}_{\text{VS}}(t), t > 0.$$

In this equation CDF is the cumulative density function (i.e., cumulative probability) of motor responses to multisensory audiovisual (AVS) stimuli and unisensory auditory (AS) and visual (VS) stimuli (see also Ulrich, Miller, & Schroter, 2007). Miller (1982) demonstrated that motor reaction times to multisensory stimuli are more rapid than can be predicted by summing the CDFs for the unisensory stimuli and proposed a coactivation model suggesting that motor responses are faster to multisensory stimuli because the two signals merge their inputs to reach a motor response initiation criterion faster. Studies employing Miller's method have consistently found that the motor responses of adults to multisensory stimuli cannot be explained by race-models and are consistent with coactivation models (e.g., Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002; Fournier & Eriksen, 1990; Giray & Ulrich, 1993; Hughes, Reuter-Lorenz, Nozawa, & Fendrich, 1994). However, race-models can account for saccadic reaction time measures (but not accuracy measures) to low intensity multisensory stimuli in complex auditory and visual background scenarios (Corneil, Van Wanrooij, Munoz, & Van Opstal, 2002).

The effects of auditory noise on multisensory facilitation appear to mature with post-natal experience. In all subhuman species tested including humans (Jaime & Lickliter, 2006; Lickliter, Bahrick, & Honeycutt, 2002; Lickliter, Bahrick, & Markham, 2006; Stein, 2005; Wallace, Perrault, Hairston, & Stein, 2004; Wallace & Stein, 1997, 2000, 2001). Although, human infants are able to transfer information across the senses at birth (e.g., Kaye & Bower, 1994; Meltzoff & Borton, 1979; Sai, 2005; Slater, Quinn, Brown, & Hayes, 1999; Streri & Gentaz, 2004), benefits from the integration of temporally synchronous multisensory stimuli is generally not observed till some time after (Bahrick, 1988, 2001; Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter, 2000; Flom & Bahrick, 2007; Gogate & Bahrick, 1998; Hollich, Newman, & Juszyk, 2005; Lewkowicz, 1996, 1998a, 1998b; Morrongiello, Fenwick, & Nutley, 1998; also see Walker-Andrews, 1997 for review). It is not until at least 8 months postnatal that infants exhibit multisensory facilitation of reflexive head and eye movements during spatial localizations that is consistent with coactivation models (Neil, Chee-Ruiter, Scheier, Lewkowicz, & Shimojo, 2006). The importance of post-natal experience is further highlighted by studies that show multisensory abilities, particularly those linked to the control of actions, to be impaired in adults who experience visual deprivation at birth (e.g., Putzar, Goerendt, Lange, Rosler, & Roder, 2007; Roder, Rosler, & Spence, 2004). Furthermore, studies using modified versions of the McGurk paradigm, have shown that the influence of vision on speech perception is not as strong in either infants or primary school age children as in adults (Desjardins, Rogers, & Werker, 1997; Desjardins & Werker, 2004; Massaro, 1984; Massaro, Thompson, Barron, & Laren, 1986; McGurk & MacDonald, 1976). Multisensory integration that influences higher order cognitive processes, such as the discrimination and detection of nominated stimuli, also continues

to develop throughout childhood (Barutchu, Crewther, & Crewther, 2009; Gori, Del Viva, Sandini, & Burr, 2008; Nardini, Jones, Bedford, & Braddick, 2008). Barutchu et al. (2009) used a simple audiovisual detection task to show that multisensory facilitation of motor responses can be predicted by race-models in children as old as 6 years. Together the evidence suggests that experience and post-natal development play an important role in the maturation of multisensory facilitation throughout childhood.

To date little is known about the development of multisensory facilitation in noisy environments in school age children. In this study we focused on easily perceivable stimuli, and background noise levels (high SNRs) that allowed the collection of an adequate number of motor response samples from children who are likely to show immature sustained attention (e.g., Betts, McKay, Maruff, & Anderson, 2006). Reducing auditory SNRs increases task difficulty. Therefore, high auditory SNRs were chosen as the auditory signal remains salient and holds external validity (e.g., the audiovisual integration of cues from an umpire blowing his whistle during a match over roaring sports fans). Thus, the aim of this study was to determine the effect of continuous auditory noise on multisensory facilitation of responses to multisensory stimuli in 8-year-old children, 10-year-old children and adults. A simple audiovisual detection task was employed where participants were randomly presented with auditory, visual, and audiovisual stimuli, as well as blank invalid trials. Auditory SNRs of 30, 22, 12 and 9 dB were varied in a block design (smaller SNRs indicating increased auditory background noise). It was hypothesized that a reduction in SNR would affect children more than adults by inducing relatively more errors and slower motor responses. Multisensory facilitation was expected to be greater in adults than children, and to be less affected by a decrease in SNRs.

Method

Participants

In total, sixteen 8-year-old children, sixteen 10-year-old children and 21 adults volunteered to participate in this study. Children were recruited from a local Catholic primary school of middle socio-economic status in Melbourne, Australia. All children were born in Australia, and some were bilingual first generation Australians. Most adult participants were university students who responded to a flyer advertising the study. Two children and one adult who were unable to perform the detection task were excluded from data analyses (see results section for details). The remaining participants in each age group were 20 adults (10 females and 10 males, M age = 20 years and 10 months and $SEM = 10$ months), fifteen 8-year-olds (nine females and six males, M age = 8 years and 3 months and $SEM = 2$ months) and fifteen 10-year-olds (seven females and eight males, M age = 10 years and 8 months and $SEM = 11$ months). All adults and parents of children gave informed consent. All participants were right-handed, had normal hearing and normal or corrected to normal vision. Adults and children reported no psychological or neurological diagnoses (parents reported on the behalf of children). The Purdue Pegboard (Tiffin, 1999) and the Wechsler Intelligence Scale for Children Prorated – Fourth Edition – Australian (WISC-IV) (Wechsler, 2003) were administered to all children. All children were in the normal range for WISC-IV prorated Full Scale Intelligence Quotients (FSIQs) and its subscales: Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), and Processing Speed Index (PSI) (see Table 1 means IQ measures for child groups). Adults' intellectual abilities were not assessed.

Table 1 about here

Audiovisual Detection Task

Multisensory integration was assessed using an audiovisual detection task. The auditory stimulus was a 1500 Hz pure tone with 5 ms rise and fall times delivered via headphones at an intensity of 72 dB sound pressure level (SPL, A-weighted, fast). Direct Sound Extreme Isolation® headphones were used to attenuate external environmental noise. The visual stimulus was a centrally positioned white disc (3 degrees visual angle) on a grey background presented on a 20 inch CRT monitor positioned approximately 1 meter from the participant. The auditory and visual stimuli were combined to create four stimulus conditions: auditory stimulus alone (AS), visual stimulus alone (VS), a temporally coincident audiovisual stimulus (AVS) and a blank stimulus with no presentations. The blank stimulus was used as a control to ensure that participants were only responding to the stimuli and not pressing the button randomly. All stimuli (including the blank stimulus) were randomly presented. The duration of exposure was 102 ms. Each stimulus was separated by a randomly varying inter-stimulus interval (ISI) ranging between 1500 – 2500 ms. Stimuli were presented in blocks of 20 stimuli during practice trials and blocks of 80 stimuli during test trials.

During the audiovisual detection task the auditory SNR was manipulated using white noise (0.1 Hz – 24 kHz) with an additional band pass filter (1450 Hz – 1550 Hz, roll-off = 12 dB/octave). Four noise levels were used: no added noise (measured at 42 dB SPL within the headphones), 50 dB SPL, 60 dB SPL and 63 dB SPL (calibrated using a sound

level meter set to A-weighted, slow). Therefore, with the auditory signal set to 72 dB SPL there were four SNR conditions employed: 30 dB (no added noise), 22 dB, 12 dB and 9 dB (note that higher background noise corresponds to lower SNR). These auditory SNRs were chosen based on the outcomes of pilot studies with the aim to maintain high accuracy and allow the collection of an adequate number of motor responses from children. For each noise condition participants were presented with 2 blocks of 80 stimuli of the audiovisual detection task. Auditory noise was continuous throughout each block.

Procedure

Children were assessed over two sessions in a quiet unused classroom during school hours. Adult participants were tested during a single 1-hour session in a sound attenuated room. To maintain some similarity with an unused classroom, the door of the sound attenuated room was maintained open during testing. All participants had their vision and hearing assessed first. Following auditory and visual screening, participants were administered either the audiovisual detection tasks, the Purdue Pegboard or the WISC-IV in a counterbalanced order. All tests were administered across two sessions each of approximately 50 minutes duration.

During the audiovisual detection task participants were seated 1 meter away from the CRT screen and asked to fixate centrally on a cross that appeared continuously in the centre of the screen. Participants were presented with AS, VS, AVS and blank stimuli, and were instructed to press a button with their right index finger only after they saw a flash, heard a noise-burst, or when both appeared simultaneously. They were instructed not to press the button at any other time. All participants initially performed the no added noise (SNR = 30 dB) condition. All participants who performed with an overall accuracy above

80% in the 30 dB SNR condition were administered the remaining SNR conditions. Order of the 22 dB, 12 dB and 9 dB SNR conditions was counterbalanced. For each SNR condition, participants were given up to two brief practice blocks of 20 stimuli. Practice trials were followed by two consecutive blocks of 80 stimuli for each SNR condition. Between all blocks participants were given breaks. Motor reaction times (MRTs) and accuracy were recorded.

Results

Psychometric Measures

To ensure that the two child groups did not significantly differ in their age appropriate cognitive skills, independent sample t-tests were employed to compare standardized scores on the WISC-IV. No significant differences were found between the child groups on the WISC-IV FSIQ or any of the WISC-IV subscales: VCI, PRI, WMI, and PSI (see Table 1). Age related differences in motor coordination and dexterity, as assessed using the Purdue Pegboard, were also analyzed using one-way analysis of variance (ANOVA) and showed an improvement with age, $F(2, 47) = 55.46, p < .001$. Follow-up post-hoc comparisons using the Scheffe method showed that right hand performance on the Purdue Pegboard did not significantly differ between the two child groups, and that the adult group performed significantly better than both child groups.

Effects of Auditory Background Noise on Accuracy

The effects of auditory background noise on children's and adults' accuracy were assessed by calculating the percentage of errors to each stimulus: AS, VS, AVS and blank. Only trials with MRTs ranging between 150 ms and 1000 ms were accepted as

correct responses. Less than 1% of trials were rejected based on this criterion. Error rates to blank stimuli were used as a control to ensure that participants were only responding to target stimuli and were not included in further data analyses. Accuracy measures revealed that one child in the 8-year-old group, one child in the 10-year-old group and one adult had error rates above 60% for at least one of the background noise conditions. For these individuals, samples of MRTs were too low for an accurate assessment of processing speed. Therefore, these three participants were excluded from all further data analyses. Further inspection of individual data showed that a large proportion of adults did not make errors for most stimuli and SNR conditions; adult group mean error rates were very low ($M < 2.5\%$) with an upper bound $CI < 5\%$ ($Mnd = 0\%$) for all stimuli and SNR conditions and were not statistically analyzed further (see Figure 1). In addition, many children did not make errors in the 30 dB SNR (no background noise) condition, in turn, accuracy measures were positively skewed and violated the assumption of normality ($M < 5.5\%$ with an upper bound $CI < 7\%$) (see Figure 1). Therefore, error rates for the stimuli AS, VS and AVS and two child groups were compared only across three SNRs (22, 12 and 9 dB) conditions using a three-way mixed Analysis of Variance (ANOVA). Significant interactions were followed-up with a simple effect analysis (see Winer, 1971 for a description of simple effects analyses).

 Figure 1 about here

A decrease in SNRs had the greatest effect on the accuracy of the auditory stimulus (AS) (Figure 1). Overall the 8-year-old group made more errors than the 10-year-old group, $F(1, 28) = 4.80$, $p < .05$, ($\eta^2 = .15$). Error rates were dependent on the

interaction between stimulus type and SNR, $F(4, 112) = 9.72, p < .001, (\eta^2 = .26)$.

Follow-up simple effects analyses consisted of pair-wise comparisons across the different stimuli and SNRs conditions. For AS, but not VS and AVS, error rates significantly increased with each decreasing step in SNR. In addition, with a SNR of 12 dB error rates were significantly higher for unisensory stimuli compared to AVS, while with a SNR of 6 dB all sensory stimuli scientifically different from each other with error rates being highest for AS and lowest for AVS. In summary, 8-year-old children tend to make more errors than 10-year-old children and error rates significantly increased with a decrease in SNR with greater increases being observed for AS than VS and AVS.

Effect of Background Noise on Motor Reaction Times (MRTs)

 Figure 2 about here

The effects of background noise on motor responses to AS, VS and AVS were also assessed. For every individual, mean MRTs were calculated for each stimulus and SNR condition. Only correct trials were included in analyses of MRTs. Adult motor responses were faster than those of children and MRTs increased with a decrease in SNR (Figure 2). The 30 dB SNR condition was used as a baseline measure and was always presented first. Therefore, the 30 dB SNR was statistically analyzed in a separate 3 stimuli (AS, VS, AVS) x 3 age groups (8-year-olds, 10-year-olds, adult) ANOVA, which revealed that MRTs for AVS are significantly faster than those for AS and VS, $F(2, 94) = 83.21, p < .001, (\eta^2 = .64)$. Overall, adults are significantly faster than both child groups, and 10-year-old children were significantly faster than 8-year-olds, $F(2, 47) = 20.50, p < .001,$

($\eta^2 = .47$). The remaining SNR conditions, presented in a counterbalanced order, were compared using a 3 stimuli (AS, VS, AVS) x 3 age groups (8-year-olds, 10-year-olds, adult) x 3 SNRs (22, 12, 9 dB SNR) mixed ANOVA. A significant interaction was observed between stimulus type and age group, $F(4, 94) = 4.77, p = .002, (\eta^2 = .17)$. Follow-up simple effects analyses using pair-wise comparisons showed that MRTs for AS, VS and AVS significantly differed between all three groups with adults recording the fastest MRTs and 8-year-olds the slowest for all stimuli type. Within all age groups AVS was significantly faster than both, AS and VS. In addition, AS was significantly slower than VS for the two child groups but not the adult group. The interaction between stimulus type and SNR was also significant, $F(4, 188) = 19.04, p < .001, (\eta^2 = .29)$. For AS, MRTs significantly decreased with each decrement in SNR, AVS stimuli were significantly slower with 12 and 9 dB SNRs than with 22 dB SNR, while MRTs for VS were not significantly affected by a decrease in auditory SNR. Furthermore, the two unisensory stimuli (AS and VS) did not significantly differ from each other only with a SNR of 22 dB.

To test whether multisensory facilitation in the presence of auditory noise can be explained by race-models the distribution of MRTs were further analyzed. Thus, the race-model's '*prediction of inequality*' (Miller, 1982) was tested using the procedure detailed in Ulrich et al. (2006). Cumulative density functions (CDFs) were derived by determining the probability of MRTs from .05 to .95 in intervals of 0.1 for each age groups, SNR condition and stimulus type (see Miller, 1982 for details on deriving CDFs).

 Figure 3 about here

For the race-model's '*prediction of inequality*' to be violated the CDF for AVS needs to be significantly faster or to the left of the added AS+VS CDF for the fastest MRTs. As can be observed in Figure 3 the CDF for AVS of adults is to the left of the added AS+VS CDF for the faster MRTs. In contrast, for children there is relatively less of a difference between the AVS CDF and the AS+VS CDF. For each SNR difference between the AVS CDF and the AS+VS CDF across the 10 probability values was assessed using a 2(AVS x AS+VS) x 3(8-year-olds, 10-year-olds, and adults) x 10 (.05 to .95 probability incrementing in 0.1 intervals) mixed ANOVA. Significant three-way interactions were observed for all four SNR conditions and, in turn, followed-up with simple effects analyses comparing AVS and AS+VS CDF at each probability (in Figure 3 * indicates when AVS is significantly faster than AS+VS, suggesting that the race-model cannot predict the level of multisensory facilitation observed). In the 30 dB SNR condition AVS was significantly faster than AS+VS CDF for all probabilities up to .75 for adults but only up to .15 probability for 8-year-olds, with MRTs at .05 probability not reaching significance for 10-year-olds, $F(18, 423) = 7.23, p < .001, (\eta^2 = .24)$. In the 22 dB SNR condition AVS CDF was not significantly faster than AS+VS CDF for MRTs below .25 probability for children, with AVS CDF being faster only to .65 probability in adults, $F(18, 423) = 23.53, p < .001, (\eta^2 = .50)$. With a SNR of 12 dB the significant difference between AVS CDF and AS+VS CDF diminished further to .55 for adults. Once again children failed to show significant differences between AVS CDF and AS+VS CDF for the fastest MRTs at .05 probability, $F(18, 423) = 19.85, p < .001, (\eta^2 =$

.46). For the lowest 9 dB SNR, ASV CDF was significantly faster than AS+VS CDF only for adults and up to .55 probability, $F(18, 423) = 19.03, p < .001, (\eta^2 = .45)$. In summary, with a decrease in SNRs the probability of AVS CDF being significantly faster than AS+VS CDF also decreases. In addition, differences between the AVS CDF and AS+VS CDF are much less in children than adults, i.e., in noisy conditions race-models are able to explain multisensory facilitation in children but not adults.

Discussion

The present study shows that the facilitating effect of multisensory integration diminishes with reduced auditory SNR in both adults and children. Analysis of the distribution of motor responses using CDFs revealed that in adults, multisensory facilitation in all SNR conditions is consistent with coactivation models. In contrast, children showed limited multisensory facilitation that is consistent with coactivation models with the 10-year-old group failing to reach significance for the fastest motor responses for all SNR conditions. Thus, the findings of this study suggest that both multisensory facilitation and audiovisual signal detection in noise continue to develop throughout childhood.

Consistent with Kaplan-Neeman et al. (2006), adult MRTs were slower with decreasing SNRs even though accuracy measures remained very high. Motor reaction times appear to be a more sensitive measure of the effect of auditory noise than accuracy. In contrast, both error rates and MRTs to auditory stimuli increased with lower SNRs in children. Previous studies have reported that auditory noise degrades the intelligibility of speech more for children than adults (e.g., Eisenberg et al., 2000; Fallon et al., 2000; Papso & Blood, 1989). Improvements in speech perception in noise have been reported between age 5 and early adolescence (e.g., Elliott, 1979; Johnson, 2000). The present

study extends these findings by showing that the accuracy of detecting simple non-speech related stimuli in auditory noise also continues to develop throughout childhood.

Multisensory facilitation of mean MRTs was observed for all age groups. In line with previous findings (Barutchu et al., 2009; Fournier & Eriksen, 1990; Giray & Ulrich, 1993; Hughes et al., 1994; Miller, 1982), multisensory facilitation in adults is consistent with coactivation models. This suggests that in adults sensory inputs are merged to reach a response initiation criterion faster for multisensory stimuli than either sensory input in isolation. Children in the 8-year-old group also showed some violations of the race-model's prediction of inequality but only for the faster motor responses and with a much narrower range of significant violations. It should be acknowledged that the limited violation of the race-model's prediction of inequality may be related to the higher variability (Ulrich & Giray, 1986) and decreased accuracy (Miller, 2004) of motor responses in this age group. The result is also likely to represent further evidence suggesting multisensory facilitation may still be immature in school age children.

Human studies and single cell recordings in mammals have previously suggested that multisensory integration is dependent on postnatal experience (Putzar et al., 2007; Roder et al., 2004; Stein, 2005). Furthermore, school age children do not integrate sensory information in an optimal way, suggesting that multisensory integration continues to mature throughout childhood (Barutchu et al., 2009; Gori et al., 2008). Bahrick and Lickliter (2000) have suggested that in infants the temporal coincidence of multiple signals captures and guides attention, which in turn, facilitate learning and memory by highlighting the amodal properties of stimuli and bringing them to the 'foreground.' Indeed, sustained attention and other higher-order cognitive processes, recruited during the detection of prescribed stimuli, do continue to develop throughout

childhood and adolescence (e.g., Betts et al., 2006; Kanaka et al., 2008; Mabbott, Noseworthy, Bouffet, Laughlin, & Rockel, 2006; Smith & Chatterjee, 2008). Together these studies suggest that the speed advantage of multisensory integration may not translate to optimal motor facilitation until higher order cognitive processes reach a certain level of maturity, or alternatively until motor processes to all type of stimuli reach maturity.

Both the present study and Barutchu et al. (2009) showed a decline in violations of the race-model in the 10-year-old children. The problem of increased variability and reduced accuracy cannot account for the diminished facilitation observed in 10-year-olds as they showed no greater variability in motor responses and are significantly more accurate than the 8-year-olds. Furthermore, age appropriate intellectual abilities as measured by the WISC-IV did not significantly differ between 8-year-olds and 10-year-olds. Similar U-shaped developmental trends have been previously reported in studies investigating spatial-location bias (Hund & Plumert, 2002; Spencer & Hund, 2003), performance on mathematical equivalence problems (McNeil, 2007), and language acquisition (Plunkett & Marchman, 1991; Strauss, 1982). In the present study, it is likely that 8-year-olds, who are less accurate at detecting auditory and visual information are more dependent on multisensory facilitation than 10-year-old children, in turn, giving the appearance of a U-shaped developmental trend. Alternatively, other cognitive processes required for the detection of prescribed stimuli may decline during early adolescence masking the small amount of multisensory integration that is taking place in 10-year-olds. During early adolescence, marked changes in both cognitive processes and neural reorganization have been reported, with neuroimaging studies showing the proportion of grey matter decreasing from late childhood onwards (see Paus, 2005 for a review). Thus,

the observed dip in multisensory integration in 10-year-olds may also be related to this neural and cognitive reorganization that takes place during late childhood, disrupting the coordination between higher order cognitive processes, such as attention and decision making, and action. Further research is required to determine the factors that are driving this U-shape developmental trend and establish when adult-like integration appears during a simple detection task.

According to the trends predicted by the inverse effectiveness hypothesis, one would expect multisensory facilitation to increase under degraded auditory conditions. In the present study, SNRs were low enough to increase error rates in children and slow down mean motor responses to auditory stimuli in all age groups, yet violations of the race-models' prediction of inequality decreased and mean motor responses to audiovisual stimuli were slower for low SNRs. Therefore, trends observed in motor responses fail to support the inverse effectiveness hypothesis. In line with the present study, Corneil et al. (2002) have shown that saccadic reaction times to audiovisual stimuli in complex background environments can also be predicted by race-models. More recent studies have also shown that in adults maximal gain from multisensory integration occurs in intermediate auditory background noise conditions during speech perception (Ma et al., 2009; Ross et al., 2007). The authors propose a Bayesian explanation, i.e., under such conditions, sensory signals are combined in an optimal way, taking into consideration the variance of the underlying noise distribution of each individual sensory signal (Alais & Burr, 2004; Ernst & Banks, 2002; Ma et al., 2009). It is important to note that different strategies are likely to be employed during audiovisual integration of speech cues; under intermediate levels of auditory background noise, language and prior experience may further facilitate multisensory facilitation. In contrast, the observed gradual decline in

multisensory facilitation with an increase in auditory noise in the present study may be due to the fact that the stimuli employed in the present study have no pre-existing associations.

In the present study, observed decline in multisensory facilitation with reduced SNR may also be linked to an altered attention bias across the senses. The presence of auditory background noise degrades the auditory signal making it harder to detect. Despite instructions to maintain equal attention to both senses, an increase in the difficulty of detecting the auditory signal in noise is likely to bias attention to one or other of the senses. As integrative processes are known to be strongly linked to attention, such biases across the two senses may degrade multisensory facilitation. For example, physiological and neuroimaging studies have localized multisensory integration to the same sub-cortical (Stein & Meredith, 1993) and cortical (Corbetta & Shulman, 2002; Downar, Crawley, Mikulis, & Davis, 2000) brain regions often considered to play a crucial role in single sense attention. Behavioral studies have further shown that the discrimination under multisensory conditions improves if they appear in an attended location (see Spence & McDonald, 2004 for review) and that the strength of the McGurk effect reduces when demands on attention are increased (Alsius, Navarra, Campbell, & Soto-Faraco, 2005). Recently, Mozolic and colleagues (2008) have also shown that when attention is biased to audition or vision, the facilitation of motor responses can be accounted for by race-models. Therefore, in the present study a reduction of SNR may have biased attention to audition or vision and, in turn, have had an adverse effect on integrative processes. It is possible that for maximal multisensory facilitation, bias in attention across the senses cannot exceed a certain criterion. Further research

manipulating states of attention to sensory stimuli is needed to explore the validity of this hypothesis.

Multisensory facilitation during a simple detection task continues to develop throughout childhood and the proportion of multisensory facilitation diminishes with increased auditory noise in both children and adults. Further research is needed to establish whether visual background noise has a similar effect to auditory background noise and to establish the role of attention bias on multisensory facilitation.

References

- Alais, D., & Burr, D. (2004). The ventriloquist effect results from near-optimal bimodal integration. *Current Biology*, *14*(3), 257-262.
- Alsius, A., Navarra, J., Campbell, R., & Soto-Faraco, S. (2005). Audiovisual integration of speech falters under high attention demands. *Current Biology*, *15*(9), 839-843.
- Bahrick, L. E. (1988). Intermodal learning in infancy: learning on the basis of two kinds of invariant relations in audible and visible events. *Child Development*, *59*(1), 197-209.
- Bahrick, L. E. (2001). Increasing specificity in perceptual development: infants' detection of nested levels of multimodal stimulation. *Journal of Experimental Child Psychology*, *79*(3), 253-270.
- Bahrick, L. E., Flom, R., & Lickliter, R. (2002). Intersensory redundancy facilitates discrimination of tempo in 3-month-old infants. *Developmental Psychobiology*, *41*(4), 352-363.
- Bahrick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Developmental Psychology*, *36*(2), 190-201.
- Barutchu, A., Crewther, S. G., & Crewther, D. P. (2009). The race that precedes coactivation: Development of multisensory facilitation in children. *Developmental Science*, doi: 10.1111/j.1467-7687.2008.00782.x.

- Betts, J., McKay, J., Maruff, P., & Anderson, V. (2006). The development of sustained attention in children: the effect of age and task load. *Child Neuropsychology, 12*(3), 205-221.
- Binnie, C. A., Montgomery, A. A., & Jackson, P. L. (1974). Auditory and visual contributions to the perception of consonants. *Journal of Speech and Hearing Research, 17*(4), 619-630.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience, 3*(3), 201-215.
- Cornel, B. D., Van Wanrooij, M., Munoz, D. P., & Van Opstal, A. J. (2002). Auditory-visual interactions subserving goal-directed saccades in a complex scene. *Journal of Neurophysiology, 88*(1), 438-454.
- Desjardins, R. N., Rogers, J., & Werker, J. F. (1997). An exploration of why preschoolers perform differently than do adults in audiovisual speech perception tasks. *Journal of Experimental Child Psychology, 66*(1), 85-110.
- Desjardins, R. N., & Werker, J. F. (2004). Is the integration of heard and seen speech mandatory for infants? *Developmental Psychobiology, 45*(4), 187-203.
- Downar, J., Crawley, A. P., Mikulis, D. J., & Davis, K. D. (2000). A multimodal cortical network for the detection of changes in the sensory environment. *Nature Neuroscience, 3*(3), 277-283.
- Eisenberg, L. S., Shannon, R. V., Martinez, A. S., Wygonski, J., & Boothroyd, A. (2000). Speech recognition with reduced spectral cues as a function of age. *Journal of the Acoustical Society of America, 107*(5 Pt 1), 2704-2710.

- Elliott, L. L. (1979). Performance of children aged 9 to 17 years on a test of speech intelligibility in noise using sentence material with controlled word predictability. *Journal of the Acoustical Society of America*, *66*(3), 651-653.
- Erber, N. P. (1969). Interaction of audition and vision in the recognition of oral speech stimuli. *Journal of Speech and Hearing Research*, *12*(2), 423-425.
- Erber, N. P. (1971). Auditory and audiovisual reception of words in low-frequency noise by children with normal hearing and by children with impaired hearing. *Journal of Speech and Hearing Research*, *14*(3), 496-512.
- Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*(6870), 429-433.
- Fallon, M., Trehub, S. E., & Schneider, B. A. (2000). Children's perception of speech in multitalker babble. *Journal of the Acoustical Society of America*, *108*(6), 3023-3029.
- Flom, R., & Bahrick, L. E. (2007). The development of infant discrimination of affect in multimodal and unimodal stimulation: The role of intersensory redundancy. *Developmental Psychology*, *43*(1), 238-252.
- Forster, B., Cavina-Pratesi, C., Aglioti, S. M., & Berlucchi, G. (2002). Redundant target effect and intersensory facilitation from visual-tactile interactions in simple reaction time. *Experimental Brain Research*, *143*(4), 480-487.
- Fournier, L. R., & Eriksen, C. W. (1990). Coactivation in the perception of redundant targets. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(3), 538-550.
- Gilkey, R. H., & Good, M. D. (1995). Effects of frequency on free-field masking. *Human Factors*, *37*(4), 835-843.

- Gillmeister, H., & Eimer, M. (2007). Tactile enhancement of auditory detection and perceived loudness. *Brain Research, 1160*, 58-68.
- Giray, M., & Ulrich, R. (1993). Motor coactivation revealed by response force in divided and focused attention. *Journal of Experimental Psychology: Human Perception and Performance, 19*(6), 1278-1291.
- Gockel, H., Moore, B. C., Plack, C. J., & Carlyon, R. P. (2006). Effect of noise on the detectability and fundamental frequency discrimination of complex tones. *Journal of the Acoustical Society of America, 120*(2), 957-965.
- Gogate, L. J., & Bahrick, L. E. (1998). Intersensory redundancy facilitates learning of arbitrary relations between vowel sounds and objects in seven-month-old infants. *Journal of Experimental Child Psychology, 69*(2), 133-149.
- Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology, 18*(9), 694-698.
- Grant, K. W., & Seitz, P. F. (2000). The use of visible speech cues for improving auditory detection of spoken sentences. *Journal of the Acoustical Society of America, 108*(3 Pt 1), 1197-1208.
- Hollich, G., Newman, R. S., & Jusczyk, P. W. (2005). Infants' use of synchronized visual information to separate streams of speech. *Child Development, 76*(3), 598-613.
- Hughes, H. C., Reuter-Lorenz, P. A., Nozawa, G., & Fendrich, R. (1994). Visual-auditory interactions in sensorimotor processing: saccades versus manual responses. *Journal of Experimental Psychology: Human Perception and Performance, 20*(1), 131-153.

- Hund, A. M., & Plumert, J. M. (2002). Delay-induced bias in children's memory for location. *Child Development, 73*(3), 829-840.
- Jaime, M., & Lickliter, R. (2006). Prenatal exposure to temporal and spatial stimulus properties affects postnatal responsiveness to spatial contiguity in bobwhite quail chicks. *Developmental Psychobiology, 48*(3), 233-242.
- Johnson, C. E. (2000). Children's phoneme identification in reverberation and noise. *Journal of Speech, Language, and Hearing Research, 43*(1), 144-157.
- Kanaka, N., Matsuda, T., Tomimoto, Y., Noda, Y., Matsushima, E., Matsuura, M., et al. (2008). Measurement of development of cognitive and attention functions in children using continuous performance test. *Psychiatry and Clinical Neurosciences, 62*(2), 135-141.
- Kaplan-Neeman, R., Kishon-Rabin, L., Henkin, Y., & Muchnik, C. (2006). Identification of syllables in noise: electrophysiological and behavioral correlates. *Journal of the Acoustical Society of America, 120*(2), 926-933.
- Kaye, K. L., & Bower, T. G. R. (1994). Learning and intermodal transfer of information in newborns. *Psychological Science, 5*(5), 286-288.
- Kobayashi, M., Morimoto, M., & Sato, H. (2007). Optimum speech level to minimize listening difficulty in public spaces. *Journal of the Acoustical Society of America, 121*(1), 251-256.
- Lewkowicz, D. J. (1996). Infants' response to the audible and visible properties of the human face: 1. Role of lexical-syntactic content, temporal synchrony, gender, and manner of speech. *Developmental Psychology, 32*, 347-366.

- Lewkowicz, D. J. (1998a). Sensory dominance in infants: 1. Six-month-old infants' responses to auditory-visual compounds. *Developmental Psychology*, *24*, 155-171.
- Lewkowicz, D. J. (1998b). Sensory dominance in infants: 2. Ten-month-old infants' response to auditory-visual compounds. *Developmental Psychology*, *24*, 171-182.
- Lickliter, R., Bahrick, L. E., & Honeycutt, H. (2002). Intersensory redundancy facilitates prenatal perceptual learning in bobwhite quail (*Colinus virginianus*) embryos. *Developmental Psychology*, *38*(1), 15-23.
- Lickliter, R., Bahrick, L. E., & Markham, R. G. (2006). Intersensory redundancy educates selective attention in bobwhite quail embryos. *Developmental Science*, *9*(6), 604-615.
- Lovelace, C. T., Stein, B. E., & Wallace, M. T. (2003). An irrelevant light enhances auditory detection in humans: a psychophysical analysis of multisensory integration in stimulus detection. *Brain Research. Cognitive Brain Research*, *17*(2), 447-453.
- Ma, W. J., Zhou, X., Ross, L. A., Foxe, J. J., & Parra, L. C. (2009). Lip-reading AIDS word recognition most in moderate noise: a bayesian explanation using high-dimensional feature space. *PLoS ONE*, *4*(3), e4638.
- Mabbott, D. J., Noseworthy, M., Bouffet, E., Laughlin, S., & Rockel, C. (2006). White matter growth as a mechanism of cognitive development in children. *Neuroimage*, *33*(3), 936-946.
- Martin, B. A., Sigal, A., Kurtzberg, D., & Stapells, D. R. (1997). The effects of decreased audibility produced by high-pass noise masking on cortical event-

- related potentials to speech sounds/ba/and/da. *Journal of the Acoustical Society of America*, 101(3), 1585-1599.
- Massaro, D. W. (1984). Children's perception of visual and auditory speech. *Child Development*, 55(5), 1777-1788.
- Massaro, D. W., Thompson, L. A., Barron, B., & Laren, E. (1986). Developmental changes in visual and auditory contributions to speech perception. *Journal of Experimental Child Psychology*, 41(1), 93-113.
- McGurk, H., & MacDonald, J. (1976). Hearing lips and seeing voices. *Nature*, 264(5588), 746-748.
- McNeil, N. M. (2007). U-shaped development in math: 7-year-olds outperform 9-year-olds on equivalence problems. *Developmental Psychology*, 43(3), 687-695.
- Meltzoff, A. N., & Borton, R. W. (1979). Intermodal matching by human neonates. *Nature*, 282(5737), 403-404.
- Miller, J. (1982). Divided attention: evidence for coactivation with redundant signals. *Cognitive Psychology*, 14(2), 247-279.
- Miller, J. (2004). Exaggerated redundancy gain in the split brain: a hemispheric coactivation account. *Cognitive Psychology*, 49(2), 118-154.
- Morrongiello, B. A., Fenwick, K. D., & Nutley, T. (1998). Developmental changes in associations between auditory-visual events. *Infant Behavior & Development*, 21(4), 613-626.
- Mozolic, J. L., Hugenschmidt, C. E., Peiffer, A. M., & Laurienti, P. J. (2008). Modality-specific selective attention attenuates multisensory integration. *Experimental Brain Research*, 184(1), 39-52.

- Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current Biology*, *18*(9), 689-693.
- Neil, P. A., Chee-Ruiter, C., Scheier, C., Lewkowicz, D. J., & Shimojo, S. (2006). Development of multisensory spatial integration and perception in humans. *Developmental Science*, *9*(5), 454-464.
- Okamoto, H., Stracke, H., Ross, B., Kakigi, R., & Pantev, C. (2007). Left hemispheric dominance during auditory processing in a noisy environment. *BMC Biology*, *5*, 52.
- Papso, C. F., & Blood, I. M. (1989). Word recognition skills of children and adults in background noise. *Ear and Hearing*, *10*(4), 235-236.
- Paus, T. (2005). Mapping brain maturation and cognitive development during adolescence. *Trends in Cognitive Sciences*, *9*(2), 60-68.
- Plunkett, K., & Marchman, V. (1991). U-shaped learning and frequency effects in a multi-layered perceptron: implications for child language acquisition. *Cognition*, *38*(1), 43-102.
- Putzar, L., Goerendt, I., Lange, K., Rosler, F., & Roder, B. (2007). Early visual deprivation impairs multisensory interactions in humans. *Nature Neuroscience*, *10*(10), 1243-1245.
- Raab, D. H. (1962). Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences*, *24*, 574-590.
- Roder, B., Rosler, F., & Spence, C. (2004). Early vision impairs tactile perception in the blind. *Current Biology*, *14*(2), 121-124.

- Ross, L. A., Saint-Amour, D., Leavitt, V. M., Javitt, D. C., & Foxe, J. J. (2007). Do you see what I am saying? Exploring visual enhancement of speech comprehension in noisy environments. *Cerebral Cortex*, *17*(5), 1147-1153.
- Saberi, K., Dostal, L., Sadralodabai, T., Bull, V., & Perrott, D. R. (1991). Free-field release from masking. *Journal of the Acoustical Society of America*, *90*(3), 1355-1370.
- Sai, F. Z. (2005). The role of the mother's voice in developing mother's face preference: Evidence for intermodal perception at birth. *Infant and Child Development*, *14*, 29-50.
- Slater, A., Quinn, P. C., Brown, E., & Hayes, R. (1999). Intermodal perception at birth: intersensory redundancy guides newborn infants' learning of arbitrary auditory-visual pairings. *Developmental Science*, *2*(3), 333-338.
- Smith, S. E., & Chatterjee, A. (2008). Visuospatial attention in children. *Archives of Neurology*, *65*(10), 1284-1288.
- Spence, C., & McDonald, J. (2004). The cross-modal consequence of the exogenous spatial orientation of attention. In C. Calvert, C. Spence & B. E. Stein (Eds.), *The handbook of multisensory processes* (pp. 3-25). Cambridge: The MIT Press.
- Spencer, J. P., & Hund, A. M. (2003). Developmental continuity in the processes that underlie spatial recall. *Cognitive Psychology*, *47*(4), 432-480.
- Stein, B. E. (2005). The development of a dialogue between cortex and midbrain to integrate multisensory information. *Experimental Brain Research*, *166*(3-4), 305-315.

- Stein, B. E., London, N., Wilkinson, L. K., & Price, D. D. (1996). Enhancement of perceived visual intensity by auditory stimuli: A psychophysical analysis. *Journal of Cognitive Neuroscience*, *8*, 497-506.
- Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. Cambridge: The MIT Press.
- Strauss, S. (1982). *U-Shaped behavioural growth*. New York: Academic Press.
- Streri, A., & Gentaz, E. (2004). Cross-modal recognition of shape from hand to eyes and handedness in human newborns. *Neuropsychologia*, *42*(10), 1365-1369.
- Sumby, W. H., & Pollack, I. (1954). Visual contribution to speech intelligibility in noise. *Journal of the Acoustical Society of America*, *26*, 212-215.
- Talarico, M., Abdilla, G., Aliferis, M., Balazic, I., Giaprakis, I., Stefanakis, T., et al. (2007). Effect of age and cognition on childhood speech in noise perception abilities. *Audiology and Neuro-Otology*, *12*(1), 13-19.
- Tiffin, J. (1999). *Quick reference guide for the purdue pegboard #32020 - Test administrator's manual* (Rev. ed.): Lafayette Instruments.
- Todd, J. W. (1912). Reaction to multiple stimuli. *Archives of Psychology*, *25*, 1-65.
- Ulrich, R., & Giray, M. (1986). Separate-activation models with variable base times: testability and checking of cross-channel dependency. *Perception and Psychophysics*, *39*(4), 248-254.
- Ulrich, R., Miller, J., & Schroter, H. (2007). Testing the race model inequality: an algorithm and computer programs. *Behavior Research Methods*, *39*(2), 291-302.

- Walker-Andrews, A. S. (1997). Infants' perception of expressive behaviors: differentiation of multimodal information. *Psychological Bulletin*, *121*(3), 437-456.
- Wallace, M. T., Perrault, T. J., Jr., Hairston, W. D., & Stein, B. E. (2004). Visual experience is necessary for the development of multisensory integration. *Journal of Neuroscience*, *24*(43), 9580-9584.
- Wallace, M. T., & Stein, B. E. (1997). Development of multisensory neurons and multisensory integration in cat superior colliculus. *Journal of Neuroscience*, *17*(7), 2429-2444.
- Wallace, M. T., & Stein, B. E. (2000). Onset of cross-modal synthesis in the neonatal superior colliculus is gated by the development of cortical influences. *Journal of Neurophysiology*, *83*(6), 3578-3582.
- Wallace, M. T., & Stein, B. E. (2001). Sensory and multisensory responses in the newborn monkey superior colliculus. *Journal of Neuroscience*, *21*(22), 8886-8894.
- Wechsler, D. (2003). *Wechsler intelligence scale for children - Australian Standardisation* (4th ed.). Sydney: Harcourt Assessment.
- Winer, J. B. (1971). *Statistical principles in experimental design*. New York: McGraw-Hill Book Company.
- Woodhouse, L., Hickson, L., & Dodd, B. (2008). Review of visual speech perception by hearing and hearing-impaired people: clinical implications. *International Journal of Language and Communication Disorders*, 1-18.
- Zwicker, E. (1965). Temporal Effects in Simultaneous Masking and Loudness. *Journal of the Acoustical Society of America*, *38*, 132-141.

Zwislocki, J. J., Buining, E., & Glantz, J. (1968). Frequency distribution of central masking. *Journal of the Acoustical Society of America*, 43(6), 1267-1271.

Figure Captions

Figure 1. Mean ($\pm 95\%$ CI) percent error rates for blank, auditory (AS), visual (VS), and audiovisual (AVS) stimuli, in SNR conditions: 30, 22, 12 and 9 dB, and age groups: adults, 8-year-olds and 10-year-olds.

Figure 2. Mean motor reaction times ($\pm SEM$) for auditory (AS), visual (VS), audiovisual (AVS) stimuli in the 30, 22, 12 and 9 dB SNR conditions, for the 8-year-old group, 10-year-old group, and adult group.

Figure 3. Cumulative density functions (CDFs) for auditory (AS), visual (VS), audiovisual (AVS) stimuli and the added AS+VS CDF for 8-year-olds, 10-year-olds and adults and each SNR condition: 30, 22, 12 and 9 dB. Post hoc pair-wise comparisons were applied to the 10 probability values used to plot CDFs starting at .05 to .95 incrementing by .1. An asterisk (*) next to each probability level indicates $p < .05$ for the AVS CDF being faster than the AS+VS CDF.

Table 1

Mean (M) and Standard Error of Mean (SEM) and Significant Differences (Sig) between the 8-year-old, 10-year-old and Adults Groups for Right Hand Performance on Pegboard (PG) and WISC-IV Full Scale Index, VCI, PRI, WMI and PSI.

	7-8 year olds	10-11 year olds	Adults	Sig
<i>M PG – Right Hand (SEM)</i>	12.21 (0.39)	13.19 (0.41)	16.87 (0.25)	$p < .001$
<i>M WISC – Full Scale (SEM)</i>	103 (3.63)	107 (3.90)	N/A	$p > .05$
<i>M WISC – VCI (SEM)</i>	103 (3.45)	106 (4.04)	N/A	$p > .05$
<i>M WISC – PRI (SEM)</i>	104 (3.45)	105 (3.80)	N/A	$p > .05$
<i>M WISC – WMI (SEM)</i>	104 (2.89)	108 (4.35)	N/A	$p > .05$
<i>M WISC – PSI (SEM)</i>	96 (4.63)	100 (3.35)	N/A	$p > .05$

Figure
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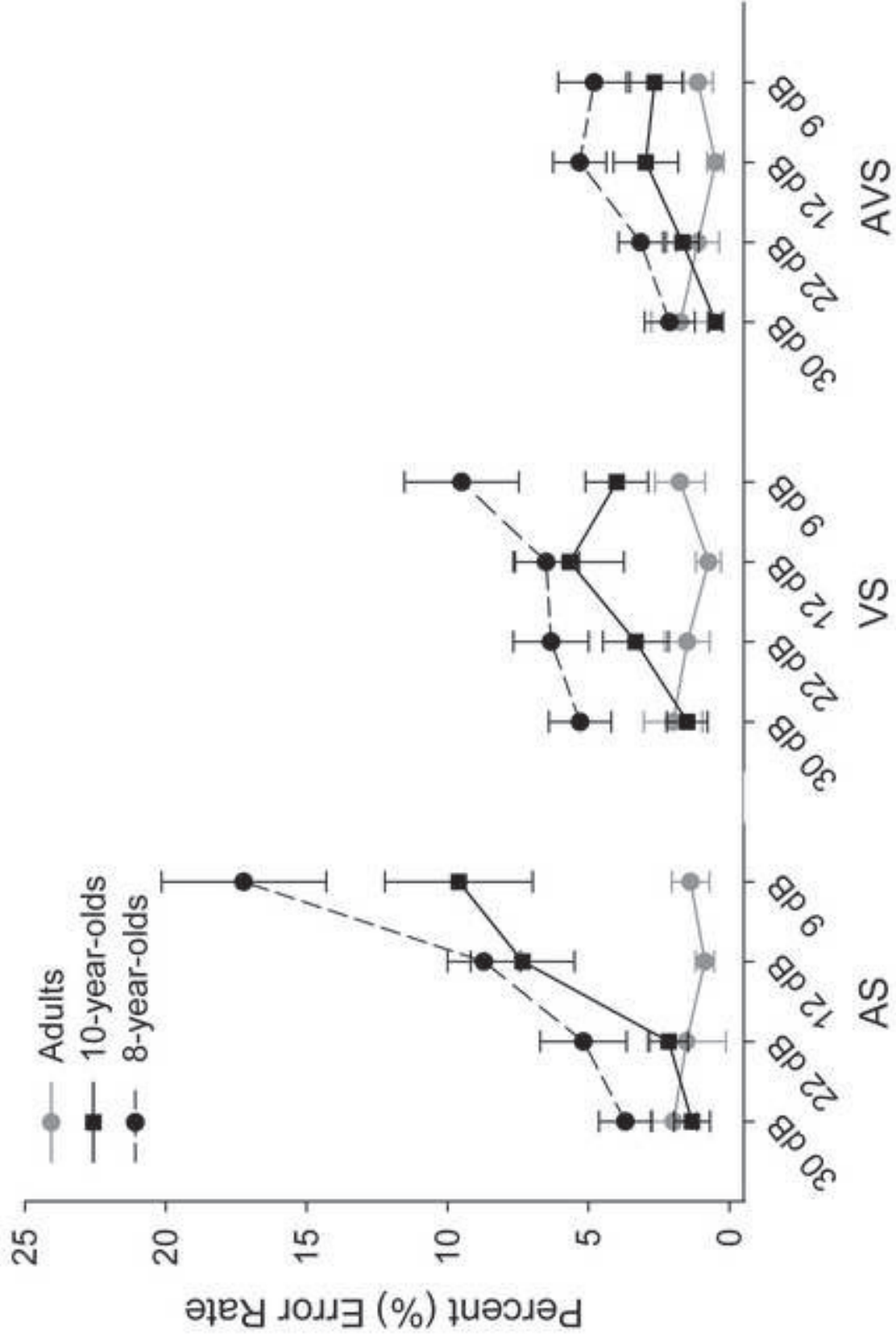


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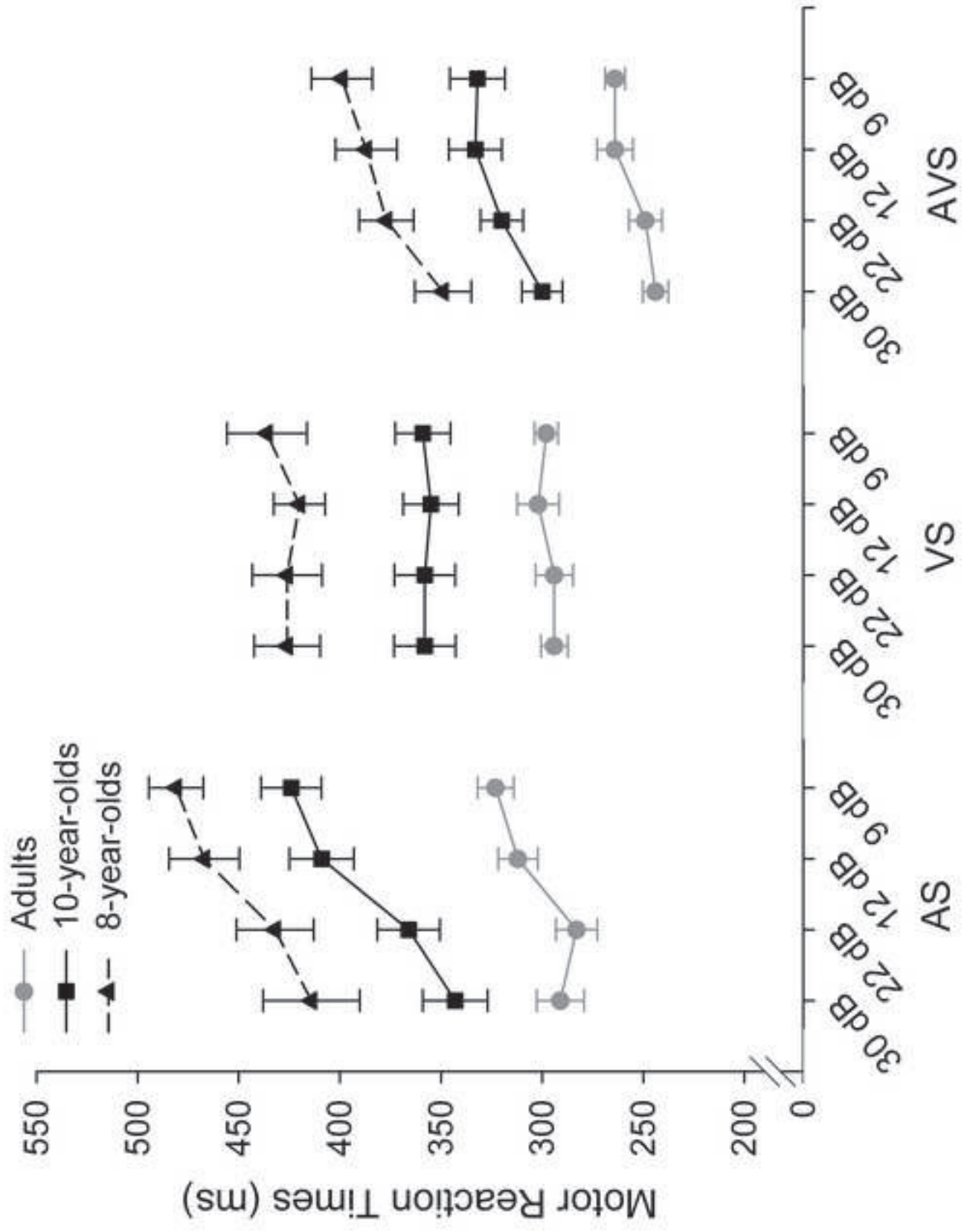


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