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Re-Submitted: 31/08/2010

The Relationship between Multisensory Integration and IQ in Children

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Acknowledgments

Thank you to the staff, pupils, and families of the schools that participated in this research study: St Martin of Tours Primary School, Rosanna, Our Lady Help of Christians Primary School, Eltham, and St Francis Xavier College, Ballarat, in Victoria, Australia. This research was supported by Neville and Di Bertalli, and a La Trobe University Postgraduate Writing-up Award. The Bionic Ear Institute acknowledges the support it receives from the Victorian Government through its Operational Infrastructure Support Program.

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Abstract

It is well accepted that multisensory integration has a facilitative effect on perceptual and motor processes, evolutionarily enhancing the chance of survival of many species, including humans. Yet, there is a limited understanding of the relationship between multisensory processes, environmental noise and children's cognitive abilities. Thus, this study investigated the relationship between multisensory integration, auditory background noise and the general intellectual abilities of school age children (*N* = 88, *M* age = 9 years, 7 months) using a simple audiovisual detection paradigm. We provide evidence that children with enhanced multisensory integration in quiet and noisy conditions are likely to score above average on the full-scale Wechsler Intelligence Scale for Children (WISC-IV). Conversely, ~ 45% of tested children, with relatively low verbal and non-verbal intellectual abilities, showed reduced multisensory integration in either quiet or noise. Interestingly, ~ 20% of children showed improved multisensory integration abilities in the presence of auditory background noise. The findings of the present study suggest that stable and consistent multisensory integration in quiet and noisy environments is associated with the development of optimal general intellectual abilities. Further theoretical implications are discussed.

Key words: Auditory, Visual, Motor Reaction Times, Cognition, Intelligence

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Multisensory integration and the ability to consolidate inputs from different sensory systems are important for compiling holistic representations of the environment. In adults, the integration of spatially and temporally aligned multisensory stimuli can enhance perceptual abilities (e.g., Gillmeister & Eimer, 2007; Stein, London, Wilkinson, & Price, 1996) and facilitate motor actions, leading to significantly faster motor responses than in response to unisensory stimuli alone (e.g., Miller, 1982). In noisy environments, multisensory presentation of stimuli can also improve speech perception in both adults (e.g., Ross, Saint-Amour, Leavitt, Javitt, & Foxe, 2007; Sumby & Pollack, 1954) and children (Erber, 1971). Indeed, multisensory stimuli provide an ‘enriched’ representation of the environment (Bremner & Spence, 2008). Furthermore, given that integrative brain processes can facilitate the speed and accuracy of various perceptual processes and behaviours, it is not surprising that the development of multisensory abilities early in life has been implicated in perceptual learning (Bahrick & Lickliter, 2000), and the acquisition of general intellectual and cognitive abilities (Birch & Belmont, 1964; Piaget, 1952; Rose, Feldman, & Wallace, 1992).

Many multisensory abilities emerge during infancy, however, it is important to distinguish between two main classes of these abilities. C*ross-modal matching* refers to the ability to transfer information and detect equivalence between sensory stimuli (Stein et al., 2010). Indeed infants at 4 days postnatal have been shown to have the ability to match tactile and visual information (e.g., Kaye & Bower, 1994; Streri & Gentaz, 2004). *Multisensory integration*, on the other hand, is the ability to combine inputs from different sensory systems, and significantly alters neural, perceptual and behavioural processes (Stein et al., 2010). Although multisensory integration and its influences on various perceptual processes emerges within the first year of life (e.g., Bahrick, 2001; Flom & Bahrick, 2007; Morrongiello, Fenwick, & Nutley, 1998; Neil, Chee-Ruiter, Scheier, Lewkowicz, & Shimojo, 2006), it continues to mature throughout childhood (Gori, Del Viva, Sandini, & Burr, 2008; Massaro, 1984; Nardini, Jones, Bedford, & Braddick, 2008; Picard, 2007; Tremblay et al., 2007). The facilitative effect of multisensory integration on motor actions also has a prolonged developmental course beyond 10 years of age. Barutchu and colleagues used a simple detection paradigm to demonstrate that although children's motor reaction times (MRTs) are significantly faster for audiovisual compared to unisensory presentations of auditory or visual stimuli, multisensory integration and its facilitative effect was shown to be immature in children as old as 12 years (Barutchu, Crewther, & Crewther, 2009; Barutchu et al., 2010). More recently, Barutchu et al. (2010) have used a similar audiovisual detection paradigm to demonstrate that auditory background noise has a greater adverse effect on audiovisual integration in children than in adults, further highlighting the immature nature of multisensory integration in children and its susceptibility in noisy environments.

The hypothesis that multisensory processes may contribute to the development of cognition is supported by studies demonstrating low intellectual abilities in children who have poor cross-modal matching abilities, as assessed by the Wechsler Intelligence Scale for Children (WISC) (Birch & Belmont, 1964; Rose, Feldman, Futterweit, & Jankowski, 1998; Rose et al., 1992). Birch and Belmont (1964) demonstrated that 'good' readers have better auditory-visual temporal pattern matching abilities compared to children who were classified as 'poor' readers. Children's auditory-visual temporal pattern matching abilities were also shown to be related to their WISC IQ measures independent of reading ability (Birch & Belmont, 1964). Tactile-visual cross-modal matching abilities in 1-year-old infants have also been reported to predict cognitive abilities and IQ measures in 6-year-olds (Rose et al., 1992), and 11-year-olds (Rose et al., 1998). Moreover, children with learning disabilities, characterised as having significantly poor reading and language related skills, have been shown to be less likely to integrate audiovisual speech information in the presence of auditory background noise (Hayes, Tiippana, Nicol, Sams, & Kraus, 2003). This was demonstrated by a reduction in the perception of the multisensory illusion known as the *McGurk effect* (e.g., in this case the lip movements of /aka/ coupled with the sound /apa/ led to the illusory percept of /ata/) in children with learning disabilities when the task was performed in the presence of auditory noise. When investigating non-verbal IQ, on the other hand, Barutchu et al. (2009) did not find a significant relationship between the degree of multisensory facilitation of MRTs and non-verbal IQ in children, when IQ was measured using the Raven's Coloured Progressive Matrices Test.

Developmental research investigating the link between multisensory processes and learning is mostly limited to infants (e.g., Bahrick & Lickliter, 2000). The present study extends previous research by focusing on the relationship between multisensory integration and general intellectual abilities in children. Although few previous studies have shown a significant relationship between 'cross-modal matching,' reading and general intellectual abilities (Birch & Belmont, 1964; Rose et al., 1998; Rose et al., 1992), the relationship between 'multisensory integration' and WISC IQ measures is unknown. Furthermore, to our knowledge, no published study has investigated the relationship between children's general intellectual abilities and the facilitative effect of multisensory integration in the presence of auditory background noise, which is the main focus of the present study. This relationship is of interest given the omnipresence of auditory noise in most learning environments and the fact that previous studies have shown background noise to modulate multisensory integration processes in adults (Ross et al., 2007; Sumby & Pollack, 1954), in 'normal' children (Barutchu et al., 2010), and in children with learning disabilities (Hayes et al., 2003). In the study presented here, multisensory integration is defined on the basis of whether children's motor reaction times (MRTs) to multisensory stimuli could be predicted by race models (Raab, 1962). Race models assume that multisensory stimuli are processed by independent parallel sensory systems and multisensory facilitation to be a consequence of the faster sensory system always initiating the motor response (Raab, 1962). As highlighted by Miller (1982), race models are bound by the '*prediction of inequality,'* which stipulates that the most rapid MRTs for multisensory stimuli cannot be faster than what can be predicted by either unisensory stimulus (for a detailed explanation see Miller, 1982). In adults, a test of this 'inequality' has been commonly used to demonstrate that the level of gain from multisensory integration is too great to be predicted by race models, while race models are often predictive of children's MRT for multisensory stimuli (Barutchu et al., 2009). Thus, in the present study, children were classified into groups with 'good' or 'poor' multisensory integration abilities depending on whether the MRT advantage from multisensory integration for each child could be predicted by race models. In light of the finding reported by Rose et al. (1998), we hypothesised that the level of multisensory facilitation would significantly correlate with verbal IQ measures on the WISC-IV. We also predicted that children with 'good' multisensory integration abilities in quiet and noise would score higher on verbal IQ measures than children identified as having 'poor' multisensory integration abilities.

Method

Participants

For this study we recruited primary school children over 7 years of age, as the MRTs of some children above 7 years of age are likely to be facilitated by multisensory integration beyond the predictive bounds of race models with minimal developmental improvements throughout childhood (Barutchu et al., 2009) . In total, 88 right-handed children (*M* age = 9 years, 7 months, *CI* = ± 3 months) with normal hearing, normal or corrected to normal vision, and no prior history of psychiatric or neurological diagnoses were recruited. All children were recruited from Catholic primary schools in Victoria (located in regions of middle socio-economic status), Australia. School teachers distributed information sheets, consent forms and a brief demographic questionnaire to all students over 7 years of age. Only students who returned the consent forms signed by a parent or a legal guardian participated in the study. All children were born in Australia and came from a wide variety of ethnic backgrounds. Of the 88 children who participated in the study, 3 were unable to perform the audiovisual detection task and were not included in further data analyses (see Preliminary Analyses subsection for more details). All procedures were approved by the Royal Victorian Eye and Ear Hospital Human Research Ethics Committee, Melbourne, and the Human Research Ethics Committee, La Trobe University, Melbourne.

Screening and Psychometric Measures

Visual screening measures included the assessment of distant and near vision (using Logarithmic Visual Acuity Charts), binocular vision (Randot Stereotest) and colour vision (Pseudoisochromatic Plates Ishihara Compatible – IPIC). Hearing was assessed using an audiometer to ensure that children could hear at 20 dB sound pressure level (SPL) at frequencies from 250 Hz to 8000 Hz, incrementing in one-octave steps. Overall intelligence and cognitive abilities of children were assessed using the WISC-IV to obtain a pro-rated Full Scale Intelligence Quotient (FSIQ), Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), and Processing Speed Index (PSI). All tests were administered with strict adherence to test instructions. Measures on the WISC–IV Australian pro-rated showed that all children had FSIQs above 80.

Audiovisual Detection Task

During the audiovisual detection task participants were presented with four stimuli: an auditory stimulus (AS), a visual stimulus (VS), an audiovisual stimulus (AVS) and a blank stimulus with no presentations. The AS was a 1500 Hz pure tone (5 ms onset and offset ramps) delivered using closed headphones at 72 dB SPL. A centrally positioned white disc (3.5 cm radius presented at a distance of 1 meter) on a grey background (20 inch cathode ray tube – CRT monitor) was used as the VS. During AVS trials, AS and VS were presented simultaneously (sound onsets were synchronised to the refresh rate of the CRT monitor). The blank stimulus, where only the grey background was maintained on the monitor, was used as a control to ensure that participants were only responding to the stimuli and not pressing the button randomly. All stimuli were presented for the duration of 102 ms with the inter-stimulus interval randomly varied between 1500 – 2500 ms.

Two auditory noise conditions were employed: quiet and noise. In the quiet condition the ambient sound level in the headphones, without any added stimulus presentation, measured at 42 dB SPL. For the noise condition, continuous white noise (0.1 Hz – 24 kHz) was filtered through a band pass filter (centre frequency = 1500 Hz, rolloff = 12 dB/octave) and presented at 63 dB SPL as participants performed the audiovisual detection task. With the auditory signal set to 72 dB SPL, the signal-to-noise ratios (SNRs) for the quiet and noise conditions were 30 dB and 9 dB, respectively. The parameters of the auditory signal and noise were chosen based on outcomes of pilot studies to allow for the collection of an adequate number of motor responses from children.

Procedure

Children were assessed over two sessions in a quiet unused schoolroom during class time. All participants' vision and hearing were initially assessed in session one. The WISC-IV and the audiovisual detection tasks, which were performed in quiet and noisy conditions, were divided across the two test sessions and were performed in a counterbalanced order (i.e., participants were administered the entire WISC-IV in session one and the audiovisual tasks in a counterbalanced order in session two, or visa versa). During the audiovisual detection task, participants were seated 1 meter away from the CRT monitor and asked to fixate centrally on a cross that appeared continuously in the centre of the screen. Participants were randomly presented with AS, VS, AVS and blank stimuli, and instructed to press a button with their right index finger only when they saw a flash, heard a tone-burst, or when both appeared simultaneously, and not to press the button at any other time. For the quiet and noise conditions, participants were given up to two practice blocks of 20 trials. The practice blocks were followed by two consecutive blocks of 80 trials consisting of random presentations of AS, VS, AVS and blank stimuli with equal probability (i.e., 20 presentations of each type of stimulus) with short breaks between each block. Children's MRTs and accuracy were recorded. The total test time per child was approximately 1.5 hours.

Preliminary Analyses

Multisensory Child Group Identification Procedure and Group Characteristics

Children were classified into groups based on their relative MRTs to unisensory and multisensory stimuli during the audiovisual detection tasks in quiet and noise conditions. Only trials with MRTs ranging between 150 ms and 1000 ms were accepted as correct responses, and percentage (%) error rates were calculated for each stimulus type. Errors of omission, also known as misses, were calculated for AS, VS and AVS stimuli, while for blank stimuli error rates represent errors of commission (false alarms). Only children with error rates below 35% for all stimulus types in both quiet and noise conditions were included in further data analyses. Three children did not meet this inclusion criterion in the noise condition (2 males and 1 female). For these children, a reliable estimate of the MRT for the audiovisual detection task could not be obtained due to the low number of samples.

Table 1 about here

To test whether the level of multisensory facilitation can be predicted by race models, cumulative density functions (CDFs) were calculated by determining the probability of MRTs from .05 to .95 in intervals of .1 for each child, stimulus type and background noise condition. The two unisensory CDFs for the auditory and visual stimuli were summed (AS CDF + VS CDF) and compared against the AVS CDF (see Ulrich, Miller, & Schroter, 2007 for algorithms and a detailed explanation of this procedure). This analysis tests whether race models can predict the fastest MRTs for multisensory stimuli. Thus, for each child a classification of ‘good’ multisensory integration was assumed if at least two of the probabilities .35 and below had faster MRTs for the AVS CDF than for the AS+VS CDF (this is an indication that the level of multisensory facilitation is too great to be predicted by race models). Using this criterion, four groups were identified (see Table 1 and Figure 1): children who showed ‘good’ multisensory integration in both quiet and noise conditions (Good Quiet/Good Noise), those who showed ‘good’ multisensory integration in quiet but ‘poor’ integration in the noise condition (Good Quiet/Poor Noise), and children who showed ‘poor’ multisensory integration in quiet but ‘good’ in noise conditions (Poor Quiet/Good Noise). Six children (all male) were also identified as being ‘poor’ integrators in both quiet and noise conditions (Poor Quiet/Poor Noise). Given the low number of participants in this group, and the fact that these six males were on average younger (Table 1), they were not included in the main statistical analyses reported in results (for additional analyses of the Poor Quiet/Poor Noise group see Appendix A).

Figure 1 and Table 2 & 3 about here

In order to confirm group differences, a series of 2(AVS CDF and AS+VS CDF) x 2(quiet and noise condition) x 3(child groups) mixed ANOVAs were applied at each of the ten probability values used to fit the CDFs. Significant three-way interactions were observed for probability values .05 to .75 (see Table 3), which were followed-up with simple effects analyses (Winer, 1971) using planned contrasts (with Bonferroni corrections) comparing the AVS CDF and the AS+VS CDF for each individual child group and noise level. Hence, a significant interaction at each probability was followed-up with 6 planned contrasts. Figure 1 depicts regions of the AVS CDF that are significantly too fast to be predicted by race models (i.e., where

AVS CDFs is significantly faster than AS+VS CDFs) for each child group when the audiovisual tasks were performed in quiet and noisy conditions. A one-way ANOVA revealed that age differences between these three groups did not approach significance (see Table 1). Also, group differences in percent error rate for AS, VS and AVS stimuli (misses) and blank stimuli (false alarms) did not approach significance (see Table 2).

Results

The Relationship between IQ, MRTs and Multisensory Integration In Quiet and Noisy Conditions

Prior to subdividing children into groups, correlation analyses were applied to establish the overall relationship between age, MRTs to unisensory and multisensory stimuli, multisensory facilitation measures and WISC-IV IQ scores. As expected, the indices of the WISC-IV moderately correlated with each other (Table 4). Mean MRTs for each stimulus (AS, VS and AVS) were highly correlated with each other and moderately correlated with age. Thus, in the subsequent analyses presented below, age was used as a covariate. Note that the MRTs to sensory stimuli did not significantly correlate with any of the WISC-IV IQ measures. The degree of multisensory facilitation (as calculated by subtracting MRTs to AVS from the faster of the two unisensory stimuli – AS or VS) also did not significantly correlate with either IQ measures or mean MRTs to sensory stimuli. We also noted the lowest probability at which race models could reliably predict MRTs in quiet (Race-Q) and noisy (Race-N) conditions (i.e., the lowest probability at which AS+VS CDF is consistently faster than the AVS CDF – on this measure the higher the probability value the less likely that race models could predict MRTs for multisensory stimuli). Interestingly, a significant correlation was observed between Race-N and WISC-IV verbal index measure (VCI), with Race-Q and remaining IQ measures, including FSIQ not reaching significance. This correlation suggests that in children with higher VCI measures, race models are less likely to predict MRTs for AVS stimuli. Race-Q, however, did negatively correlate with MRTs for both unisensory and multisensory stimuli, indicating that under quiet conditions race models begin to predict MRTs at high probabilities for individuals with faster MRTs. This relationship was not observed for the Race-N measure, suggesting that different strategies or mechanisms are employed when integrating audiovisual information in noise.

Table 4 about here

Intellectual Abilities of Children with 'Good' and 'Poor' Multisensory Integration

On average, children who showed 'good' multisensory integration in both quiet and noise conditions had above average FSIQ scores (See Figure 2A). A one-way analysis of covariance (ANCOVA) and Tukey post-hoc comparisons further confirmed that FSIQ scores were significantly higher for children in the Good Quiet/Good Noise group than those who showed 'poor' multisensory integration in either quiet or noise conditions, $F(2, 75) = 5.94$, $p = .004$, $\eta^2 = .14$ (Figure 2A), even when the effect of age was accounted for. An assessment of individual cases revealed that only 15% of children in the Good Quiet/Good Noise group had FSIQs below the 50th percentile (standardised for age), while 44% and 50% of children in the Good Quiet/Poor Noise and Poor Quiet/Good Noise groups, respectively, had FSIQ below the 50th percentile.

Figure 2 about here

A similar pattern was observed for the WISC-IV index scores with children in the Good Quiet/Good Noise group outperforming those in the other two groups (Figure 2B). For the WISC-IV indices (VCI, PRI, WMI, PSI), group differences were compared using multivariate analysis of covariance (MANCOVA) followed with post hoc comparisons using the Tukey method. Amongst the WISC-IV indices, VCI scores were significantly lower for children who showed 'poor' multisensory integration only in auditory noise (Good Quiet/Poor Noise group – 75% scoring below the 50th percentile) than for those who showed 'good' integration in both conditions (Good Quiet/Good Noise group – only 28% scoring below the 50th percentile), $F(2, 75) = 5.87$, $p = .004$, $\eta^2 = .14$. Although a similar trend was observed for WMI, it did not reach significance ($p = .06$). In addition, children in the Poor Quiet/Good Noise group scored significantly lower for the PRI than children with 'good' multisensory integration in both conditions, $F(2, 75) = 3.43$, $p = .04$, $\eta^2 = .08$.

Discussion

In the study presented here, ~55% of children showed stable and consistent multisensory integration in both noise and quiet, and on average, scored in the high to superior range of the full scale WISC-IV. The remaining ~45% of children showed multisensory facilitation that was within the predictive confines of race models. Those with 'poor' multisensory integration in the presence of auditory noise also had below average verbal comprehension abilities. Interestingly, and somewhat unexpectedly, ~20% of children showed 'poor' multisensory integration only in quiet conditions, but not in the presence of auditory background noise. These children demonstrated lower scores on the non-verbal IQ measure PRI than children with enhanced multisensory integration abilities.

In general, multisensory integration and its facilitative effect on motor actions was much less predictable than is generally observed in adults (Barutchu et al., 2009), indicating that multisensory integration is not adult-like by 9 years of age. Indeed, multisensory integration abilities substantially differ among children, and it may be that these differences are representative of different levels of behavioural or cortical maturity, with some children showing developmental lags in multisensory signal processing abilities. Presumably, the facilitative effect of multisensory integration on behaviours or actions that are dependent on sustained attention and stimulus detection will develop with age, similar to the manner in which higher order processes, such as attention, decision-making processes and related cortical brain regions functionally associated with such behaviours continue to develop throughout childhood and adolescence (e.g., Betts, McKay, Maruff, & Anderson, 2006; reviewed in Paus, 2005). Consistent with prior reports, the small and non-significant correlation between MRTs and the degree of gain in motor speed as a consequence of multisensory integration suggests that multisensory facilitation and general motor processes may follow a different developmental trajectory (Barutchu et al., 2009; Hulme, Smart, Moran, & Raine, 1983).

As previously shown, multisensory facilitation in quiet conditions did not significantly correlate with non-verbal IQ measures (Barutchu et al., 2009), but a significant correlation was observed between the verbal measure VCI and the probability at which race models began to reliably predict MRTs in the presence of auditory noise. Group analyses also showed intellectual abilities to be significantly higher for children with enhanced multisensory integration abilities relative to those who showed ‘poor’ integration in either quiet or noise conditions. Furthermore, the main contributor to the low FSIQ of the WISC-IV, in children who were ‘poor’ integrators in noise, was the verbal index (VCI). Even though the stimuli employed in the current study did not have a verbal or phonetic component, children who failed to show ‘good’ multisensory integration in auditory noise had verbal skills with a group mean well below age appropriate IQ levels. This reduction in verbal skills cannot be fully accounted for by poor motor performance nor processing speed, as PSI measures did not significantly differ between the groups, and not surprisingly, VCI did not significantly correlate with mean motor responses to any of the stimuli. Prior studies have shown that transfer of information across the senses in infancy can predict verbal abilities in school age children (Rose et al., 1998; Rose et al., 1992), suggesting that fundamental multisensory abilities may be important to the acquisition of verbal skills. Studies have also shown that the superior temporal sulcus (STS), including Wernicke’s language area, is involved in the integration of information that is not always related to language (e.g., Calvert, 2001; Raij, Uutela, & Hari, 2000). Thus, altered integrative processes in the presence of noise in these multisensory brain regions may adversely affect the ability to form the appropriate association between visual objects and events, and their corresponding auditory components.

In general, children and young adolescents are more susceptible to auditory background noise than adults, particularly with regard to the perception of speech (e.g., Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Fallon, Trehub, & Schneider, 2000; Papso & Blood, 1989). In the present study, the MRTs of most children were slower with background auditory noise, although some children showed an unexpected improvement in multisensory integration in the presence of noise. This poor multisensory integration in quiet conditions may be partly related to an increase in the variability of motor response times (Ulrich & Giray, 1986). The observed improvements in noise may also be related to some children strategically using the spatial and temporal coincidence of audiovisual signals to extract target signals from auditory background noise. Previously it has been shown that the interference of auditory noise on speech perception can be minimised if distracting sounds are coupled with matching visual cues that are in close spatial proximity (Driver, 1996). Alternatively, to maintain a good level of performance in noise, these children may have strategically increased their level of concentration and attention and, in turn, enhanced their level of multisensory integration. Indeed, prior studies have suggested that attention can modulate multisensory processes at both a behavioural and neural level (e.g., Driver & Spence, 1998; Sokolov, Pavlova, Lutzenberger, & Birbaumer, 2004; Talsma & Woldorff, 2005). Difficulties in sustaining attention in children who are 'poor' integrators in quiet conditions would also explain the reduction in non-verbal intelligence scores (PRI) observed in this group. As verbal skills were not significantly affected in these children, only mechanisms related to motor or attention processes may be altered. Since multisensory integration involves a network of cortical processes, including primary sensory regions, parietal regions, association cortices and the motor pathways (reviewed in Calvert, 2001), it is likely that a disruption of multisensory integration at different stages of cortical processing will have different cognitive, sensory or motor consequences.

Conclusion

Enhanced multisensory integration is associated with the development of intellectual abilities in primary school age children. A large proportion of children demonstrated 'poor' multisensory integration in either noise or quiet conditions, with characteristic differences in their verbal and non-verbal intellectual abilities. It appears that these children are in different stages of development and show different levels of interference or benefit from the presence of auditory background noise. One factor likely to contribute to the stability of multisensory processes and its contribution to the development of IQ in children is attention. Although prior studies have shown attention to modulate multisensory processes in adults and infants, further research is need to establish the relationship between attention and multisensory integration and their contributions to the development of general intellectual abilities in children. Future research is also needed to establish the biological and environmental factors that contribute to optimal multisensory integration in children. Such research would enable strategic intervention strategies to be tailored to maximise multisensory facilitation throughout development and, in turn, enhance the general intellectual abilities of all school age children.

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Table 1

Total Number (n) of Children, Number of Males and Females, and Mean (M) Age for Each Child Group: Good Quiet/Good Noise, Good Quiet/Poor Noise, Poor Quiet/Good Noise, and Poor Quiet/Poor Noise.

	Good Quiet/ Good Noise	Good Quiet/ Poor Noise	Poor Quiet/ Good Noise	Poor Quiet/ Poor Noise
Group (*n*)	47	16	16	6
Males (*n*)	17	7	6	6
Females (*n*)	30	9	10	0
M Age (± *CI*)	9, 8 (±0, 5)	9, 10 (±0, 8)	9, 5 (±0, 8)	9, 2 (±1, 10)

Note: Age is Denoted in ‘Years, Months.’

Table 2

Mean Percentage Error Rate (SD) for AS, VS, AVS and Blank Stimuli in Quiet and Noise Conditions for Child Groups: Good Quiet/Good Noise, Good Quiet/Poor Noise, Poor Quiet/Good Noise and Poor Quiet/Poor Noise.

		Good Quiet/ Good Noise	Good Quiet/ Poor Noise	Poor Quiet/ Good Noise	Poor Quiet/ Poor Noise
Quiet	Blank	1.77 (2.57)	2.17 (2.98)	3.48 (5.75)	3.95 (5.06)
	AS	3.43 (5.80)	3.41 (3.58)	7.90(10.02)	4.15 (3.73)
	VS	4.09 (4.12)	5.14 (4.42)	6.43 (7.39)	2.96 (2.50)
	AVS	1.46 (2.42)	2.02 (2.62)	2.63 (3.28)	5.38 (5.06)
Noise	Blank	3.26 (4.22)	3.61 (5.62)	7.49 (9.01)	5.42 (4.31)
	AS	6.33 (8.33)	10.24 (9.51)	7.97 (7.98)	5.78 (5.78)
	VS	3.67 (4.16)	5.63 (6.61)	5.20 (7.43)	4.58 (3.68)
	AVS	1.87 (2.68)	2.63 (3.66)	3.60 (4.28)	2.90 (1.86)

Note: Percent error rates for AS, VS and AVS stimuli represent ‘misses’ or a failure to make a motor response, while for blank stimuli error rates represent the percentage of false alarms.

Table 3

Outcomes of Ten Three-Way ANOVAs Performed at Each Probability (.05 to .95) Value Used to Fit Cumulative Density Functions (CDFs). The F-statistic [F(3,76)] for the Three-Way Interactions, their Significance Levels (p-values) and Related Effect Size (η^2) are Reported.

Probability	$F(3,76)$-statistic	p-values	Effect size (η^2)
.05	15.52	$p < .001$	.29
.15	14.53	$p < .001$	.27
.25	34.87	$p < .001$	.47
.35	10.53	$p < .001$	.22
.45	7.55	$p = .001$	.17
.55	9.70	$p < .001$	.20
.65	7.45	$p = .001$	.16
.75	3.39	$p = .04$	.08
.85	1.03	$p > .05$	.02
.95	1.15	$p > .05$	.03

Table 4

Correlation Matrix Comparing Age, WISC-IV Scores (FSIQ, VCI, PRI, WMI, PSI), Motor Reaction Times to Sensory Stimuli in Quiet (AS – Q, VS – Q, and AVS – Q) and Noisy Conditions (AS – N, VS – N, AVS – N), Percentage of Multisensory Facilitation in Quiet (Facil-Q) and Noisy (Facil-N) Conditions, and the Probability at Which Race Models Could Predict Motor Reaction Times for Multisensory Stimuli in Quiet (Race – Q) and Noisy (Race – N) Conditions.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Age	-	**-.27**	-.11	**-.32**	-.13	-.15	-.22	**-.28**	**-.24**	**-.29**	**-.31**	**-.30**	-.06	-.04	.18	-.08
2. FSIQ		-	**.75**	**.81**	**.58**	**.59**	-.17	-.06	-.07	.04	.07	.04	-.01	.14	.04	.15
3. VCI			-	**.40**	**.30**	**.25**	-.18	-.12	-.11	-.04	-.04	-.07	-.04	.12	-.03	**.29**
4. PRI				-	**.40**	**.35**	-.06	.07	.02	-.18	-.21	-.21	.08	.02	.06	.04
5. WMI					-	.07	-.18	-.14	-.13	-.06	-.05	-.09	.08	.14	.08	.15
6. PSI						-	-.09	-.03	.01	-.03	-.04	-.01	-.13	.17	.05	-.05
7. AS–Q							-	**.90**	**.94**	**.82**	**.77**	**.82**	-.19	-.20	**-.31**	-.07
8. VS–Q								-	**.94**	**.82**	**.86**	**.87**	-.13	-.13	**-.26**	.002
9. AVS–Q									-	**.84**	**.82**	**.86**	**-.38**	-.16	**-.40**	-.001
10. AS–N										-	**.89**	**.95**	-.13	-.17	**-.33**	-.054
11. VS–N											-	**.93**	-.11	.08	**-.25**	.04
12. AVS–N												-	-.12	**.25**	**-.31**	-.14
13. Facil–Q													-	-.05	**.49**	-.11
14. Facil–N														-	.14	**.47**
15. Race–Q															-	.03
16. Race–N																-

Note: Grey highlight $= p < .05$.

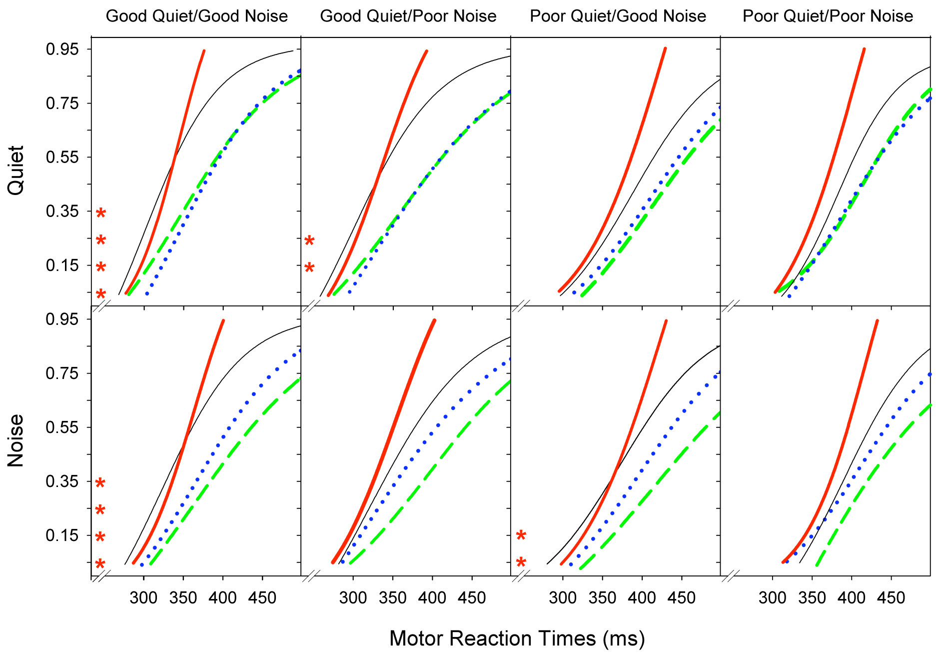

Figure 1. Cumulative density functions (CDFs) for auditory (AS – green dashed line), visual (VS – blue dotted line), audiovisual (AVS – black line) stimuli and the added AS+VS CDF for child groups (red thick line): Good Quiet/Good Noise, Good Quiet/Poor Noise, Poor Quiet/Good Noise, and Poor Quiet/Poor Noise. CDFs were calculated by determining the probability of MRTs from .05 to .95 in intervals of .1 (y-axis depicts probability). An asterisk (*) next to each probability level indicates a significant violation of the race models' prediction of inequality ($p < .05$ with a Bonferroni correction), when the AVS CDF is significantly faster than the summed AS+VS CDF at that probability level.

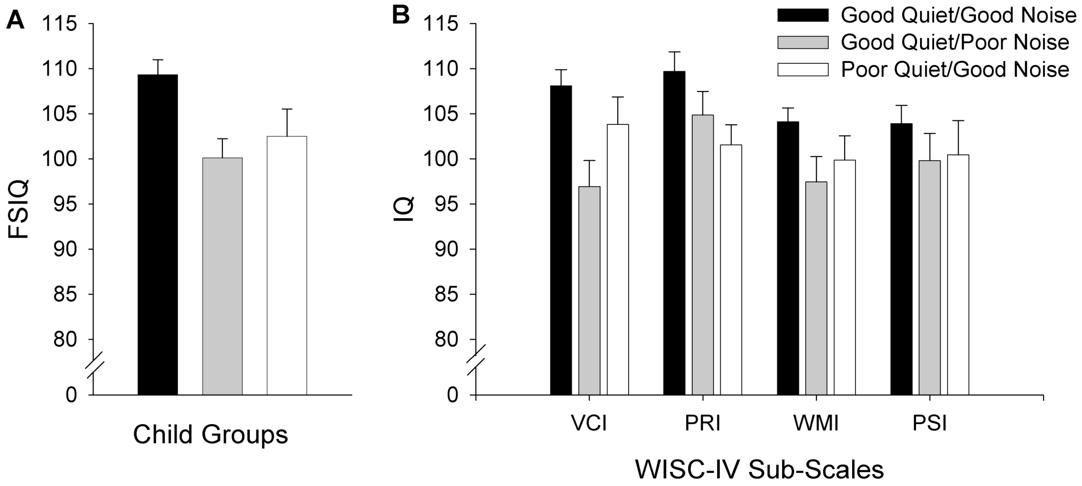

Figure 2: Mean Full Scale Intelligence Quotient (FSIQ) measures (+*SEM*) for child groups: Good Quiet/Good Noise, Good Quiet/Poor Noise, and Poor Quiet/Good Noise groups (**A**). Mean IQ scores (+*SEM*) on the WISC-IV subscales: Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI) and Processing Speed Index (PSI) for children in the Good Quiet/Good Noise, Good Quiet/Poor Noise, and Poor Quiet/Good Noise groups (**B**).

Appendix A

The six male children identified as poor multisensory integrators in both quiet and noisy conditions (Poor Quiet/Poor Noise group) were sex and age match to children who showed good multisensory facilitation in both quiet and noise (Good Quiet/Good Noise group). As can be observed in Table S3, children with poor multisensory facilitation in both quiet and noise tended to score lower on WISC-IV measures than children in the Good Quiet/Good Noise group. However, given the very low sample size, *t*-test comparisons were only significant for the WISC PSI sub-scale and level of gain in motor speed in noise (Facil – N) (see Table A1).

Table A1

Mean (Years, Months) ± Standard Error of the Mean (SEM) for Age, Full Scale Intelligence Quotient (FSIQ), Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), Processing Speed Index (PSI), and Level of Multisensory Facilitation in Quiet (Facil – Q) and Noise (Facil – Noise). For Independent Sample t-Tests (df =10) t-Values and p-Values are Also Presented.

	Good Quiet/Good Noise	Poor Quiet/Poor Noise	*t*-values	*p-values*
Age	9, 3 ± 0, 8	9, 2 ± 0, 9	0.07	> .05
FSIQ	113 ± 6.05	105 ± 5.26	0.96	> .05
VCI	111 ± 6.94	105 ± 5.75	0.59	> .05
PRI	112 ± 8.80	107 ± 6.61	0.44	> .05
WMI	102 ± 3.65	103 ± 3.77	-.19	> .05
PSI	113 ± 5.05	97 ± 3.41	2.63	.03*
Facil – Q	36.26 ± 8.47	18.21 ± 10.14	1.37	> .05
Facil – N	48.63 ± 6.19	23.55 ± 7.23	2.64	.03*

Note: * $p < .05$.