On the Relationship between Dynamic Visual and Auditory Processing and Literacy Skills; Results from a Large Primary-school Study

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Three hundred and fifty randomly selected primary school children completed a psychometric and psychophysical test battery to ascertain relationships between reading ability and sensitivity to dynamic visual and auditory stimuli. The first analysis examined whether sensitivity to visual coherent motion and auditory frequency resolution differed between groups of children with different literacy and cognitive skills. For both tasks, a main effect of literacy group was found in the absence of a main effect for intelligence or an interaction between these factors. To assess the potential confounding effects of attention, a second analysis of the frequency discrimination data was conducted with performance on catch trials entered as a covariate. Significant effects for both the covariate and literacy skill was found, but again there was no main effect of intelligence, nor was there an interaction between intelligence and literacy skill. Regression analyses were conducted to determine the magnitude of the relationship between sensory and literacy skills in the entire sample. Both visual motion sensitivity and auditory sensitivity to frequency differences were robust predictors of children's literacy skills and their orthographic and phonological skills. Copyright © 2002 John Wiley & Sons, Ltd.

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INTRODUCTION

Proficient readers, particularly of inconsistent orthographies such as English, need to use multiple strategies to accurately and swiftly decode lexical strings. For example, the correct pronunciation of exception words such as 'foreign' depends on the ability to access the item from the orthographic lexicon at the whole word level with minimal aid from the phonological processor, which yields insufficient output to successfully name this word. In contrast, most words, including those with very low word frequencies such as 'antidisestablishmentarianism', can be successfully read aloud using a phonological 'sounding out' strategy even if they have not been encountered previously. Establishing a flexible and adept word retrieval system that is sensitive to both phonological and orthographic structure is therefore central to developing reading expertise. This is especially true in languages where the rules that specify the mappings between grapheme and phoneme are not invariant.

The ability to use these subprocesses in visual word recognition does not, however, develop spontaneously; children must be taught how to read, and more advanced decoding strategies depend upon the foundational knowledge accrued previously. For example, knowledge of the rudiments of the alphabetic principle enables children to attempt word pronunciations based first on single letters and letter clusters, but later they are able to also utilize large grain sizes of information, such as how to pronounce common spelling patterns up to the level of the whole word (Ehri, 1997; Goswami, 1988). Yet, when children first begin to learn to read, they may use holistic visual analysis to retrieve words from lexicon by sight rather than relying upon phonological decoding skills that are not yet fully developed (Frith, 1985; Ehri and Wilce, 1985). This pre-alphabetic stage (Ehri and Wilce, 1985) precedes the rapid gains in sight word recognition achieved by most children once the rules that specify how words may be decoded alphabetically are well learned.

For poor readers a deficit in acquiring awareness of how graphemes systematically map onto phonemes is one main impediment to their reading progress (Bradley and Bryant, 1978; Wagner and Torgeson, 1987; Rack *et al.*, 1992). However, while the strong relationship between the development of phonological awareness and learning to read holds for most languages (see Goswami, 1997, for review), disabled readers of more transparent orthographies (such as German or Italian) may not demonstrate obvious deficits in some measures of phonological skill because the rules which specify the grapheme–phoneme mappings in these languages are extremely consistent and therefore overlearned by most readers (Wimmer, 1993). Instead, the reading deficit in these more transparent orthographies can be more obviously observed in achievement measures that place a high demand on orthographic processing, such as spelling, and in tasks of reading fluency. Similarly, in English-speakers, a small subset of disabled readers have deficits in word recognition that reflect impaired orthographic, but relatively normal phonological, processing skills (Castles and Coltheart, 1993; Manis *et al.*, 1996). Other experimental studies have shown that phonological and orthographic processing operate with at least partial independence and can yield different patterns of reading disorder when they are impaired (Stanovich *et al.*, 1997; Castles *et al.*, 1999). The development of both orthographic and phonological skills is also influenced by genetic mechanisms, and it has been shown that these skills are, at least in part, inherited independently (Olson *et al*., 1989, 1994) and may map onto different chromosome loci (Fisher *et al*., 1999, 2002).

Sensory processing in reading disability

A distinct yet overlapping stream of research has focused on the neural mechanisms of reading disability, and in particular, the role of sensory processing in literacy skill acquisition and dysfunction (see Habib, 2000; Talcott and Witton, 2002, for review). A number of studies have shown that groups of poor readers are less able to detect and discriminate basic auditory and visual stimuli than both age and reading-age matched controls (see Farmer and Klein, 1995, for review; cf. Studdert-Kennedy and Mody, 1995). When disabled readers' performance was impaired, this has been attributed mainly to poor temporal processing of stimuli; either when they are brief or rapidly presented (see Farmer and Klein, 1995), or dynamic and changing in real time (Witton *et al*., 1998, Witton *et al*., in press).

The most consistent evidence for an auditory processing deficit associated with reading disability has been demonstrated on measures of frequency discrimination. Groups of dyslexics have been shown to have higher thresholds (i.e. reduced sensitivity) on tasks that require the detection of small frequency differences between two tones. This effect has been measured psychophysically in both adult dyslexics and controls (e.g. McAnally and Stein, 1996; Hari *et al*., 1999; cf. Hill *et al*., 1999; Ahissar *et al*., 2000; France *et al*., 2002) and in dyslexic and control children (Tallal, 1980; deWeirdt, 1988). It has also been shown in dyslexic and control adults using more direct electrophysiological measures of the neural processing that underlies stimulus detection (Baldeweg *et al*., 1999; Nagarajan *et al*., 1999). Furthermore, sensitivity to frequency differences may parallel reading ability, and especially phonological skill, in adults (Ahissar *et al*., 2000). This suggests a more direct mechanistic link between acoustic processing and reading skill. Auditory processing could affect the proficiency with which phonological skills are acquired and represented in the brain, via mechanisms of speech perception (McBride-Chang, 1996).

Sensory deficits in poor readers have also been identified in the visual modality. Early work by Lovegrove and colleagues provided evidence for an association between developmental dyslexia and selectively reduced sensitivity of the transient system, which mediates the fast and accurate temporal processing of stimuli in the visual system (Lovegrove *et al*., 1986; for reviews, see Lovegrove, 1991; Lovegrove and Williams, 1993; see also Hogben, 1997; Stein and Walsh, 1997; cf. Skottun, 2000). The sensitivity of the transient visual system, at a cortical level, is commonly measured by assessing sensitivity to coherent motion in random dot kinematograms (Newsome and Paré, 1988; Newsome *et al*., 1989). A number of psychophysical studies have shown that groups of poor readers are less sensitive than controls to motion stimuli (Cornelissen *et al*., 1995; Witton *et al*., 1998; Everatt *et al*., 1999; Slaghuis and Ryan, 1999; Hansen *et al*., 2001). Differences between groups have also been demonstrated with more direct, neuroimaging techniques (Eden *et al*., 1996; Demb *et al*., 1997). Sensitivity to such dynamic visual stimuli has also been more directly linked with the facility with which orthographic information can be extracted from text (Cornelissen *et al.*, 1998; Talcott *et al.*, 2000); some authors have argued for a link between transient visual sensitivity and mechanisms of phonological assembly (Cestnick and Coltheart, 1999).

Caveats: links between sensory processing and literacy skills

In the literature, the association between deficits of sensory skills and reading difficulties has had a long and tumultuous history. Ever since Pringle-Morgan (1896) published a case-study of a child with 'visual word-blindness', it has been suggested by some researchers (cf. Hulme, 1988; see Farmer and Klein, 1995 for review) that deficits in sensory skills can play a causal role in some children's failure to develop proficient reading skills. Groups of children (and adults) with dyslexia have been shown to be less sensitive than controls on tasks of processing basic visual, acoustic and sensorimotor stimuli (see reviews by Stein and Walsh, 1997; Fawcett and Nicolson, 1999; Wright *et al.*, 2000), but these deficits are rarely characteristic of all the poor readers within the group. Negative findings of overall group differences in sensory processing have also been reported (e.g. Gross-Glenn *et al.*, 1995; Walther-Müller, 1995; Hill *et al.*, 1999), suggesting that differences in sample selection might mediate some of the different patterns of result found across studies. In light of the ubiquitous deficits in phonological skills demonstrated by poor readers of all ages (Wagner and Torgeson, 1987; Rack *et al.*, 1992; van Izendoorn and Bus, 1994; Pennington *et al.*, 1990) these small (or, sometimes, non-existent) effects have sometimes been interpreted as evidence that sensory skills play no role in the aetiology of reading impairments (Hulme, 1988; Bishop *et al.*, 1999). However, this argument appears to assume that reading difficulties must result from a single underlying deficit, without giving much credence to the hypothesis that reading difficulties can result from the contribution of a number of factors. For example, although the most proximal cause of most reading impairments is in phonological processing, a number of factors could potentially constrain this general ability, ranging from low-level sensory (e.g. basic acoustic processing of speech) to high-level cognitive (e.g. intelligence) variables.

Two main issues, with respect to the role of sensory processing skills in reading disability, appear to lie at the core of much of the disagreement on this issue in the field of dyslexia research as a whole. First, the majority of studies have employed small, selected groups of dyslexic and control readers for their analyses. At best, such studies are limited in their ability to generalize the magnitude of any effects between groups to the overall population. At worst, small samples of subjects selected on the basis of inclusionary criteria that are idiosyncratic to a particular study can over- or under-estimate both the prevalence of a particular deficit in a group of individuals and the magnitude of any overall difference between groups on the task of interest. Also, *group* differences on a given task may not reflect the performance of any individual, making it difficult to assess the nature of the relationship between performance on, for example, a task of sensory processing and on a measure of cognitive or linguistic skill.

In this study, we therefore, evaluated the role of sensory skills in reading development and disability by obtaining a large, epidemiological sample ($n = 350$) of school children, between the ages of 7 and 11 years. Such a large, unselected, sample enabled the assessment of the variability in sensitivity on two tasks of sensory processing (frequency discrimination and motion detection) in the general population of school age children in normal classrooms. We did not sample special classrooms, in which we would expect to find the children with the most severe reading impairments; instead we tested children across a wide range of reading ability that enabled us to conservatively estimate the magnitude of differences between good and (relatively) poor readers on our tasks. Each child in the cohort also completed an assessment battery that included measures of general intelligence, literacy achievement, and reading-component skills, in addition to tasks of visual and auditory processing. Such measures enabled assessment of the relationship between measures of sensory processing and reading skills for the group as a whole, across a broad range of ability. Here we present two analyses to demonstrate these relationships. We first investigated whether overall differences in sensory processing could be demonstrated in this large sample, by comparing children divided into groups on the basis of their literacy achievement and non-verbal cognitive skills. Since sensory processing skills have been suggested to co-vary with literacy skills across a wide range of ability (e.g., Talcott *et al.*, 2000), additional analyses explored the issue of individual differences in more detail, by measuring the ability of these sensory processing measures to predict variance in reading and component skills across the sample as a whole.

METHOD

Participants

The sample comprised 350 children (179 girls, 171 boys) between the ages of 84 and 143 months [M(S.D.) = 112.6 (14.1)]. All of the children attended mainstream primary schools within the local education authority. Twenty-four schools participated, and the children were sampled from these as equally as possible. Subject participation depended on parental permission; permission slips were distributed to the parents or guardians of all of the children of the appropriate age in the school. The positive responses provided a pool from which participating children were selected at random. Children who did not have English as a first language were not included in the study, but no other selection criterion was applied.

Psychometric measures

Standardized measures of cognitive and literacy skill

The similarities, matrices, and recall of digits subscales from the British Abilities Scales (BAS-R; Elliot *et al.*, 1983) were administered as measures of children's cognitive skills. These measures comprise three of the four subscales suggested by the authors of the BAS-R as suitable for obtaining a short-form intelligence quotient. The measures sampled both verbal reasoning (similarities) and non-verbal reasoning (matrices) as well as short-term verbal working memory (recall of digits). The single word reading and spelling measures from the BAS-R were administered. The average performance on the reading and spelling measures was defined as the child's 'literacy skill' (LIT). All of the BAS measures are reported as standard scores referenced to age-adjusted, population norms [M(S.D.) = 50 (10)].

Measures of component literacy skills

Each child also completed the following measures of reading component skills: exception and non-word naming (Castles and Coltheart, 1993); spoonerisms (Gallagher and Frederickson, 1995) and a word-pseudohomophone discrimination task (Olson *et al.*, 1994). Batteries of exception word (e.g. 'yacht') and non-word (e.g. 'tegwop') naming have proven useful for assessing children's abilities to use lexical and non-lexical strategies to pronounce words and word-like letter strings (e.g. Castles and Coltheart, 1993; Coltheart and Leahy, 1996). Such measures have also become standard metrics to determine reading disability subtypes within the framework of the dual route model (Castles and Coltheart, 1993; Manis *et al.*, 1996). We used stimuli from Castles and Coltheart (1993), consisting of 30 each of exception (irregular) words and pseudowords (non-words). The exception and non-word stimuli were presented to the subjects in lists; these were printed in clear, 14-point, lower-case Arial font (*sans serif*), on a laminated sheet of paper. The children were instructed to read the words out-loud, and to proceed as quickly as possible without making unnecessary errors. They were told to provide their best guess when they were unsure about the pronunciation of a word and then to proceed to the next word. Both the total number of errors and the time taken to read all 30 words were recorded for each set of words. Accuracy data were converted to percent correct for analysis. A 3 minute maximum time limit was imposed for each list (although this limit was very rarely reached).

Spoonerisms

The Spoonerisms subtest of phonological assessment battery (PhAB; Gallagher and Frederickson, 1995) was administered to each child. This measure taps the ability of the subject to perform increasingly difficult phoneme elisions for words that are presented to them orally. The measure is divided into three separate sections of increasing difficulty. Practice items are administered at the beginning of each section. In Section 1, the initial phoneme from a real word is removed and replaced with another phoneme to yield a new word. For example 'dog' and '1' makes 'log'. In Section 2, two real words are read aloud and the task is to delete the initial phonemes from each of the words, and to replace the phoneme from the first word with the phoneme from the second word. For example, 'dog' and 'lick' makes 'log'. In the final section the subject generates Spoonerisms by deleting the initial phoneme from each of two words, substituting one for the other. For example, 'little pup' makes 'pittle lup'. A total of 40 responses were scored: 10 each from parts 1 and 2; and 20 (a score of 1 per each item correct) for the Spoonerisms. Percent correct was determined for the entire list.

Word-pseudohomophone discrimination

A word-pseudohomophone discrimination test, adapted from Olson *et al*. (1994), assessed orthographic sensitivity. Subjects viewed two words that were presented side-by-side in 18-point font on a computer screen; one was a real word target (e.g. 'rain') the other was a pseudohomophone foil (e.g. 'rane'). This is considered a task of orthographic skill because the correctly spelled word in the word-pseudohomophone pair cannot be determined from the output of the phonological processor alone, because this mechanism yields the same output for both items (Olson *et al*., 1994). The children were instructed that, although both items *sound* like real words, only one of them is spelled correctly. Their task was to decide which of the words was the correctly spelled target and to press the appropriate button on the computer keyboard as quickly as possible, without making unnecessary errors by trading accuracy for speed. Feedback was presented on the computer screen following each response. Eighty items were presented, following a series of eight practice items. Percent correct and response latency for the 80 experimental items were scored off-line.

Psychophysical measures of sensory thresholds

Auditory frequency discrimination

We measured sinusoidal frequency discrimination for tone pairs that were centred around 500 Hz (e.g. 480 vs 520 Hz). Frequency ranged from 420 to 580 Hz in 1-Hz steps in two interleaved staircases, one starting from 480 Hz and working up, the other starting at 580 Hz and working down. Tonal stimuli were generated as wave files and were output through a Soundblaster sound card in a laptop PC. Each stimulus lasted 300 ms onset-to-offset, had cosine-gated 20-ms rise and fall times, and was presented binaurally through calibrated Sennheiser HD520 headphones at a comfortable listening level (approximately 60 dB SPL).

On each experimental trial, two tones occurred in sequence; these were separated by a 400-ms silent inter-stimulus interval. Following each trial, the child orally reported to the experimenter whether the stimuli had identical pitches ('same') or different pitches ('different'). The experimenter then entered the child's response into the computer. The child did not receive feedback about his or her performance. Two estimates of threshold were obtained using an interleaved adaptive staircase procedure. Each staircase followed a 1-up, 2-down rule to estimate the 70.7% correct point on the psychometric function (Levitt, 1970). After two successive correct trials, the frequency-difference between the tones was decreased by 1 Hz. After an incorrect trial, the frequency-difference was increased by 1 Hz. In addition, a random 20% of trials were 'catch' trials in which the frequency difference was either 0 or 60 Hz, (a value above the detection threshold even for the children with the lowest sensitivities to these stimuli). The catch trials were not used in the calculation of child's threshold; they were used to estimate the participant's general vigilance to the auditory task and any response bias in their same/different judgements. Threshold was defined as the arithmetic mean of the last six of eight reversals for each staircase. These two frequency resolution estimates were averaged to determine the subject's overall threshold. The correlation, across all subjects, between the two threshold estimates, was high ($r = 0.76$), indicating a good degree of inter-trial reliability.

Visual coherent motion

The coherent motion stimuli were random dot kinematograms. These comprised two patches of 300 high-luminance (80.6 cd/m^2) white dots (1 pixel), presented on the dark background (0.98 cd/m^2) of an LCD laptop computer display. At a fixed viewing distance of 57 cm, each patch subtended $10 \times 14^\circ$ visual angle, separated horizontally by 5°.

The percentage of coherently moving dots (angular velocity $= 7.0^\circ\,s^{-1}$) within a given software animation frame (50 ms) was varied adaptively to the subject's detection threshold. This was defined as the proportion of dots required for the subject to detect reversing motion in either the left or right panel. The coherent dots changed direction every 1000 ms throughout the 2500-ms stimulus interval. The non-coherent dots moved randomly between frames in a Brownian manner. In order to eliminate the possibility of detecting the direction of coherent motion by following the trajectory of a single dot, each dot had a fixed lifetime of five animation frames (250 ms) after which it would disappear before being regenerated at a random place within the stimulus patch. Percentage of coherent motion was corrected for finite dot lifetimes so that in the case when all dots were moving coherently during an animation frame, and the dots had a lifetime of five frames, this is described as 80% coherence.

The children were asked to visually inspect each stimulus patch and report which patch contained coherent motion by pointing with their finger. The experimenter recorded these responses by pressing an appropriate key on the computer. The child did not receive feedback about his or her performance. Coherent motion was varied to the subject's motion detection threshold by a weighted, 1-up, 1-down, 2-alternative forced-choice adaptive procedure (Kaernbach, 1991). For each correct response, the modulation depth was reduced by 1 dB (a factor of 1.122) and for each incorrect response the modulation depth was increased by 3 dB (a factor of 1.412). Threshold estimates were determined by taking the geometric mean of the last six of eight reversal points within a given series of trials. Each series was repeated twice, with the arithmetic mean of these two estimates defined as the subject's coherent motion detection threshold. The correlation, across all subjects, between the two threshold estimates was 0.71, a value that indicates adequate inter-trial reliability.

For each psychophysical test, we monitored the child's performance on practice trials at stimulus values that were well above their detection threshold. This verified that they understood the tests and could complete them reliably.

RESULTS

Group differences in visual and auditory sensitivity

The sample of 350 children was divided into groups of high and low ability by performing median splits on the age-standardized measure of non-verbal intelligence (BAS matrices) ($Mdn = 54$); and quartile splits on the measure of literacy skill, the average of the reading and spelling standard scores (first through third quartile splits corresponded to standard scores of 46.9, 53.7, and 61.0, respectively). Descriptive statistics for the resulting groups on the study measures are shown in Table 1.

Table 1. Descriptive statistics for the subgroups of children as defined by median split on the non-verbal measure of cognitive skills and quartile splits on literacy skill performance

Measure (unit) Mean (S.D.)	Nonverbal Intelligence >50%ile				Nonverbal Intelligence <50%ile			
	GROUP 1 Literacy <25%ile ($n = 27$)	GROUP 2 Literacy 25–49%ile ($n = 38$)	GROUP 3 Literacy 50–74%ile ($n = 49$)	GROUP 4 Literacy 75–100%ile ($n = 68$)	GROUP 5 Literacy <25%ile ($n = 60$)	GROUP 6 Literacy 25–49%ile ($n = 47$)	GROUP 7 Literacy 50–74%ile ($n = 41$)	GROUP 8 Literacy 75–100%ile ($n = 20$)
AGE (mos.)	108.7 (11.2)	109.3 (13.4)	111.7 (12.5)	104.7 (12.0)	116.6 (14.3)	119.4 (16.6)	119.0 (14.6)	111.9 (14.6)
MAT (SS)	61.1 (3.9)	61.7 (4.8)	63.4 (5.3)	64.3 (4.9)	47.7 (6.0)	49.3 (5.1)	50.6 (4.8)	49.7 (5.4)
SIM (SS)	57.6 (7.8)	57.9 (7.2)	62.0 (7.1)	66.5 (5.9)	52.0 (8.0)	54.4 (9.1)	58.3 (8.3)	60.7 (8.0)
DIG (SS)	43.6 (7.1)	48.1 (8.7)	51.1 (9.3)	52.4 (8.9)	40.8 (8.1)	44.6 (8.5)	48.2 (8.4)	51.2 (10.8)
SWR (SS)	42.9 (4.7)	52.2 (3.9)	59.3 (4.1)	68.4 (4.1)	40.6 (5.2)	50.4 (3.3)	58.8 (4.1)	65.9 (12.9)
SPL (SS)	41.9 (3.0)	50.0 (3.7)	55.8 (4.7)	63.5 (4.7)	41.3 (4.5)	50.1 (2.5)	54.5 (3.8)	61.0 (4.6)
EXC (PC)	34.0 (16.2)	51.9 (16.3)	63.2 (14.5)	67.6 (10.7)	34.2 (18.3)	54.3 (15.5)	66.0 (12.4)	69.5 (12.9)
NON (PC)	35.7 (17.0)	64.0 (20.9)	77.4 (18.2)	85.1 (10.6)	34.3 (20.2)	60.8 (22.2)	79.5 (13.4)	85.2 (12.3)
SPO (PC)	51.0 (18.2)	64.0 (20.4)	75.1 (18.2)	80.0 (13.6)	41.4 (20.8)	63.8 (22.5)	71.2 (13.1)	67.4 (18.9)
ORT (PC)	64.9 (10.5)	75.2 (12.1)	84.4 (8.4)	87.4 (8.4)	68.1 (10.8)	79.8 (10.2)	85.8 (8.3)	90.8 (7.9)
MOT (%)	1.20 (0.13)	1.22 (0.18)	1.17 (0.14)	1.17 (0.13)	1.30 (0.24)	1.28 (0.22)	1.18 (0.20)	1.16 (0.19)
FRE (Hz)	1.29 (0.15)	1.23 (0.13)	1.22 (0.17)	1.23 (0.14)	1.32 (0.16)	1.28 (0.18)	1.22 (0.16)	1.27 (0.21)
CT (PC)	0.74 (0.14)	0.83 (0.16)	0.85 (0.13)	0.84 (0.14)	0.76 (0.15)	77.9 (15.7)	0.80 (0.15)	0.87 (0.12)

MAT: BAS matrices, SIM: BAS similarities, BASD: BAS Recall of Digits, SWR: BAS single-word reading, SPL: BAS spelling, EXC: Exception word naming, NON: non-word naming, SPO: Spoonerisms performance; ORT: word pseudohomophone discrimination; MOT: log 10 coherent motion threshold; FRE: log 10 frequency discrimination threshold; CT: catch trials of frequency discrimination task; SS: standard score (population mean (S.D.) = 50 (10)), PC: percent correct.

The distributions of the sensitivity data for both the frequency discrimination and coherent motion detection tasks were non-Gaussian, requiring log 10 transformation for normalization prior to statistical analysis. Two two-way (literacy group × intelligence group) ANOVAs, with frequency difference threshold and coherent motion threshold as the dependent variables, were computed, with all effects evaluated at a significance level of 0.05. For the motion task, the ANOVA revealed a significant main effect of literacy skill [$F(1, 346) = 4.48$, $p < 0.01$), in the absence of a significant main effect for intelligence ($p = 0.10$) or an interaction between these factors ($p = 0.28$). The ANOVA for the frequency discrimination task yielded similar results; a significant main effect of literacy group [$F(1, 346) = 5.11$, $p < 0.01$], in the absence of either a main effect of intelligence ($p = 0.28$) or an interaction effect ($p = 0.56$). Figure 1 presents boxplots of the subgroups' thresholds on the sensory processing tasks. Although the interaction effect for the motion task was not significant, a one-way ANOVA with Tukey *post hoc* tests revealed that Group 5, the children with BAS matrices scores below the 50th percentile and literacy skills in the lowest quartile, was less sensitive to coherent motion than groups 3, 4 and 7. No significant between-group effects were found for the frequency discrimination measure.

In addition to effects of intelligence, there are a number of other candidate variables that could potentially modulate group effects on the measures of sensory processing (or any other measure). One such variable is the child's ability to maintain vigilance during the administration of the psychophysical task. In the frequency discrimination task, 20% of the overall trials were catch trials in which the stimuli were either of the same pitch or had a frequency difference of 60 Hz, a pitch difference detectable by even the most poorly performing subjects. Because these easily detectable stimuli occur at random throughout the test session, performance on these trials can provide a good measure of the participant's vigilance during testing. We therefore used catch trial performance as a covariate in an ANCOVA to control for individual differences in task vigilance on the frequency discrimination task. The analysis revealed a strong effect of the covariate [$F(1, 346) = 13.70$, $p < 0.001$], yet the overall pattern of a main effect of literacy group [$F(1, 346) = 2.61$, $p < 0.05$], without a main effect of intelligence group ($p = 0.21$) or an interaction between these factors ($p = 0.73$), was still evident. Despite the apparent modulating effect of attentional vigilance on performance on the frequency discrimination measure, there were no significant differences between groups on catch trial performance [One-way ANOVA, $F(7, 341) = 0.96$, $p > 0.05$].

Regression analyses

Zero-order correlations between the study measures are shown in Table 2. Relationships between the sensory processing tasks and measures of literacy skill were explored for the sample as a whole using hierarchical multiple regression analysis. As in Table 1, we use the standardized test of non-verbal reasoning (matrices) as our measure of cognitive skill.

Regression analyses were performed on the overall measure of literacy skill and, separately, for the summary measures of orthographic and phonological

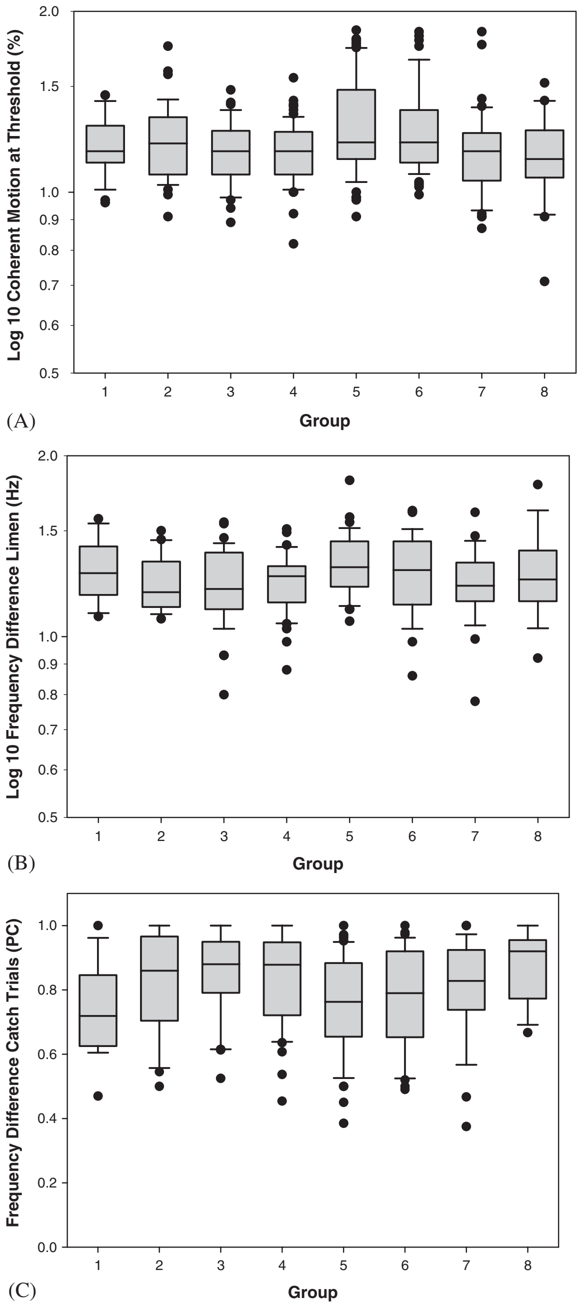

Figure 1. Boxplots of the subgroups' thresholds on the sensory processing tasks of coherent motion detection (A), frequency discrimination (B), and proportion correct (PC) on the catch trials in the frequency discrimination task (C). Lines within boxplots depict group medians, box edges define the 25th and 75th percentiles, and whisker edges define the 10th and 90th percentiles for these data. Solid circles represent outlying data points. See text and Table 1 for further details.

processing. These summary measures were derived for each individual by taking the first principal component for the two tasks of ORT and EXC designated as orthographic processing; and NON and SPO, designated as phonological processing. These component measures are not age-standardized. Because they correlate significantly with age (orth: $r = 0.42$; phon: $r = 0.25$), age was always entered as the first regressor, followed by entry of either performance on the measure of non-verbal intelligence or a sensory threshold. Summaries of the regression models are shown in Table 3.

Tables 3(a) and 3(b) show the relationships between sensitivity to our sensory stimuli and literacy skill. Table 3(a) shows the relationship between literacy skill and frequency discrimination (FRE) both before and after entering the non-verbal intelligence measure (MAT). Entry of FRE prior to MAT shows that auditory thresholds accounted for 8% of the variance in literacy skill. Entering MAT first reduces the unique variance in literacy accounted for by this measure to 4%, suggesting that about half of the variance accounted for by the auditory measure overlaps with that accounted for by non-verbal intelligence. Entry of catch trial performance (CT) as an additional regressor did not capture additional variance in literacy skill beyond that accounted for by MAT and FRE.

Table 3(b) shows the relationship between visual coherent motion sensitivity (MOT) and literacy skill both before and after entering MAT. Entry of MOT prior to MAT shows that visual thresholds accounted for 7% of the variance in literacy skill. Entering MAT first reduces the unique variance accounted for by this measure to 3%, suggesting that about 4% of the variance in literacy skill accounted by this variables overlaps with non-verbal intelligence.

Tables 3(c) and 3(d) summarize the relationships between the sensory processing tasks and the measure of phonological skill. Table 3(c) shows that thresholds for auditory frequency discrimination can account for 12% of the

Table 2. Correlations between study measures. Critical values for r at $p < 0.01 = 0.14$; ($n = 350$)

	AGE	MAT	SIM	DIG	SWR	SPL	EXC	NON	SPO	ORT	MOT	FRE
MAT	−0.37											
SIM	−0.26	0.47										
DIG	−0.10	0.29	0.36									
SWR	−0.13	0.43	0.54	0.46								
SPL	−0.28	0.39	0.42	0.38	0.79							
EXC	0.39	0.18	0.34	0.30	0.74	0.54						
NON	0.21	0.28	0.31	0.34	0.75	0.65	0.75					
SPO	0.22	0.36	0.39	0.39	0.61	0.49	0.62	0.69				
ORT	0.39	0.14	0.21	0.23	0.65	0.59	0.81	0.67	0.52			
MOT	−0.18	−0.13	−0.15	−0.10	−0.20	−0.17	−0.26	−0.24	−0.27	−0.25		
FRE	−0.20	−0.20	−0.27	−0.18	−0.25	−0.08	−0.27	−0.35	−0.37	−0.27	0.13	
CT	0.14	0.19	0.15	0.31	0.32	0.18	0.34	0.30	0.28	0.28	−0.24	−0.27

MAT: BAS matrices, SIM: BAS similarities, BASD: BAS Recall of Digits, SWR: BAS single-word reading, SPL: BAS spelling, EXC: Exception word naming, NON: non-word naming, SPO: Spoonerisms performance; ORT: word pseudohomophone discrimination; MOT: log10 coherent motion threshold; FRE: log10 frequency discrimination threshold; CT: catch trials of frequency discrimination task.

Table 3

	Multiple R	R^2	R^2 change		Multiple R	R^2	R^2 change
(a) Auditory processing and literacy skill (DV)							
IV1. AGE	0.21	0.04		IV1. AGE	0.21	0.04	
IV2. MAT	0.44	0.19	0.15	IV2. FRE	0.35	0.12	0.08
IV3. FRE	0.48	0.23	0.04	IV3. MAT	0.48	0.23	0.11
IV4. CT	0.48	0.23	0.003*	IV4. CT	0.43	0.23	0.003*
(b) Visual processing and literacy skill (DV)							
IV1. AGE	0.21	0.04		IV1. AGE	0.21	0.04	
IV2. MAT	0.44	0.19	0.15	IV2. MOT	0.33	0.11	0.07
IV3. MOT	0.47	0.22	0.03	IV3. MAT	0.47	0.22	0.11
(c) Auditory processing and phonological skill (DV)							
IV1. AGE	0.25	0.06		IV1. AGE	0.25	0.06	
IV2. MAT	0.53	0.28	0.22	IV2. FRE	0.42	0.18	0.12
IV3. FRE	0.57	0.32	0.04	IV3. MAT	0.57	0.32	0.14
IV4. CT	0.57	0.32	0.001*	IV4. CT	0.57	0.32	0.001*
(d) Visual processing and phonological skill (DV)							
IV1. AGE	0.25	0.06		IV1. AGE	0.25	0.06	0.06
IV2. MAT	0.53	0.28	0.22	IV2. MOT	0.35	0.12	0.06
IV3. MOT	0.56	0.31	0.03	IV3. MAT	0.56	0.31	0.19
(e) Auditory processing and orthographic skill (DV)							
IV1. AGE	0.41	0.17		IV1. AGE	0.41	0.17	
IV2. MAT	0.52	0.27	0.10	IV2. FRE	0.48	0.23	0.06
IV3. FRE	0.55	0.30	0.03	IV3. CT	0.52	0.27	0.04
IV4. CT	0.57	0.32	0.02	IV4. MAT	0.57	0.32	0.05
(f) Visual processing and orthographic skill (DV)							
IV1. AGE	0.41	0.17		IV1. AGE	0.41	0.17	
IV2. MAT	0.52	0.27	0.10	IV2. MOT	0.49	0.24	0.07
IV3. MOT	0.58	0.34	0.07	IV3. MAT	0.58	0.34	0.10

Summary of the models in which sensory skills were entered as predictor variables of various aspects of reading performance. DV: dependent variable; IV: independent variable (followed by order of entry); *= variable that, when entered, did not explain significant additional variance in the dependent variable of interest.

variance in phonological skill when entered prior to MAT. When entered into the regression after MAT, FRE accounts for a much lower 4% of the variance in phonological skill, suggesting a broad overlap in the variance of phonological skill accounted for by these two measures. Table 3(d) shows that visual motion thresholds can account for up to 6% of the variance in phonological skill; a value that is reduced to 3% when MAT is entered prior to MOT.

Tables 3(e) and 3(f) depict the relationships between sensory processing on our measures and the summary measure of orthographic skill. Table 3(e) shows that thresholds for auditory frequency discrimination can account for 6% of the variance in orthographic sensitivity when entered prior to the MAT variable. When entered after MAT, FRE accounts 3% of the variance in orthographic skills. It was only for the orthographic skills variable that performance on the frequency discrimination catch trials accounted for significant independent variance (2–4%) beyond that accounted for by MAT and FRE. Visual motion thresholds can account for 7% of the variance in phonological skills; a value that remains constant irrespective of whether or not MAT is entered prior to MOT in the regression analysis.

DISCUSSION

Sensory processing differences between good and poor readers?

In a large, epidemiological sample, we found differences in sensory thresholds between groups of children, defined on the basis of standardized measures of non-verbal intelligence and literacy skill. ANOVA results revealed main effects of reading ability for both auditory frequency discrimination and coherent motion detection. In both analyses there was an absence of a main effect of intelligence level or an interaction between intelligence and literacy skill. The finding that sensory thresholds varied as a function of literacy skill converges with recently published evidence (Olson and Datta, 2002). Olson and Datta employed measures of visual contrast sensitivity to test groups of good and poor readers divided according to their overall reading skill. They found a significant main effect of reading group that suggested a linear relationship between contrast sensitivity and reading ability. The effects we found, like Olson and Data, are not large (Eta^2 for the main effects of both sensory measures is approximately 0.04). However, the pattern of results we found suggests that dynamic visual and auditory sensitivity vary with literacy skill.

There is mixed evidence in the literature for differences in sensory processing between groups of poor reader for measures of both visual and auditory processing (see Farmer and Klein, 1995; Talcott and Witton, 2002). In this context, our results suggest that there are a number of potentially important variables that may modulate between-group effects in studies of this kind. In addition to the magnitude of both the reading deficit in the clinical sample of interest, and the difference in reading level between groups (see also Olson and Datta, 2002), our results suggest that it may also be important to consider other subject variables such as intelligence, age, attention, as well as individual patterns of reading deficit (e.g. subtypes).

Although there were few statistically significant differences on the sensory tasks between our groups of readers (defined on intelligence and reading measures), the differences found were limited to those comparisons that involved readers with BAS matrices scores below the 50th percentile and reading skills in the lower quartile. Despite the overall lack of a statistically significant main effect of intelligence, or an interaction between intelligence and reading ability, there remained evidence for significant covariance between sensory thresholds, measures of literacy skill, and our measure of non-verbal intelligence. This was especially apparent in our regression analyses; these showed substantial covariance between the non-verbal intelligence measure and measures of both literacy skill and performance on the sensory processing tasks (see Tables 1 and 3). Results from studies that employed groups of poor readers and controls who are group-matched on intelligence variables, therefore, may differ substantially from those that match subjects in a pair-wise manner.

A second issue pertains to the potential confounding influences of attentional variables. These could be either specific to a sensory task or more generalized, to affect overall performance on any psychometric or psychophysical task battery. In the analyses involving frequency discrimination thresholds, we found a main effect of catch-trials performance when entered as a covariate. This suggests a modulatory influence of attentional variables on sensory thresholds. Despite this, the relationship between reading skill and auditory processing is robust, because the overall pattern of main and interaction effects did not depend on whether or not this variable was entered as a covariate in the analysis.

We also found no evidence that any particular group of children was less able than the others to maintain vigilance on the frequency discrimination task (see Figure 1C). If catch trial performance on our auditory test can be used as a general index of children's attention, our results do not suggest that children with overt deficits in attention fall into any particular reading group. However, this does not rule out the possibility that children with attentional difficulties might cluster in subgroups of reading disability defined in other ways (for example, in accordance with dual route reading models, see for e.g. Castles and Coltheart, 1993; Manis *et al.*, 1996). It may also be important to experimentally examine other aspects of attention with respect to relationships between literacy achievement and cognitive (or sensory) skills. Attention can serve at least three main functions: (1) orienting to environmental stimuli; (2) detecting signals for detailed processing; and (3) maintaining an alert state (Posner and Petersen, 1990). All three are relevant to the study of reading, although such studies are usually more concerned with the significant comorbidity between dyslexia and attention-deficit disorder. It will therefore be important in the future to establish better experimental metrics of attentional processing.

Finally, it may be important to consider issues regarding the heterogeneity of the dyslexic sample with respect to the underlying nature of their reading deficit when assessing evidence for and against an associated sensory deficit. There is some evidence that sensory deficits may be restricted to particular subtypes of poor reader. Two studies of visual contrast sensitivity (Borsting *et al.*, 1996; Ridder *et al.*, 1997) have suggested that deficits in the sensitivity of the peripheral visual system to sensory transients are only evident in a subgroup of dyslexics who demonstrate 'dysphoneidesia' (impaired lexical and phonological processing) under Boder's subtyping hierarchy (Boder, 1973). In contrast, Cesnick and Coltheart (1999) showed that a subtype of dyslexics with specifically impaired phonological decoding skills (perhaps equivalent to Boder's 'dysphonetic' subtype) was specifically impaired on a measure of apparent motion detection. In the auditory/speech domain, little work has been done, although Manis *et al.* (1996) showed that speech perception deficits were representative of poor readers only if they had phonological processing difficulties. Such evidence suggests that methods of sample ascertainment may be a critical variable underlying these mixed results across studies. Broader, opportunity-based, samples may contain a mixture of poor readers with very different profiles on measures of the component skills underlying reading performance (e.g. orthographic and phonological skills). This would reduce the statistical power in detecting a sensory deficit if it were present in only a subset of poor readers. Alternatively, samples of poor reader ascertained with very restrictive inclusionary criteria could include (or exclude) those individuals who would be most likely to demonstrate a deficit in a particular domain of sensory processing.

Do sensory skills predict literacy skills?

For the sample as a whole, our auditory and visual measures predicted significant proportions of the variance in both literacy skill and component reading measures (orthographic and phonological processing). Between 3 and 8% of the variance in literacy skills could be predicted from sensory thresholds on a single measure of sensory processing, even after accounting for the effects of age and our non-verbal measure of intelligence.

With a smaller sample, including an entire classroom of children, Talcott *et al*. (2000) showed strong relationships between motion processing and orthographic coding skills and between auditory processing of frequency modulation (FM) and phonological skills. Motion and orthographic processing correlated to 0.45 after removing the effects of IQ and reading skill, whereas FM and phonological skill were correlated to 0.49. Our present data partially replicate these previous results, although the proportion of the variance in component literacy skills that can be accounted for by sensory processing is lower in this sample. We also have less evidence than that shown by Talcott *et al*. (2000) that the effects of visual and auditory processing are specific to the domains of orthographic and phonological processing, respectively. Nevertheless, we have replicated the finding that children's sensitivity to these stimuli covaries with their phonological and orthographic skills. We also found that an attentional variable explained unique variance on the summary measure of orthographic processing but not on the measure of phonological skill. This suggests that encoding and retrieval of exception words to memory may be specifically disrupted by decreases in attentional resources.

Small effects: causes or correlates

Our data are mute with respect to nature of the mechanism that links sensory processing to literacy skill. In other words our data do not permit us to discount the hypothesis that differences in sensory sensitivity between good and poor readers are simply neurological markers associated with, but not directly related to reading skill. Although our regression data would seem to dispel this argument somewhat, one issue that remains to be clarified is how such relatively small effects in sensory processing could modulate the development of reading and component skills. As an example, we will consider a potential causal chain between poor acoustic processing and deficient phonological skills.

The effect-size of differences between groups of good and poor readers in studies of auditory processing (like that for visual processing) is often small (see for e.g. McAnally and Stein, 1996; Witton *et al*., 1998; Menell *et al*., 1999). It is therefore unlikely that these small differences in the ability to detect or discriminate basic acoustic stimuli is sufficient to directly cause difficulties in distinguishing between phonemes in speech. However, any degradation of phonemic representations would be expected to lead to problems in becoming aware of particular grapheme–phoneme relationships. These degradations could therefore cascade to cause deficits in other phonological tasks such as in recoding of single words (Shankweiler *et al.*, 1979; Wagner and Torgeson, 1987; Manis *et al.*, 1997).

Tallal (1980) suggested that, because acoustic discriminations of some stop consonant phonemes in speech require the detection of a 40-ms frequency sweep in a single formant, inability to detect rapid frequency changes could be sufficient to reduce perception of the identity of certain phonemes and therefore impair their representation in memory by making them more distorted or under-specified (Tallal, 1980; Reed, 1989; cf. Studdert-Kennedy and Mody, 1995; Brady, 1997). However, while dyslexics do have problems with phoneme discrimination (Cornelissen, Hansen, Bradley and Stein, 1996; Mody, Studdert-Kennedy and Brady, 1997; Adlard and Hazan, 1998; cf. Pennington *et al.*, 1990), the between group effects, like those for sensory processing, are usually small. It is plausible that small effect-sizes, measured in simple psychophysical paradigms such as those in this study, could be translated into large effects in the natural speech environment. For example, psychophysically measured thresholds for frequency discrimination of 40 ms tones embedded in a known pattern of other tones range between 10 and 20 Hz (Watson and Foyle, 1985). However, when tone-pattern in which the target is embedded is subject to random change, resulting in a high level of 'stimulus uncertainty', thresholds are increased to hundreds of Hz, even in highly trained subjects (Watson and Kelly, 1981). In speech, a high level of stimulus uncertainty is the rule because the modulations are embedded in complex and varying series of dynamic acoustic events. Thus, the effects of the small deficit in detecting modulations that we have described could be multiplied when experienced within natural speech.

The suggestion that impaired word recognition can result from subtle deficits in 'bottom–up' sensory processing, in addition to 'top–down' difficulties in word parsing at a more cognitive level, has been a contentious issue. It is likely that both of these factors contribute to reading skill acquisition and its dysfunction. However, aside from their separate influences, sensory and cognitive mechanisms must interact whilst reading is actually taking place. Although poor reading skills are often accompanied by acoustic and visual processing deficits, it remains unclear to what extent these problems can be considered causal factors, rather than benign symptoms that are correlated with their reading problems but not directly related to them. Rosen (1999) has suggested two complementary approaches that could be used to better clarify issues regarding causal relationships. The first is to assess the incidence of sensory processing difficulties in persons who read normally; and second, to identify and characterize poor readers who have no such processing problems. In this study our approach has been to focus primarily on the first of these issues; we were interested most in how reading skill might develop in concert with sensory skills. Our data show that sensory skills are small, yet significant predictors of literacy and component skills across the range of reading ability. We will explore the second issue pertaining to individual differences on our sensory processing tasks in future studies.

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