

Automatic Activation of Sounds by Letters Occurs Early in Reading Development,
but is not Impaired in Children with Dyslexia

Running head: AUTOMATIC ACTIVATION OF SOUNDS BY LETTERS

Abstract

The “automatic letter-sound integration hypothesis” (Blomert, 2011) proposes that the decoding difficulties seen in dyslexia arise from a specific deficit in establishing automatic letter-sound associations. We report the findings of two studies in which we used a priming task to assess automatic letter-sound integration. In Study 1, children aged between 5 and 7 years were faster to respond to a speech-sound when primed by a congruent letter, indicating that automatic activation of sounds by letters emerges relatively early in reading development. However, there was no evidence of a relationship between variations in the speed of activating sounds by letters and reading skill in this large unselected sample. In Study 2, children with dyslexia demonstrated automatic activation of sounds by letters, though they performed slowly overall. Our findings do not support the theory that a deficit in “automatic letter-sound integration” is an important cause of reading difficulties but do provide further evidence for the importance of phonological skills for learning to read.

Introduction

A great deal of research has investigated the cognitive skills that predict variations in early reading development. A range of phonological language skills appear to provide the foundation for the development of decoding: specifically phoneme awareness, rapid automatized naming and letter knowledge (Caravolas, Lervåg, Defior, Málková, & Hulme, 2013; Lervåg, Bråten, & Hulme, 2009). Of these three skills, the strongest evidence for a causal relationship is between phoneme awareness (awareness of the sound structure of spoken words) and learning to decode (Hulme & Snowling, 2014). Indeed, the dominant view, is that reading difficulties in developmental dyslexia arise from a core deficit in phonology, possibly operating in combination with other cognitive risk factors (Hulme & Snowling, 2014; Peterson & Pennington, 2015).

In contrast to this view, a number of studies conducted by Blomert and his colleagues (e.g. Blomert, 2011; Blomert & Froyen, 2010; van Atteveldt & Ansari, 2014) have proposed an alternative theory suggesting that a deficit in establishing automatic associations between letters and speech-sounds is a specific causal risk factor for dyslexia. For example, Blomert and Willems (2010) discussing a family risk study of dyslexia write “we did not find any evidence for the claim that phonological awareness deficits cause reading deficits. Instead, we found that problems in learning letter–speech sound associations and integration characterize children at familial risk for dyslexia”. This alternative claims that the phonological deficit in dyslexia is a secondary consequence of problems learning to read (cf. Hulme, Caravolas, Málková, & Brigstocke, 2005) and the primary cause is a deficit in cross-modal learning which leads to problems in forming automatic associations between visual symbols (letters) and phonological elements (phonemes).

This theory might be seen as an extension of the view that letter-sound knowledge is critical for early reading development (Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012; Melby-Lervåg, Lyster, & Hulme, 2012) and is delayed in children with dyslexia (e.g. Torppa, Poikkeus, Laakso, Eklund, & Lyytinen, 2006). However, according to the “automatic letter-sound integration hypothesis”, it is not simply the process of learning letter-sound associations, but rather whether such associations are learned to the point of being automatized that is crucial for developing fluent and efficient reading. This proposal of impaired orthographic-phonological connectivity in children with dyslexia is not entirely new (see Wimmer & Schurz, 2010) and is consistent with the finding that knowledge of letters and orthography influence performance on phonological tasks (Ehri & Wilce, 1980; Castles & Coltheart, 2004). Evidence from training studies also supports the notion that simply knowing letter-sound correspondences differs widely from achieving integration (Widmann et al., 2012; Aravena et al. 2013).

The majority of evidence for the “automatic letter-sound integration hypothesis” comes from functional magnetic resonance imaging (fMRI) and event related potential (ERP) studies. In fMRI studies, typically developing readers suppressed activation in response to mismatched (incongruent) letter-sound pairs as compared to matching letter-sound pairs (Blau et al., 2010; Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009), whereas children and adults with dyslexia failed to suppress activation in response to incongruent letter-speech-sound pairs. This failure to suppress activation (in left hemisphere regions responsible for speech processing) has been interpreted as evidence of a failure to integrate letters with their corresponding speech sounds in dyslexia; but it is notable that this evidence relates to a failure to inhibit activation of mismatching letter-sound pairs, while arguably patterns of

facilitation for matching letter-sound pairs would be more relevant to the processes involved in learning to read.

ERP studies have also suggested atypical (or developmentally delayed) associations between letters and speech-sounds in children with dyslexia (Froyen, Bonte, van Atteveldt, & Blomert, 2009; Froyen, Willems, & Blomert, 2011; Žarić et al., 2014). These studies have employed a range of experimental designs; with the original studies measuring letter-sound integration using a cross-modal mismatch negativity (MMN) paradigm. In the traditional MMN paradigm a negative ERP component is produced when a deviant auditory stimulus is presented following a standard recurring auditory stimulus. In the cross-modal variant of this task, typical 11-year-old readers demonstrate cross-modal enhancement of the MMN approximately 100-250ms after the presentation of an additional corresponding visual letter which has been interpreted as evidence for early and automatic integration (Froyen et al., 2009). In contrast, dyslexic readers of the same age were found to demonstrate only late enhancement of the MMN around 600-750ms after stimulus onset, suggesting that integration of letters and speech sounds was delayed in this group (Froyen et al., 2011), as in younger beginner readers (Froyen et al., 2009). This absence of “cross-modal enhancement” in children with dyslexia might have a variety of explanations other than a deficit in “automatic letter-sound integration”, including slowness in processing phonological information, or a general slowing of information processing. Furthermore, the reliability of MMN measures in younger children is questionable (e.g. Bishop, 2007) and more recent replications using the same cross-modal paradigm have revealed evidence of cross-modal enhancement in children with dyslexia, albeit reduced cross-modal enhancement in children with the most severe reading impairment (Žarić et al., 2014).

There have been relatively few attempts to test the “automatic letter-sound integration hypothesis” using behavioural measures. Existing studies report that children with dyslexia are slower to match letters with their corresponding speech-sounds and slower to decide whether letter-sound pairs are the same or different (Blau et al., 2010; Žarić et al., 2014). However, it is unclear from these experiments whether slower reaction times in the dyslexic group are attributable to a core phonological deficit, rather than differences in “automatic letter-sound integration”. In line with this suggestion, a wide range of experiments document impaired performance on phonological tasks in children with dyslexia (e.g. Elbro, Borstrøm, & Petersen, 1998; Griffiths & Snowling, 2002; Landerl, 2001; Litt & Nation, 2014). Any investigation of the potential role of “automatic letter-sound integration” in dyslexia must, therefore, control for the role of phonological processing. Furthermore, the comparison of children with dyslexia with typically developing children of a similar age does not control for the limited reading experience of the dyslexic group which may be a sufficient explanation for any group differences (Nash et al., 2016).

Aside from these issues, it is well known that the comparison of extreme groups (children with and without dyslexia) with relatively small sample sizes is likely to overestimate effect sizes (Preacher, Rucker, MacCallum, & Nicewander, 2005), which may explain different patterns of results across studies (e.g. Blau et al., 2010; Froyen et al., 2011; Žarić et al., 2014). As it is now widely accepted that dyslexia simply represents the lower end of a continuous distribution of reading skills in the population (Peterson & Pennington, 2015) it seems timely for this hypothesis to be tested in a large unselected sample. If problems in “automatic letter-sound integration” are a cause of dyslexia, then variations in the extent to which letters and speech-sounds are integrated

should be associated with individual differences in children's decoding ability in the general population.

To summarise, there is clear evidence that learning letter-speech sound associations is crucial for learning to read. However, evidence for the “automatic letter-sound integration hypothesis” of dyslexia is currently restricted to extreme group studies using fMRI and EEG, which are limited by their small sample sizes, the use of measures with unknown reliability and the failure to use adequate controls to exclude a range of possible alternative explanations for the results obtained. Most importantly, existing research has failed to control for the possible role of a phonological deficit making it difficult to interpret the small number of existing behavioural studies.

The current study tests the “automatic letter-sound integration hypothesis” using a priming task in which a letter prime is followed by an auditory target. The child's task is simply to decide whether the auditory target is a speech or non-speech sound. By comparing reaction times (RTs) on congruent trials where the letter prime matches the speech-sound target, with baseline trials where a novel symbol is presented, we can assess the extent to which children's responses are facilitated by a congruent letter prime. Children with highly automated letter-sound associations should show greater facilitation (faster responses to the speech sound on congruent than neutral baseline trials) than children who have not fully automated these associations. The inclusion of an incongruent condition (where the visual prime is a letter that does not correspond to the speech sound presented) will allow us to determine whether the priming effect reflects “automatic” processing. According to Posner and Snyder (2004) automatic processing is demonstrated by facilitation in the absence of interference as automatic activation of a different (incongruent) representation will not influence the processing of activated pathways.

Study 1

Our first study assesses “automatic letter-sound integration” in a large unselected sample of typically developing children aged between 5-7 years. We predict that children in this age range (who have received at least one year of formal reading instruction) will demonstrate some level of automatic activation of sounds by letters and so will be faster to identify a speech-sound following the presentation of a congruent letter prime (compared to the presentation of an incongruent letter or an irrelevant non-verbal symbol). If such an effect is demonstrated, we will be able to assess whether individual differences in this effect are associated with individual differences in reading ability. Children also completed measures of letter-sound knowledge, phoneme awareness and Rapid Automatized Naming (RAN) so that the predictive power of “automatic letter-sound integration” can be compared with these well-established predictors of reading development.

Method

Participants. One hundred and fifty-five children (77 male, 78 female) participated in the study (mean age = 6.5 years, range = 65 to 93 months). Children were unselected for reading ability. Children from Year 1 and 2 were recruited from 8 primary schools in Greater London and North Yorkshire. Due to time constraints, children from two primary schools were unable to complete all reading-related measures (N=50; see Table 1 for details of missing data). Parents were provided with information about the study and gave written consent for their child to take part. The study was approved by UCL Research Ethics Committee.

Measures and procedure. Children were tested individually in two 20-minute sessions; tasks were administered in a fixed order.

Reading. Children completed the timed word and non-word reading subtests from the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) and the Single Word Reading Test (SWRT6-16; Foster, 2007) where they were required to read aloud a list of words of increasing difficulty without time pressure.

Letter-sound knowledge. Children completed the letter-sound knowledge subtest from the York Assessment of Reading for Comprehension (YARC; Hulme et al., 2009). This test required children to say the sound corresponding to 32 letters and digraphs.

Phoneme awareness. Children completed the phoneme deletion subtest from the YARC (Hulme et al., 2009). In this test children were required to repeat a word but to ‘take away a sound’ from it. For example “Can you say sheep? Can you say it again without the /p/?”

Rapid Automatisised Naming (RAN). Children completed the digit RAN subtest from the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999). This test required children to name two 9 x 4 arrays of 6 digits as quickly and accurately as possible.

Letter-sound priming task. This task involved the successive presentation of a visual letter prime and an auditory phoneme target. Figure 1 shows the structure of a trial across the 3 experimental conditions. Children were required to decide on each trial whether the auditory stimulus was a ‘real’ speech-sound or not. Fifty percent of trials consisted of speech sounds; the other 50% of trials involved the presentation of a non-speech sound. Response time (RT) was measured to the auditory stimuli (speech/non-speech decision RT).

Auditory stimuli were recordings of the following 5 phonemes, duration in milliseconds (ms) for each are reported in parentheses; /tə/ (293ms), /də/ (263ms), /və/

(428ms), /zə/ (413ms) and /dʒə/ (357ms). Non-speech versions of these stimuli were created in Matlab by randomly assembling 5ms segments of the original signal (Ellis, 2010). These non-speech sounds were identical in length, energy and spectral composition but sounded completely unlike speech. Visual stimuli consisted of letters and novel letter-like forms. Lower case letters corresponding to the phonemes used were presented in Arial font (approximately 23 x 20mm). On 50% of trials a letter was presented and on the other 50% of trials one of five novel letter-like forms (adapted from Taylor, Plunkett, & Nation, 2011) was presented.

Stimuli were presented and responses recorded (speed and accuracy) using E-Prime Software (version 2.0) using a Psychology Software Tools Serial Response Box (SRB; model 200a) and a laptop running Windows 7. Auditory stimuli were presented through headphones.

Children were instructed to attend to both the letter and speech-sound and decide whether the sound was a ‘real’ speech-sound using “yes” and “no” response keys on the response box. Before the task began children were familiarised with the procedure in thirteen practice trials.

On each trial a centrally located fixation point was presented for 1000ms, followed by the letter or non-letter stimulus, presented in black and appearing on a white screen for 500ms. The auditory target was presented over headphones and its onset was synchronous with the offset of the visual letter. Each trial was followed by the visual prompt “Real sound?” Response times from the response box were recorded from the onset of the auditory target. The experimenter monitored the child’s performance, controlling the presentation of trials.

There were six conditions in the letter-sound priming task. In the congruent condition, the prime and target were the same letter/sound. In the incongruent condition

the prime and target were not the same letter/sound. In the baseline condition, the prime was a novel letter-like shape and the target was a speech-sound. There were three additional control conditions to prevent children detecting the relationship between primes and targets and generating expectancies. In these control conditions the target was a non-speech sound. Novel symbols and scrambled speech-sounds were yoked to create pseudo baseline, congruent and incongruent control conditions.

There were 20 trials for each condition and each condition included four trials of each pairing, apart from the incongruent condition where each letter prime was presented once and paired with all other speech-sounds. There were 135 trials in total, including 15 ‘catch’ trials to ensure children were attending to the screen. On catch trials the same letters were presented in a black and white animal print (for example, zebra stripes) and children were instructed to make a different response (using a button on the response box).

Results

Means (and standard deviations) for all measures are shown in Table 1. All measures showed a good range of scores, with the exception of letter-sound knowledge which was at ceiling (49% of children achieved the maximum score) and so this measure was excluded from subsequent correlation and regression analyses.

Letter-sound priming. Only correct responses are considered and outliers were removed from the raw reaction time (RT) data. RT data from six participants were excluded because their response accuracy was below 75%. In addition, there were missing data for five participants (the task was not administered due to time constraints). RTs over 5000ms were first removed as this was considered to reflect a lapse in attention. A non-recursive outlier removal procedure was then used (Selst & Jolicoeur, 1994). Over 90% of the RT data were included in the analyses.

Figure 2 shows the mean correct response times in each condition for the two year groups, together with 95% within-subject confidence intervals (Morey, 2008). As expected Year 1 children responded more slowly than Year 2 children. Both groups showed evidence of facilitation with RTs in the congruent condition being faster than in the baseline condition. The Year 1 group showed slightly quicker RTs in the incongruent condition compared to the baseline condition, whereas RTs in the Year 2 group were slightly slower in the incongruent condition. To assess the reliability of these differences, response times for the baseline, congruent and incongruent conditions in Year 1 and 2 were compared using a mixed effects linear model treating participants and items as crossed random effects. In this model the difference between baseline and congruent, and baseline and incongruent RT were represented by two dummy codes, and year group was represented by another dummy code (Year 1 vs. Year 2).

Both groups showed facilitation: RTs in the congruent condition were significantly faster than in the baseline condition for children in the Year 1 group (marginal mean difference = -132.71 = [95% *CI* -171.37 -94.05], $z = -6.73$, $p < .001$; $d = .39$) and Year 2 (marginal mean difference = -74.55 = [95% *CI* -102.56, -46.55], $z = -5.22$, $p < .001$; $d = .29$). The size of this effect was significantly larger in the Year 1 group than Year 2 group (estimated difference = 58.26, $z = 2.35$, 95% confidence interval = [-9.75, 106.76], $p = .019$). Further analysis confirmed that this interaction reflects a scaling effect. Using z-scores generated for RTs in each year group revealed a significant main effect of condition ($F(2, 5) = 5.34$, $p = .0051$), but no main effect of year group ($F(1, 5) = .00$, $p = .9601$) and a non-significant interaction between condition and year group ($F(2, 5) = .17$, $p = .8421$).

Neither group showed a significant difference between RTs in the baseline and incongruent conditions (Year 1 marginal mean difference = -30.38 = [95% *CI* -68.94, 8.18], $z = -1.54$, $p = .123$, $d = .09$; Year 2 marginal mean difference = 13.32 = [95% *CI* -14.67, 41.30], $z = 0.93$, $p = .351$, $d = -.05$).

Summary data for all conditions of the experiment, including the control conditions where non-speech sounds were presented, are shown in Supplementary table (S1). Accuracy in the control and experimental conditions is comparable (and high). In the experimental trials RTs are faster on congruent trials than baseline trials (responses to phonemes that match a preceding letter are faster compared to trials where the phoneme is preceded by a novel letter-like form). As expected, however, this effect is absent from the control conditions where corresponding scrambled phonemes are presented. Interestingly, the fastest RTs in the control conditions are to trials where a novel symbol precedes a scrambled phoneme. This suggests that when children are presented with a real letter prime, they expect to hear a real speech-sound, as opposed to a non-speech sound.

Correlations. Pearson correlations (and partial correlations controlling for age) between variables for both year groups combined are shown in Table 2. Measures of reading were very strongly correlated (r 's between .90 and .92) and so reading factor scores were calculated using principal axis factoring. Age was moderately correlated with all measures, and given that the two year groups showed comparable letter-sound priming subsequent analyses focus on relationships in the two groups combined after partialling out age.

Correlations between average RTs across the three priming task conditions (baseline, congruent, incongruent) are strong indicating that these measures have relatively good reliabilities. Correlations between children's average RTs in each

condition and reading are weak, though significant and similar in magnitude across the different measures.

Measures of facilitation and interference were calculated using residual scores from regression analyses predicting congruent RT from baseline RT, and incongruent RT from baseline RT. Measures of facilitation and interference show negligible correlations with reading factor scores, RAN or phoneme deletion, after controlling for age. The absence of any appreciable correlation between the degree of letter-speech sound facilitation and reading fails to support the main prediction of the “automatic letter-sound integration hypothesis”.

Predicting reading ability. Given that response times in all three conditions of the letter-sound priming task correlated with reading, a regression model was used to explore whether RT on the letter-sound priming task was a unique predictor of reading ability above and beyond established predictors. This regression analysis was computed for a sub-sample of 98 children with complete data across all measures. Since all three RT measures correlated strongly with each other, and similarly with the reading factor score, we used principal axis factoring with the three RT measures to compute an RT factor score. This RT factor score showed a moderately strong correlation with our Reading factor score ($r = -.47$) and even after controlling for age, phoneme deletion and RAN (which predicted 72.71% of the variance in reading) accounted for a small additional proportion of the variance in the reading factor (1.29%; $p = .035$).

Discussion

We used a priming task to investigate whether typically developing children show evidence of “automatic letter-sound integration”, and whether variations in this skill are associated with variations in reading ability. According to the “automatic letter-sound integration hypothesis”, associations between letters and speech-sounds

must become fully automated for children to achieve fluent reading (van Atteveldt & Ansari, 2014). Children in our priming task were significantly quicker to decide whether a sound was a speech or non-speech sound when primed by a congruent letter. This demonstrates that there are strong associative links between printed letters and the speech-sounds they represent and supports the view that letters become multi-modal as a result of repeated exposure over time (Blomert, 2011).

The finding that children with just one year of reading experience demonstrate evidence of automatic activation of sounds by letters contrasts with some claims from earlier neuroimaging studies that integration emerges much later (i.e. integration is more automatic but not yet “adult-like” in advanced readers with four years reading instruction; Froyen et al., 2009). In our study, the priming task provides a behavioural assessment of “automatic letter-sound integration”, and the only viable explanation for the facilitation effect found (a visual letter speeds up responses to a matching spoken letter sound) is that children have associative links in memory between visual letters and their corresponding speech sounds.

One unexpected finding was that after RAN and phoneme deletion had been accounted for, overall RT in the priming task was an additional predictor of reading ability. This finding suggests that speeded responses in the speech/non-speech discrimination task are a sensitive measure of the quality of a child’s underlying phonological representations (Hulme & Snowling, 2014).

Study 2

The findings from Study 1 clearly challenge the “automatic letter-sound integration hypothesis”, but do not rule out the possibility that children with severe reading difficulties (dyslexia) might suffer from deficits in such a process. Study 2 uses

the same letter-sound priming task to assess automatic activation of sounds by letters in children with dyslexia.

Method

Participants. One hundred and thirty one children participated in the study. There were 20 children with dyslexic difficulties aged between 9 and 11 years; 20 typically developing chronological age (CA) matched controls and 91 typically developing reading-matched controls (RA) aged between 6 and 7 years. The dyslexic group were recruited from specialist schools for children with dyslexia in North London and Surrey. Fifteen children in this group had received a formal diagnosis of dyslexia from an Educational Psychologist, the remaining five children in the dyslexic group had reading and/or spelling standard scores 1.5 *SD* below average.

Data from 91 typically developing children in Study 1 were used to form the RA control group. The CA matched group were recruited from mainstream schools in Greater London. The study was approved by UCL Research Ethics Committee.

Measures and procedure. Children were tested individually on the following measures in a 20-minute session. Tasks were completed in a fixed order.

Reading. Children in the dyslexic and CA matched groups completed the Word Reading subtest from the Wechsler Individual Achievement Test II (WIAT II; Wechsler, 2005). Children in the RA and CA matched groups completed the Single Word Reading Task (SWRT 6-16; Foster, 2007). Both measures required children to read aloud a list of words that became increasingly difficult. Age equivalent scores allowed us to match dyslexic and typically developing children for reading ability.

Letter-sound priming task. The task used was identical to the priming task described in Study 1.

Results

Means, standard deviations and tests of group differences for standardised measures of reading and the priming task are shown in Table 3. There were no significant group differences in accuracy on the priming task, however the dyslexic and RA group were significantly slower than the CA group across all three conditions.

Letter-sound priming. RT data were treated as in Study 1. The mean correct response times in each condition, together with 95% within-subject confidence intervals (Morey, 2008) are shown for each group in Figure 3. It is clear that all three groups show an identical pattern across conditions, with faster responses in the congruent than baseline condition, but no appreciable slowing in the incongruent condition. Contrary to the hypothesis that dyslexia is characterized by a deficit in automatizing letter-sound associations, the dyslexic group show at least as large, or possibly a larger, facilitation in the congruent condition. Overall, the RTs in dyslexic group are considerably slower than in the chronological age matched group, and roughly equal to those of children matched for reading age.

Response times for the baseline, congruent and incongruent conditions for the three groups were compared using a mixed effects linear model treating participants and items as crossed random effects. In this model the difference between baseline and congruent, and baseline and incongruent RT were represented by two dummy codes, and Group was represented by another pair of dummy codes (dyslexic vs. RA; dyslexic vs. CA).

RTs in the congruent condition were significantly faster than in the baseline condition (marginal mean difference = $-171.77 = [95\% \text{ CI } -226.34, -117.19]$, $z = -6.17$, $p = .000$, $d = .40$) but there was no difference in RT between the baseline and incongruent RT (marginal mean difference = $-1.88 = [95\% \text{ CI } -56.07, 52.31]$, $z = -0.07$,

$p = .946$, $d = -.01$). Children with dyslexia were significantly slower than the CA group (marginal mean difference = $-303.54 = [95\% \text{ CI } -445.15, -161.94]$, $z = -4.20$, $p = .000$, $d = -.60$) but did not differ significantly from the RA group (marginal mean difference = $-57.59 = [95\% \text{ CI } -169.16, 53.98]$, $z = -1.01$, $p = .312$, $d = -.05$).

Finally, children with dyslexia showed a significantly larger priming effect than either the RA (marginal mean difference = -84.67 , $z = -2.77$, $95\% \text{ CI } = [-144.67, -24.68]$, $p = .006$) or CA group (marginal mean difference = -84.17 , $z = -2.17$, $95\% \text{ CI } = [-160.13, -8.20]$, $p = .030$). However, as in Study 1, further analysis confirmed that this significant interaction reflects a scaling effect. Using z-scores generated for each group revealed a significant main effect of condition ($F(2, 8) = 6.55$, $p = .002$) but no main effect of group ($F(2, 8) = .01$, $p = .988$) and a non-significant interaction between condition and group ($F(4, 8) = .15$, $p = .961$).

Summary data for all conditions of the experiment in Study 2, including the control conditions where non-speech sounds were presented, are displayed in a Supplementary table (S2). Accuracy in the control and experimental conditions is comparable (and high) across the three groups. The overall pattern of RTs is consistent across groups and with data from Study 1. While responses to phonemes that match a preceding letter (congruent) are faster compared to trials where the phoneme is preceded by a novel letter-like form (baseline), as expected this effect is absent from the control conditions where corresponding scrambled phonemes are presented. Furthermore, children with dyslexia show the same pattern as the two TD groups; faster RTs in the control condition where a novel symbol precedes a scrambled phoneme. We propose this difference is driven by a relative slowing in RT when children are presented with a real letter prime followed by a scrambled phoneme.

Discussion

In this study children with dyslexia, as well as both control groups, showed priming. All groups of children were significantly faster to identify a speech sound following the presentation of a congruent letter, compared to the presentation of a novel symbol or incongruent letter. The present results, therefore, contradict previous claims that dyslexia is characterised by a deficit in “automatic letter-sound integration”. Further analyses showed that there was no significant difference in the relative size of the priming effect across the three groups after accounting for group differences in RT. However, there was evidence that children with dyslexia in our study were significantly slower to identify the speech-sound compared to the CA matched group. These slower responses in children with dyslexia suggest they found making a decision about whether a target was a speech-sound harder than control children.

General Discussion

A number of recent studies have proposed that reading difficulties in children with dyslexia are caused by a deficit in “automatic letter-sound integration” (see van Atteveldt & Ansari, 2014 for a review). We conducted two studies using a letter-sound priming task to examine this hypothesis. The first showed that children with just a year’s formal reading instruction show clear evidence of automatic activation of sounds by letters: associative links between letters and their corresponding speech sounds enabled children to process a speech sound more quickly. The second study, using the same task, showed that children with dyslexia demonstrate automatic activation of sounds by letters to at least as great an extent as either age-matched or reading-ability matched control children. Our findings provide no support for the theory that dyslexia is the result of a deficit in “automatic letter-sound integration”, and have important implications for theories of reading development and reading disorders.

The Relationship between “Automatic Letter-sound Integration” and Learning to Read

It is well established that letter-sound knowledge is one of the best predictors of early variations in word reading skill (Hulme et al., 2012; Hulme & Snowling, 2014; Melby-Lervåg et al., 2012) and children with dyslexia frequently show difficulties in developing secure letter-sound knowledge (e.g. Thompson et al., 2015; Torppa et al., 2006). The “automatic letter-sound integration hypothesis” suggests that some children learn letter-sound correspondences to levels of perfect accuracy, but fail to make such correspondences automatic. Such a putative failure to automate letter-sound associations is claimed to be a proximal cause of problems in learning to read. To quote van Atteveldt and Ansari (2014), “The crucial step in becoming literate in an alphabetic script is therefore to automate the associations between letters and speech sounds”. In this view, one major cause of dyslexia is a failure to “automate” the links between letters and speech sounds, even when such letter sound relationships have been learned to perfect levels of accuracy.

To test this hypothesis we require a robust measure of the extent to which individual children possess automatic links between letters and sounds. The priming task developed here provides such a measure, and has yielded some clear, if surprising, results. Our first study showed that children within the first year of learning to read show clear evidence of rapid access to speech sounds from their corresponding letters (letter speech-sound priming) with meaningful differences amongst children in the extent of such priming. However, after controlling for differences attributable to age there was a negligible correlation between the degree of letter-sound priming and children’s reading skills. It should be emphasised that given the large sample size, we had high power to detect such an effect, even if it had been small in magnitude. Our

second study showed that children with severe reading difficulties (dyslexia) show at least as much letter-sound priming as typically developing children of the same age.

Study 1 also showed that overall RT in the letter-sound priming task (the speed of deciding whether a sound was a speech-sound or not) was a weak but unique predictor of reading ability. In line with this, in Study 2, children with dyslexia were overall very slow on this task. These results suggest that the task of making speeded judgements about whether a sound is speech or not, is a sensitive index of phonological processing, and so related to reading ability.

Is Dyslexia Associated with a Deficit in “Automatic Letter-sound Integration”?

Previous evidence that deficits in “automatic letter-sound integration” are important in dyslexia has come from neuroimaging studies, though recently published studies have led to an increasingly complicated picture and there is currently no generally accepted neural signature for “automatic letter-sound integration” (see Kronschnabel, Brem, Maurer, & Brandeis, 2014; Nash et al., 2016; Žarić et al., 2014). Unlike these neuroimaging studies, which are hampered by small sample sizes and extreme group designs, Study 1 tested the “automatic letter-sound integration hypothesis” in a large unselected sample while also assessing a range of phonological skills that are known to be close correlates of reading ability. However, our measure of letter-sound integration (facilitation in the letter-sound priming task) showed a negligible correlation with reading ability, although overall speed of performance on the speech sound judgement task, was a moderately strong correlate of reading ability.

Automatic Activation of Sounds by Letters

Our finding that children respond faster to a speech sound if it matches a preceding letter clearly indicates that letters and their corresponding sounds have become strongly associated in memory as a result of early literacy instruction. Analysis

of additional control conditions involving scrambled speech targets confirms that this effect is unique to these learned associations. Whether this priming effect is “automatic” is an important question. The idea of a process being automatic has a long history in cognitive psychology (James, 1890) and is typically interpreted to mean that a process occurs rapidly, efficiently and without conscious attention or effort (Moors & De Houwer, 2006).

In evaluating automaticity, we can consider a ‘cost benefit analysis’ of the data (Posner & Snyder, 2004). According to Posner and Snyder (2004) facilitation and interference represent separate mechanisms; with facilitation an indicator of automatic processing and interference signalling attentional processing. In other words, automatically activated pathways facilitate the processing of related information, whereas automatic activation of incongruent information will not result in an inhibitory effect. In contrast, if attention is directed to the processing of information (i.e. the participant is consciously attending to the relationship between letters and speech-sounds) there will be a cost in response to incongruent information. Our finding of facilitation, in the absence of inhibition, according to the arguments of Posner and Snyder (2004), provides evidence that the facilitation effect reflects an automatic process that is not under conscious control.

Previous work using similar cost-benefit analyses, reported evidence of ‘facilitation-without-cost’ in the rapid processing of non-predictive symbolic (arrow) directional cues, whereas the presentation of gaze cues produced ‘facilitation-plus-cost’ which was interpreted as an attentional effect (Langdon & Smith, 2005). That the present study finds evidence of facilitation-without-cost following a non-predictive prime (congruent trials occurred only 14% of the time) points strongly towards automatic processing.

An alternative view is that facilitation and interference operate via a common mechanism and that the presence of one predicts the other (Cohen Kadosh, Cohen Kadosh, Henik, & Linden, 2008; Roelofs, van Turennout, & Coles, 2006). Following this view, the absence of interference in the present study may reflect an issue with the baseline and incongruent condition comparison. A limitation of using novel symbols as “neutral” stimuli is that these symbols are also technically “incongruent” with the speech-sound target. Thus, the absence of a difference between the baseline and the incongruent condition may reflect similar processing of the mismatch between visual prime and auditory target.

Phonological Skills and Learning to Read

It is now well established that in alphabetic languages variations in learning to read are predicted by three distinct phonological skills: phoneme awareness, letter-sound knowledge and Rapid Automatized Naming (RAN; Caravolas et al., 2012; Furnes & Samuelsson, 2010; Hulme & Snowling, 2013). In Study 1 we included these measures as predictors of reading ability. For children in this study letter-sound knowledge was essentially at ceiling levels, reflecting the fact that the children had been exposed to intensive, phonic reading instruction for at least a year in school. However, our study replicates many earlier studies in showing that phoneme awareness and RAN were powerful, and independent predictors of reading ability (these 2 predictors alone accounted for some 68% of the variance in reading).

A novel finding in Study 1 was that the speed with which a child could identify an isolated speech sound was an additional predictor of reading ability after controlling for age, phoneme deletion and RAN. We suggest that this reflects aspects of the quality or ease of access to phonological representations, which may in turn predict individual differences in reading. The finding that children with dyslexia were significantly slower

to decide whether a sound was speech or not is in line with this theory. However, it is not clear from our study whether performance is influenced by the quality of, or ease of access to, phonological representations (cf. Boets et al., 2013). An alternative view is that children with dyslexia may show quite general slowing in reaction time tasks which is not specific to tasks involving phonological judgements (Nicolson, 1994). Since we did not assess simple or choice RT in this study we cannot evaluate the extent to which the slow RTs here reflect a general slowing in information processing speed or a more specific effect on speed of phonological processing. Further research is needed to disentangle these possibilities and to clarify the nature of the phonological deficit in dyslexia.

Summary and Conclusions

The “automatic letter-sound integration hypothesis” claims that difficulties in learning to read result from weakened associations between letters and speech-sounds (e.g. Aravena, Snellings, Tijms, & van der Molen, 2013; Blau et al., 2010; Froyen et al., 2011). Our findings provide no support for this theory. Children after one year of reading instruction show clear evidence of automatic access to speech-sounds from their corresponding letters but there was no meaningful relationship between the degree of letter-sound integration and children’s reading skills. Furthermore, Study 2 found that children with dyslexia show letter-sound integration that is at least as strong as that found in typically developing children of the same age.

An additional, and unexpected, finding from Study 1 was that the speed with which a child could identify an isolated speech-sound was a unique predictor of reading ability after controlling for age, phoneme awareness and RAN. We suggest that speeded performance on this task may reflect aspects of the quality or ease of access to speech representations. Results from our second study support this interpretation, as children

with dyslexia were significantly slower to identify the speech-sound target, which may reflect impaired phonological processing in this group. Together, these findings provide additional support for the importance of phonological representations for learning to read.

References

- Aravena, S., Snellings, P., Tijms, J., & van der Molen, M. W. (2013). A lab-controlled simulation of a letter–speech sound binding deficit in dyslexia. *Journal Of Experimental Child Psychology*, 115(4), 691-707.
- Bishop, D. (2007). Using mismatch negativity to study central auditory processing in developmental language and literacy impairments: where are we, and where should we be going? *Psychological Bulletin*, 133(4), 651.
- Blau, V., Reithler, J., van Atteveldt, N., Seitz, J., Gerretsen, P., Goebel, R., & Blomert, L. (2010). Deviant processing of letters and speech sounds as proximate cause of reading failure: a functional magnetic resonance imaging study of dyslexic children. *Brain*, 133(3), 868-879.
- Blau, V., van Atteveldt, N., Ekkebus, M., Goebel, R., & Blomert, L. (2009). Reduced neural integration of letters and speech sounds links phonological and reading deficits in adult dyslexia. *Current Biology*, 19(6), 503-508.
- Blomert, L. (2011). The neural signature of orthographic–phonological binding in successful and failing reading development. *Neuroimage*, 57(3), 695-703.
- Blomert, L., & Froyen, D. (2010). Multi-sensory learning and learning to read. *International Journal of Psychophysiology*, 77(3), 195-204.
- Blomert, L., & Willems, G. (2010). Is there a causal link from a phonological awareness deficit to reading failure in children at familial risk for dyslexia? *Dyslexia*, 16(4), 300-317.
- Caravolas, M., Lervåg, A., Defior, S., Málková, G. S., & Hulme, C. (2013). Different patterns, but equivalent predictors, of growth in reading in consistent and inconsistent orthographies. *Psychological Science*, 24(8), 1398-1407.

- Caravolas, M., Lervåg, A., Mousikou, P., Efrim, C., Litavský, M., Onochie-Quintanilla, E., . . . Mikulajová, M. (2012). Common patterns of prediction of literacy development in different alphabetic orthographies. *Psychological Science*, 0956797611434536.
- Cohen Kadosh, R., Cohen Kadosh, K., Henik, A., & Linden, D. E. J. (2008). Processing conflicting information: Facilitation, interference, and functional connectivity. *Neuropsychologia*, 46(12), 2872-2879. doi:<https://doi.org/10.1016/j.neuropsychologia.2008.05.025>
- Elbro, C., Borstrøm, I., & Petersen, D. K. (1998). Predicting dyslexia from kindergarten: The importance of distinctness of phonological representations of lexical items. *Reading Research Quarterly*, 33(1), 36-60.
- Ellis, D. (2010). Time-domain scrambling of audio signals in Matlab. web resource: <http://www.ee.columbia.edu/~dpwe/resources/matlab/scramble/>.
- Foster, H. (2007). Single word reading test 6-16. *GL Assessment Limited*.
- Froyen, D. J., Bonte, M. L., van Atteveldt, N., & Blomert, L. (2009). The long road to automation: neurocognitive development of letter–speech sound processing. *Journal of Cognitive Neuroscience*, 21(3), 567-580.
- Froyen, D. J., Willems, G., & Blomert, L. (2011). Evidence for a specific cross-modal association deficit in dyslexia: an electrophysiological study of letter–speech sound processing. *Developmental Science*, 14(4), 635-648.
- Furnes, B., & Samuelsson, S. (2010). Predicting reading and spelling difficulties in transparent and opaque orthographies: A comparison between Scandinavian and US/Australian children. *Dyslexia*, 16(2), 119-142.

- Griffiths, Y. M., & Snowling, M. J. (2002). Predictors of exception word and nonword reading in dyslexic children: The severity hypothesis. *Journal of Educational Psychology, 94*(1), 34.
- Hulme, C., Bowyer-Crane, C., Carroll, J. M., Duff, F. J., & Snowling, M. J. (2012). The causal role of phoneme awareness and letter-sound knowledge in learning to read combining intervention studies with mediation analyses. *Psychological Science, 23*(6), 572-577.
- Hulme, C., Caravolas, M., Málková, G., & Brigstocke, S. (2005). Phoneme isolation ability is not simply a consequence of letter-sound knowledge. *Cognition, 97*(1), 1-11.
- Hulme, C., & Snowling, M. J. (2013). Learning to read: What we know and what we need to understand better. *Child Development Perspectives, 7*(1), 1-5.
- Hulme, C., & Snowling, M. J. (2014). The interface between spoken and written language: developmental disorders. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1634), 20120395.
- Hulme, C., Stothard, S., Clarke, P., Bowyer-Crane, C., Harrington, A., Truelove, E., & Snowling, M. (2009). *YARC York Assessment of Reading for Comprehension*. University of York, Centre for Reading and Language: GL Assessment.
- James, W. (1890). *The Principles of Psychology*. New York: Henry Holt and Company.
- Kronshabel, J., Brem, S., Maurer, U., & Brandeis, D. (2014). The level of audiovisual print–speech integration deficits in dyslexia. *Neuropsychologia, 62*, 245-261.
- Landerl, K. (2001). Word recognition deficits in German: More evidence from a representative sample. *Dyslexia, 7*(4), 183-196.
- Langdon, R., & Smith, P. (2005). Spatial cueing by social versus nonsocial directional signals. *Visual Cognition, 12*(8), 1497-1527. doi:10.1080/13506280444000805

- Lervåg, A., Bråten, I., & Hulme, C. (2009). The cognitive and linguistic foundations of early reading development: a Norwegian latent variable longitudinal study. *Developmental Psychology*, 45(3), 764.
- Litt, R. A., & Nation, K. (2014). The nature and specificity of paired associate learning deficits in children with dyslexia. *Journal of Memory and Language*, 71(1), 71-88.
- Melby-Lervåg, M., Lyster, S.-A. H., & Hulme, C. (2012). Phonological skills and their role in learning to read: a meta-analytic review. *Psychological Bulletin*, 138(2), 322.
- Moors, A., & De Houwer, J. (2006). Automaticity: a theoretical and conceptual analysis. *Psychological Bulletin*, 132(2), 297.
- Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Reason*, 4(2), 61-64.
- Nash, H. M., Gooch, D., Hulme, C., Mahajan, Y., McArthur, G., Steinmetzger, K., & Snowling, M. J. (2016). Are the literacy difficulties that characterize developmental dyslexia associated with a failure to integrate letters and speech sounds? *Developmental Science*, n/a-n/a. doi:10.1111/desc.12423
- Nicolson, R. I. (1994). Reaction times and dyslexia. *The Quarterly Journal of Experimental Psychology Section A*, 47(1), 29-48. doi:10.1080/14640749408401142
- Peterson, R. L., & Pennington, B. F. (2015). Developmental Dyslexia. *Annual Review of Clinical Psychology*, 11(1), 283-307.
- Posner, M. I., & Snyder, C. R. (2004). Attention and Cognitive Control. In D. A. Balota & E. J. Marsh (Eds.), *Cognitive Psychology: Key Readings* (pp. 205-223). New York, NY: Psychology Press.

- Preacher, K. J., Rucker, D. D., MacCallum, R. C., & Nicewander, W. A. (2005). Use of the extreme groups approach: a critical reexamination and new recommendations. *Psychological Methods, 10*(2), 178.
- Roelofs, A., van Turenout, M., & Coles, M. G. H. (2006). Anterior cingulate cortex activity can be independent of response conflict in Stroop-like tasks. *Proceedings of the National Academy of Sciences, 103*(37), 13884-13889. doi:10.1073/pnas.0606265103
- Selst, M. V., & Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *The Quarterly Journal Of Experimental Psychology, 47*(3), 631-650.
- Taylor, J., Plunkett, K., & Nation, K. (2011). The influence of consistency, frequency, and semantics on learning to read: An artificial orthography paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*(1), 60.
- Thompson, P. A., Hulme, C., Nash, H. M., Gooch, D., Hayiou-Thomas, E., & Snowling, M. J. (2015). Developmental dyslexia: predicting individual risk. *Journal of Child Psychology and Psychiatry*.
- Torgesen, J. K., Wagner, R. K., & Rashotte, C. (1999). *TOWRE-2 Test of Word Reading Efficiency*.
- Torppa, M., Poikkeus, A.-M., Laakso, M.-L., Eklund, K., & Lyytinen, H. (2006). Predicting delayed letter knowledge development and its relation to grade 1 reading achievement among children with and without familial risk for dyslexia. *Developmental Psychology, 42*(6), 1128.
- van Atteveldt, N., & Ansari, D. (2014). How symbols transform brain function: A review in memory of Leo Blomert. *Trends in Neuroscience and Education, 3*(2), 44-49.

- Wagner, R. K., Torgesen, J., & Rashotte, C. (1999). Comprehensive test of phonological processing (CTOPP). *Pro-Ed, Austin, Texas*.
- Wechsler, D. (2005). *Wechsler Individual Achievement Test (WIAT-II UK)*: Harcourt Assessment.
- Žarić, G., González, G. F., Tijms, J., van der Molen, M. W., Blomert, L., & Bonte, M. (2014). Reduced Neural Integration of Letters and Speech Sounds in Dyslexic Children Scales with Individual Differences in Reading Fluency. *PLoS One*, 9(10), 1-14.

Table 1. Descriptive statistics (means, standard deviations, and ranges) for all measures.

Measure	N	Mean	St.Dev	Min.	Max.
Age (months)	155	78.77	7.59	65.39	93.43
Letter Sound Knowledge (LSK) (/32)	104	31.10	1.18	26	32.00
LSK standard score (SS)	104	110.50	9.35	84	124.00
Single Word Reading Task (SWRT) (/60)	153	26.81	11.21	2.00	48.00
SWRT SS	153	111.39	12.14	75.00	136.00
TOWRE Sight Word Efficiency (SWE) (/104)	150	45.40	17.34	3.00	78.00
TOWRE SWE SS	150	116.61	11.26	91.00	145.00
TOWRE Phonemic Decoding Efficiency (PDE) (/63)	148	23.55	11.87	1.00	48.00
TOWRE PDE SS	148	117.09	10.15	95.00	140.00
Reading factor score	148	0.08	0.93	-1.88	1.84
RAN total time (seconds)	105	46.42	12.79	26.00	89.00
RAN scaled score	105	10.80	2.03	6.00	16.00
Phoneme Deletion (/24)	105	15.34	5.32	3.00	24.00
Phoneme Deletion SS	105	110.77	12.16	70.00	137.00
Baseline accuracy (/20)	144	19.12	1.16	15.00	20.00
Congruent accuracy (/20)	144	19.11	1.12	15.00	20.00
Incongruent accuracy (/20)	144	19.24	0.96	16.00	20.00

Table 2. Pairwise correlations among measures.

Measures	1.	2.	3.	4.	5.	6.	7.	8.
1. Reading Factor Score	-	0.67***	0.63***	-0.07	0.02	-0.17*	-0.17*	-0.22**
2. RAN	-.71***	-	-0.44***	-0.04	-0.14	0.07	0.13	0.18
3. Phoneme Deletion	.73***	-.53***	-	0.04	0.05	-0.09	-0.16	-0.13
4. Facilitation	-.20*	.05	-.09	-	0.49***	0.51***	-0.09	0.23**
5. Interference	-.11	-.05	-.07	.52***	-	0.53***	0.27***	-0.11
6. Baseline RT	-.39***	.21*	-.30**	-.55***	.56***	-	0.81***	0.79***
7. Congruent RT	-.35***	.24*	-.32**	.02	.34***	.84***	-	.75***
8. Incongruent RT	-.39***	.28**	-.30**	.31***	-.01	.82***	.79***	-
9. Age	.57***	-.33**	.50***	-.25**	-.23**	-.46***	-.39***	-.40***

Note: Partial correlations controlling for age are shown above the diagonal, and simple correlations are below the diagonal

*** = $p < .001$, ** = $p < .01$, * = $p < .05$.

Table 3. Mean (SD) age and scores on standardized measures of literacy and letter-sound priming task in the three groups.

	Mean (SD)			F	Group differences
	Dyslexic (N=19)	CA (N=20)	RA (N=90)		
Gender (M:F)	4:15	10:9	49:41	7.87* ($\chi^2(2)$)	
Age (months)	121.36 (8.37)	121.29 (3.14)	82.37 (6.76)	471.62***	(DYS = CA) > RA
Single Word Reading Test (SWRT)		45.80 (5.18)	37.70 (5.14)	41.24***	CA > RA
SWRT SS		102.20 (9.47)	120.71 (8.48)	75.67***	CA < RA
SWRT Reading Age (RA; months)		129.15 (22.06)	103.43 (11.16)	58.34***	CA > RA
WIAT Reading	94.84 (12.05)	105.00 (7.66)		10.78**	CA > DYS
WIAT Reading SS	90.25 (10.10)	99.75 (10.18)		8.78**	CA > DYS
WIAT Reading RA (months)	104.00 (20.91)	128.40 (23.89)		12.60**	CA > DYS
Baseline Accuracy	18.75 (2.10)	19.05 (1.19)	19.33 (0.94)	.78	none
Congruent Accuracy	18.85 (1.90)	19.50 (0.83)	19.37 (0.89)	.50	none
Incongruent Accuracy	19.00 (2.20)	19.45 (0.83)	19.49 (0.77)	.06	none

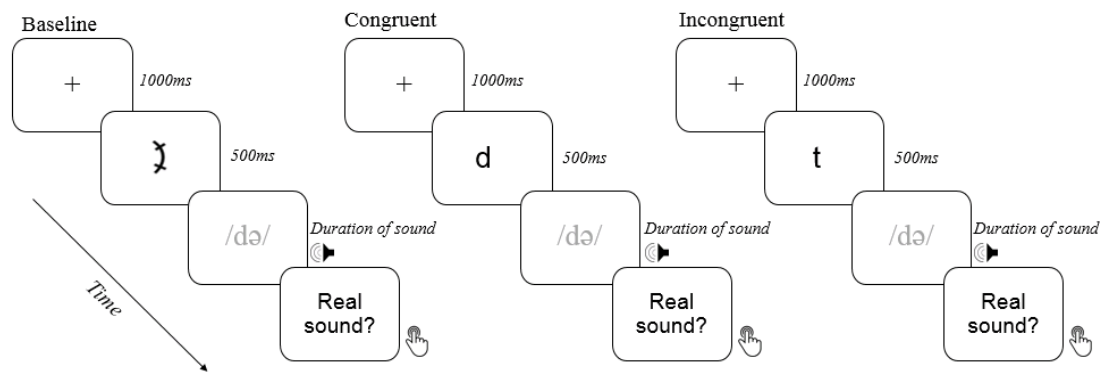


Figure 1. The structure of a trial across the three main experimental conditions

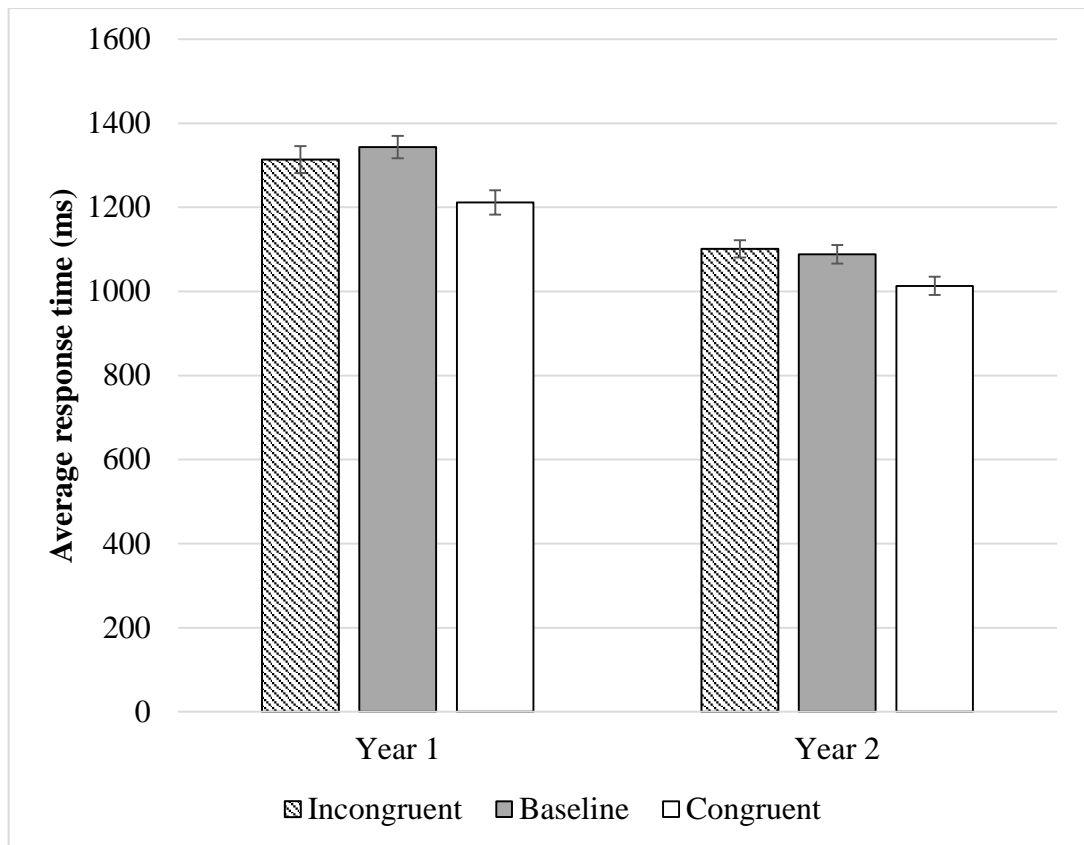


Figure 2. Average response times (and 95% CIs) for each condition of the letter-sound priming task for Year 1 (N=76) and Year 2 (N=68).

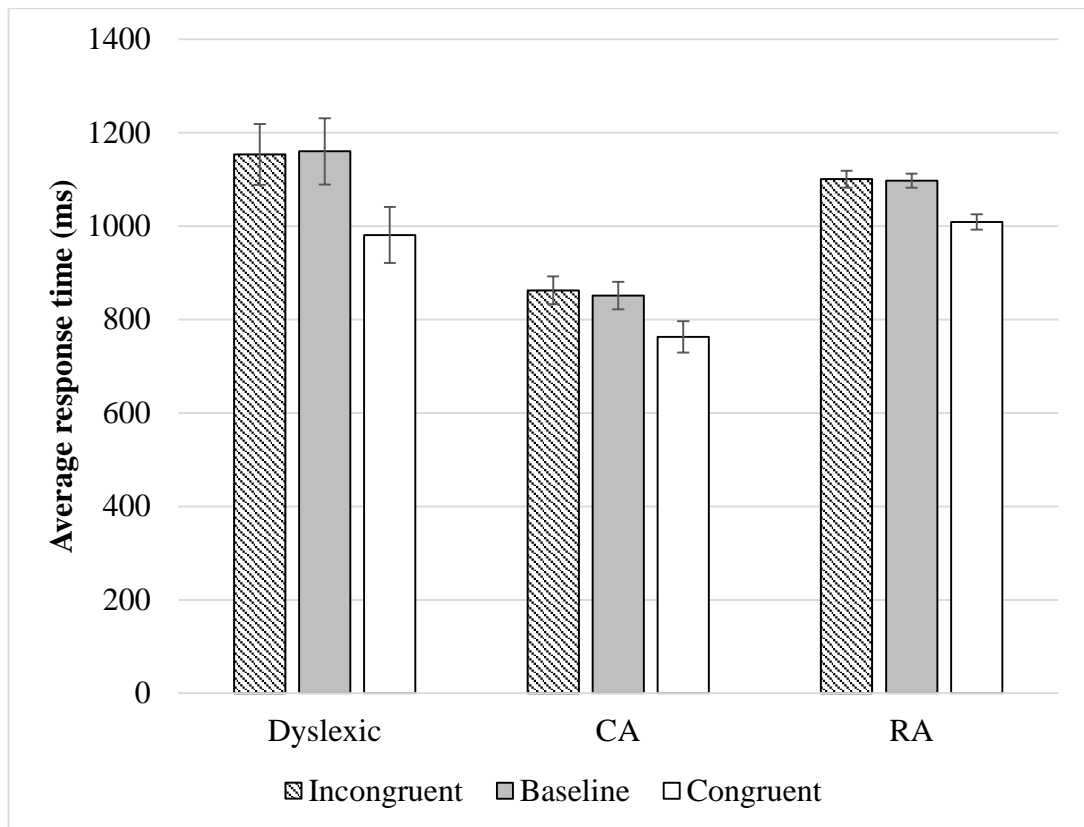


Figure 3. Average response times (and 95% within-subject CIs) for each condition of the letter-sound priming task for the three groups.

Acknowledgements

We would like to thank Imogen Long, Claire Sears and Gillian West for their assistance with data collection and the families and children who took part.

Funding: This research was supported by a PhD Studentship from University College London and ESRC Grant #####.

Table S1. Descriptive statistics (means, standard deviations, and ranges) for all conditions of the letter-sound priming task.

Measure	N	Mean	SD	Min	Max
Control 1* accuracy (/20)	146	19.43	0.85	17.00	20.00
Control 2** accuracy (/20)	146	19.15	1.01	16.00	20.00
Control 3*** accuracy (/20)	146	18.83	1.11	15.00	20.00
Control 1 average RT (ms)	146	1018.58	325.24	485.79	2126.95
Control 2 average RT (ms)	146	1070.68	310.66	611.28	2117.83
Control 3 average RT (ms)	146	1070.17	317.70	657.07	2042.05
Baseline accuracy (/20)	144	19.12	1.16	15.00	20.00
Congruent accuracy (/20)	144	19.11	1.12	15.00	20.00
Incongruent accuracy (/20)	144	19.24	0.96	16.00	20.00
Baseline average RT (ms)	144	1222.78	336.66	673.47	2198.55
Congruent average RT (ms)	144	1117.80	313.87	640.42	2230.94
Incongruent average RT (ms)	144	1213.26	310.62	732.63	2339.69

*Control 1 = novel symbol prime and nonverbal target

**Control 2 = letter prime and congruent scrambled sound

***Control 3 = letter prime and incongruent scrambled sound

Table S2. Descriptive statistics (means, standard deviations, and ranges) for all conditions of the letter-sound priming task for the three groups

Measure	Mean (SD)					
	Dyslexic (N=19)		CA (N=20)		RA (N=90)	
Control 1* accuracy (/20)	19.25	(1.25)	18.90	(1.59)	19.27	(1.00)
Control 2** accuracy (/20)	19.50	(0.69)	19.79	(0.42)	19.62	(0.69)
Control 3*** accuracy (/20)	19.05	(1.57)	18.95	(1.47)	18.78	(1.23)
Control 1 average RT (ms)	964.72	(210.77)	709.40	(168.97)	957.69	(19.27)
Control 2 average RT (ms)	879.12	(198.47)	674.67	(179.53)	912.34	(232.71)
Control 3 average RT (ms)	960.46	(287.91)	690.67	(164.28)	937.72	(205.15)
Baseline accuracy (/20)	18.75	(2.10)	19.05	(1.19)	19.33	(0.94)
Congruent accuracy (/20)	18.85	(1.90)	19.5	(0.83)	19.37	(0.89)
Incongruent accuracy (/20)	19	(2.20)	19.45	(0.83)	19.49	(0.77)
Baseline average RT (ms)	1159.81	(327.94)	851.16	(223.12)	1096.9	(232.14)
Congruent average RT (ms)	980.84	(268.29)	762.83	(189.71)	1008.47	(219.72)
Incongruent average RT (ms)	1153.41	(272.46)	862.24	(205.39)	1100.25	(229.42)

*Control 1 = novel symbol prime and nonverbal target

**Control 2 = letter prime and congruent scrambled sound

***Control 3 = letter prime and incongruent scrambled sound