AUTOMATIC INTEGRATION OF LETTERS AND SPEECH-SOUNDS IN TYPICAL READING DEVELOPMENT AND DYSLEXIA

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Declaration

I, Francina Jane Clayton, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Dyslexia is a developmental disorder characterised by difficulties in the accurate and fluent decoding of printed words. The dominant theory of dyslexia argues that reading failures are caused by a phonological processing deficit, resulting in impaired phoneme awareness and problems learning letter-sound correspondences. In recent years researchers have proposed a novel theory of dyslexia. This theory, based on neuroimaging studies of Dutch children, suggests that problems learning to read arise from a specific deficit establishing automatic associations between letters and speech-sounds. Whilst many agree that letter-sound knowledge plays an important role in learning to read, the crucial aspect of this hypothesis concerns children's ability to retrieve and apply this knowledge rapidly during reading.

This thesis is one of the first studies to use behavioural measures to assess the contribution of automatic letter-sound integration in the reading performance of English-speaking children. A behavioural priming paradigm was used to measure automatic letter-sound integration. In this task, the participant is presented with a visual letter prime, followed by an auditory speech-sound target. The effect of the letter prime upon the processing of the speech-sound is examined in a number of studies, including a large cross-sectional study of typically developing children and a study involving children with dyslexia.

Contrary to the hypothesis that dyslexia reflects a deficit in automatic letter-sound integration, the results from this research indicate that both dyslexic and typically developing children show automatic activation of speech-sounds from printed letters. Furthermore, the extent to which letters and speech-sounds are automatically integrated does not appear to predict variation in children's reading performance. Rather, baseline performance on this task (simply deciding if a sound is speech or not) is predictive of reading performance, which is argued to provide further evidence of the importance of phonological skills for the development of decoding.

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For my parents

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Chapter 1 Literature Review

1.1 Aims and scope

Over the past few decades there has been a vast amount of research dedicated to understanding how children learn to read and the deficits that may lead to reading difficulty. One theory, proposed by Blomert and colleagues suggests that problems learning to read arise from a specific deficit establishing automatic associations between letters and speech-sounds (Blomert, 2011). The aim of this chapter is to summarise and review current research in order to evaluate the role of automatic letter-sound integration in typical reading development and dyslexia.

The first section of this Chapter will outline the processes involved in early reading acquisition, with a particular focus on three skills that are believed to provide a critical foundation for the development of decoding: letter-sound knowledge, phoneme awareness and rapid automatized naming (RAN). The second section will review relevant research on developmental dyslexia, summarising evidence for a variety of possible causal risk factors. Finally, I will consider research investigating cross-modal integration of letters and speech-sounds and in particular, the extent to which a deficit in this ability may reflect a proximal cause of dyslexia.

1.2 An overview of early reading development

In the modern world written language is everywhere and children are introduced to written text from a very early age. While many children appear to learn to read and write with very little effort, mastering these skills is a complex process and critically depends on a foundation of spoken language (Hulme & Snowling, 2014). For this reason, the process of learning to read is often described as “parasitic on language” (Mattingly, 1972).

The ultimate goal of reading is to understand written text and following from this Gough and Tunmer (1986) propose that there are two broad sets of skills underlying reading comprehension: *decoding* (translating printed words into spoken form) and language comprehension. This review will focus on the development of decoding skills in order to provide a framework in which to evaluate the role of automatic letter-sound integration in typical reading development.

Firstly, theoretical models of reading development will be considered, including a summary of the computational approach to understanding reading development. This review will then consider predictors of learning to read, including an overview of the evidence to suggest that letter knowledge, phoneme awareness and RAN provide a critical foundation for the development of decoding ability.

1.2.1 Theoretical models of reading development

The process of learning to recognise words has often been described as progressing through a series of distinct stages (Ehri, 2005). While there have been a number of different models proposed (e.g. Ehri, 1995; Ehri, 2005; Frith, 1985; Marsh, Friedman, Welch, & Desberg, 1981), there appears to be broad agreement that stages of reading development are characterised by the different levels at which print and sound are associated.

When children first begin learning to read, arbitrary associations between visual information in printed words and their pronunciations are formed, referred to as the logographic stage in the Frith (1985) model. During this stage children are likely to depend upon salient visual cues, such as double letters or word length, to access meaning and as such are able to read relatively few words (Seymour & Elder, 1986).

Once children have been taught letter-sounds and names, they are able to apply this knowledge when they encounter unfamiliar letter strings. As a result children begin to learn the systematic relationship between letters in spellings (known as *graphemes*) and the speech-sounds they represent (known as *phonemes*; the smallest unit of speech). As children progress through this alphabetic stage and practice sounding out unfamiliar words letter-by-letter, this process becomes increasingly automatic and efficient until children are able to recognise whole words. This final stage is referred to as the orthographic stage of reading development (Frith, 1985).

Research by Share (1995) proposes that the experience of translating graphemes to phonemes during decoding serves a ‘self-teaching’ function in the development of whole word recognition. In his seminal study children read a passage that included a number of novel words (Share, 1999). Three days later the same children were asked to select the novel word they had read from a list of four words, including three distractors. Share found that children were significantly more likely to select the target word than a *homophone* (identically sounding word) with an alternative spelling, indicating that children had learnt the orthographic representation simply through the process of decoding. However, a subsequent replication of this study reported an inconsistent item-level relationship between children’s ability to decode a novel word and subsequent recognition, indicating that additional skills beyond grapheme-phoneme conversion are likely to be involved in orthographic learning (Nation, Angell, & Castles, 2007).

Computational models of reading have also provided an important theoretical account of how children map speech onto orthography during reading development (Seidenberg, 2005). This research has involved building connectionist models consisting of an input system representing orthography and an output system representing phonology. Both systems include individual units; in the input system these units code letters and their position in words and in the output system units code the phonological features of word pronunciation. In studies using connectionist models the process of learning to read is simulated by training associations between patterns of activation on input and output units.

One of the most influential computational models of word recognition is known as the Triangle model, originally proposed by Seidenberg and McClelland (1989). The original implementation of this model demonstrated the ability to successfully learn associations between orthographic and phonological representations, such that the input of a written word resulted in the model producing the correct ‘pronunciation’ of the corresponding spoken word. A number of ‘hidden units’ between inputs and outputs enabled the successful learning of complex mappings between orthography and phonology in the English language. Following training with a large corpus of English words, the model could accurately produce spoken representations even from written words that were not originally trained (Seidenberg & McClelland, 1989).

A computational model known as the Dual-Route Cascade model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) provides an alternative theoretical framework for the process of learning to translate written information into spoken form. While most words are read using a set of ‘Grapheme-Phoneme Correspondences’ (GPCs), Coltheart and colleagues propose an additional indirect processing route for words that cannot be translated accurately using GPCs. For example, according to this model an irregular word such as ‘yacht’ is directly translated from a whole-word orthographic representation to its corresponding phonological representation.

In a subsequent adaptation of the Triangle model, a similar route was proposed mapping orthography to phonology via a so-called ‘semantic pathway’ (Plaut, McClelland, Seidenberg, & Patterson, 1996). However, rather than including representations of word meanings in the model, the semantic pathway served to provide additional activation of phonological units that are sensitive to letter context. For example, the phonological representation of the vowel <i> in the context of /mɪnt/ or /maɪn/. This adaptation resulted in enhanced learning of irregular words. Furthermore, the study found that as training progressed, the model began to display a similar division of labour to that of the Dual-Route model, in that irregular words were processed via the semantic pathway and the phonological pathway continued to process regular words (Plaut et al., 1996). Thus, connectionist models provide a useful framework for understanding the early development of reading skills and suggest that children learn to read through the formation of increasingly efficient associations between orthography and phonology, and between orthography and semantics.

1.2.2 Predictors of early word recognition

Learning to read is widely regarded as a critical academic and developmental milestone. There has been huge scientific effort devoted to identifying reliable predictors of reading ability. It is beyond the scope of the present review to evaluate all of the suggested cognitive, biological and environmental predictors of reading. The following discussion will therefore centre on the evidence to suggest that early decoding ability critically depends on a subset of phonological language skills: namely letter knowledge, phoneme awareness and rapid automatized naming (Hulme & Snowling, 2013).

Letter knowledge

In alphabetic writing systems words are made up of individual letters. Mastering the associations between letters and the speech-sounds that they represent is central to the process of learning to read (Ehri, 2005). In order to learn these associations, it follows that children must be able to discriminate and remember individual letters.

A number of longitudinal studies provide evidence for a strong relationship between children's letter knowledge and subsequent reading development. Both knowledge of letter names (Pennington & Lefly, 2001; Share, Jorm, Maclean, & Matthews, 1984) and letter sounds (Foorman, Francis, Novy, & Liberman, 1991; Muter, Hulme, Snowling, & Stevenson, 2004) have been shown to predict early decoding (Bond & Dykstra, 1967) and subsequent reading achievement throughout the school years (Leppänen, Aunola, Niemi, & Nurmi, 2008; Vellutino & Scanlon, 1987).

Longitudinal studies have proven crucial in identifying potential causal relations between letter knowledge and reading, particularly those measuring performance prior to formal literacy instruction. However, the most convincing evidence for a causal effect comes from studies involving the training of letter knowledge. A number of intervention programmes involving explicit training of letter-sound correspondences have been shown to enhance word recognition skills, providing good evidence that letter knowledge exerts a causal influence on children’s early decoding ability (Bowyer-Crane et al., 2008; Elbro & Petersen, 2004; Levin, Shatil-Carmon, & Asif-Rave, 2006; Schneider, Roth, & Ennemoser, 2000)

In the Bowyer-Crane et al. (2008) study, children were randomly allocated into groups that received an intervention programme targeting either phonology (including training on letter-sound knowledge, phoneme awareness and direct reading instruction) or oral language skills. Both programmes were successful in promoting different aspects of children’s literacy and language skills, with the phonology with reading intervention producing significant improvements in later word recognition and spelling (compared to the oral language intervention). Subsequent path analyses using data from the intervention study reported that gains in letter knowledge and phoneme awareness fully accounted for subsequent improvements in reading performance shown by the intervention group (Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012).

There are a number of possible explanations for why letter knowledge predicts children’s reading outcomes. Some suggest that children’s letter knowledge reflects the efficiency of an underlying associative learning mechanism that is also implicated in the process of learning to read whole words (Hulme & Snowling, 2013). This theory is based on the notion that learning to read and acquiring letter knowledge both involve creating visual-phonological associations in memory. Evidence in support of this theory comes from studies of paired-associate learning (PAL) which show that children’s ability to form associations between nonsense words and novel shapes predicts individual differences in reading ability (Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Litt, de Jong, van Bergen, & Nation, 2013). Furthermore, PAL performance is impaired in children with poor decoding skills (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003) and correlates with early letter knowledge (De Jong, Seveke, & van Veen, 2000).

It has also been suggested that the relationship between letter knowledge and early reading may in fact reflect the influence of the home-literacy environment (Adams, 1994; Foulin, 2005; Sénéchal & LeFevre, 2002) or children’s general cognitive ability (Bowey, 1994; de Jong & van der Leij, 1999). This could reflect children’s exposure to reading-related activities more generally, rather than explicit teaching of letter names.

Conversely, it has been argued that letter knowledge may reflect children’s sensitivity to print or letter recognition skills, which may account for the predictive value of letter knowledge in early reading development. For example, a longitudinal study with pre-literate kindergarten children reported that performance on a visual orthographic test made the largest contribution to variance in word reading, even when controlling for individual differences in letter knowledge (Badian, 1994). In addition, a recent neuroimaging study with pre-literate kindergarten children revealed the emergence of print sensitivity in cortical areas such as the visual word form area (VWFA) following eight weeks of grapheme-phoneme training (Brem et al., 2010).

Arguably the most widely cited hypothesis as to why letter knowledge predicts reading is that letter knowledge enables children to acquire the *alphabetic principle;* namely, the understanding that spoken words are made up of phonemes and that letters represent these phonemes (Byrne & Fielding-Barnsley, 1989, 1990). Thus in addition to letter knowledge, children must also be sensitive to the phonological structure of spoken language (also referred to as *phoneme awareness*).

While many agree that both letter knowledge and phoneme awareness are important predictors of learning to read, there has been much debate concerning the precedence of these two skills. Indeed, there is evidence that children can perform well on measures of phoneme awareness in the absence of letter knowledge (Caravolas & Bruck, 1993). However it seems likely that there is a reciprocal relationship between letter knowledge and phoneme awareness (Burgess & Lonigan, 1998; Johnston, Anderson, & Holligan, 1996; Muter et al., 2004). For example, it has been suggested that when children learn that individual letters represent pronunciations, they begin to understand that words can be segmented into individual sounds, which in turn leads to increased awareness of the phonetic structure of words (Levin et al., 2006). Correspondingly there is evidence to suggest increased phonemic awareness improves the learning of letter-sound correspondences (Fox & Routh, 1984; Treiman & Baron, 1983).

For example, Caravolas, Hulme, and Snowling (2001) report evidence of a reciprocal relationship between letter-sound knowledge and phoneme isolation. In their longitudinal study early letter-sound knowledge predicted emerging phonological awareness, suggesting that children's knowledge of letter-sounds facilitated their ability to isolate the sounds in spoken words. In addition the study found that subsequent growth in phoneme awareness was dependent on earlier letter-sound knowledge and vice versa, suggesting the two skills became increasingly interactive during early reading development.

In summary, there is strong support for the role of early letter knowledge in the development of word reading. Furthermore, training studies provide evidence that this skill, in combination with sensitivity to the sound structure of spoken language, is likely to play a causal role in children's reading ability.

Phoneme awareness

Phoneme awareness is a metalinguistic skill that refers to awareness of the sound structure of spoken words, specifically the ability to identify individual phonemes in words (Hulme & Snowling, 2009). This section will focus primarily on phoneme awareness as a predictor of reading, however it is important to first acknowledge the role of phonological processing skills more generally (Wagner et al., 1997).

When considering phonological processing skills, a distinction is often made between implicit versus explicit processing. Phoneme awareness tasks fall into the latter category, as they require active reflection and manipulation of speech-sounds. Implicit phonological processing, on the other hand, simply requires access to phonological information without reflection or awareness of the sound structure of spoken words. For example, verbal short-term memory (VSTM) tasks such as non-word repetition involve implicit phonological processing. Many researchers have argued that such phonological memory skills play an important role in early reading development, enabling children to hold phonological information in memory as words are segmented and blended during decoding (Gathercole & Baddeley, 1993). While implicit phonological processing is clearly important in learning to read, performance on tasks requiring explicit phonological processing have typically revealed stronger relationships (Melby-Lervåg, Lyster, & Hulme, 2012).

Phonological awareness is thought to develop through a series of stages, with each stage involving access to increasingly smaller units of speech (Stanovich, 1992). This progression of increasing awareness is proposed to reflect the quality of stored phonological information (known as *phonological representations*).

According to the ‘Lexical Restructuring Model’ (Walley, Metsala, & Garlock, 2003), increasingly refined phonological representations emerge in response to vocabulary growth during early childhood. As children learn more words increasing lexical competition necessitates more detailed and distinctive representations. As such, when relatively few words are known, children are likely to demonstrate awareness at the word or syllable level. In English, syllables typically consist of an *onset* (the initial consonant or consonant cluster) and a *rime* (the vowel and final consonant). Children will subsequently develop awareness of these smaller units, before finally developing awareness at the phoneme level (Goswami & Bryant, 1990).

A number of studies have confirmed this developmental progression, for example one study compared the performance of over nine hundred children aged between two and five years old on a number of tasks measuring awareness at different grain sizes (Anthony, Lonigan, Driscoll, Phillips, & Burgess, 2003). In addition to confirming this sequence of awareness from large to small units, the authors also report that children typically demonstrate awareness of phonological units before being able to actively manipulate this information (for example, being able to blend or delete phonological units). These skills were also found to develop in parallel rather than in a strict stage-like manner (see also Treiman & Zukowski, 1996).

There is now a wealth of research documenting the strong relationship between phoneme awareness and literacy. This research spans four decades and includes evidence from correlational, longitudinal and intervention studies. For example, a recent meta-analysis of 135 correlational studies reported a specific and substantial relationship between concurrent measures of phoneme awareness and children's reading performance (Melby-Lervåg et al., 2012). This analysis revealed that together phonemic awareness, rime awareness and VSTM explained over 40% of the variance in children's reading performance. However of these predictors, phoneme awareness was the only independent predictor (explaining 16.1% additional variance when rime awareness and VSTM were controlled).

Longitudinal research suggests that early variations in phoneme awareness are predictive of subsequent reading ability (Compton, 2000; Lervåg, Bråten, & Hulme, 2009; Muter et al., 2004; Wagner, Torgesen, & Rashotte, 1994). Studies have typically measured children's phoneme awareness before the onset of formal literacy instruction, thus this research would be consistent with a possible causal role of phoneme awareness in children's reading development.

However, the strongest evidence for a causal relationship comes from research involving training of phoneme awareness. A number of studies have demonstrated that training phoneme awareness skills is an effective method of improving reading outcomes (Bowyer ‐ Crane et al., 2008; Byrne, Fielding-Barnsley, & Ashley, 2000; P. J. Hatcher, Hulme, & Snowling, 2004; Lundberg, Frost, & Petersen, 1988). Furthermore, training is particularly effective when combined with instruction in letter-sound correspondences (Bus & van IJzendoorn, 1999 for a meta-analysis). According to the "Phonological Linkage Hypothesis" (P. J. Hatcher, Hulme, & Ellis, 1994) explicit awareness of phonemes in words alone is not sufficient to improve reading performance. Rather, training in phoneme awareness is only effective in the context of reading experience and instruction in letter-sound correspondences.

As previously described, the intervention in the Bowyer ‐ Crane et al. (2008) study combined training in phoneme awareness with explicit training on letter-sound knowledge. Children receiving this intervention displayed significant improvements in word reading ability when compared to children receiving an oral language intervention. Given that children were randomly allocated to receive either the phonology or oral language intervention, this study provides good evidence that the effects of training were causally related to improvements in reading. Furthermore, subsequent analysis of the data revealed that improvements in phoneme awareness and letter-knowledge fully accounted for gains in reading following the intervention programme (Hulme et al., 2012).

Additional support comes from meta-analyses designed to inform government policies on the most effective approach to teach children to read. For example, a report written by the National Reading Panel for United States Congress included analysis of results from 52 peer-reviewed experimental studies (Ehri et al., 2001). This report concluded that instruction in phonological awareness has a moderate and statistically significant effect on children’s reading and spelling ability (with effect sizes d= .53 and .59, respectively).

One central issue in this field of research concerns whether phoneme awareness is a necessary prerequisite for learning to read, or whether this skill emerges as a consequence of such learning. For example, Castles and Coltheart (2004) argue that there is insufficient evidence that explicit awareness of phonemes is causally related to reading development. Rather, they suggest that the strong relationship between performance on measures of phoneme awareness and reading reflects the use of orthographic knowledge in completing these tasks.

There is indeed evidence to suggest that children draw upon their orthographic knowledge when performing phoneme awareness tasks (Seidenberg & Tanenhaus, 1979; Stuart, 1990). For example, Ehri and Wilce (1980) found that children were more likely to report that there were more phonemes in the word *pitch* compared to the word *rich*. Furthermore studies with illiterate adults have revealed impaired performance on measures of phoneme awareness when compared to adults who had recently learned to read (Morais, Bertelson, Cary, & Alegria, 1986; Morais, Cary, Alegria, & Bertelson, 1979). However this contrasts with evidence that young children can isolate phonemes in the absence of orthographic knowledge (Hulme, Caravolas, Málková, & Brigstocke, 2005; Lundberg et al., 1988; Muter et al., 2004).

It seems most likely that the development of phoneme awareness and reading share a reciprocal relationship. Longitudinal studies typically report a bi-directional relationship between measures, in that performance on phoneme awareness tasks predict later reading, but also that early reading skill predicts subsequent phoneme awareness (for example Perfetti, Beck, Bell, & Hughes, 1987; Wagner et al., 1994). Returning to the earlier suggestion that letter knowledge and phoneme awareness are reciprocally related, it is has been suggested that learning to associate print with speech enhances awareness of the sound structure of words. In turn, increased awareness of phonemes within words should enable accurate application of letter-sound correspondences during decoding (Fox & Routh, 1984; Levin et al., 2006).

As discussed earlier, the development of phoneme awareness, in combination with letter-sound knowledge, contributes to children’s acquisition of the alphabetic principle (Byrne & Fielding-Barnsley, 1990). Many researchers believe this to be a critical milestone in learning to read and this theory is often cited to explain the strong relationship between phoneme awareness and reading ability.

It has been suggested that the relationship between performance on measures of phoneme awareness and learning to read reflects the integrity of underlying phonological representations. According to the “Phonological Representations

Hypothesis" the formation of phonemically structured representations, rather than children's explicit awareness of these representations, is crucial in the development of word reading skills (Snowling & Hulme, 1994; Swan & Goswami, 1997). Such phonemic representations are proposed to facilitate acquisition of the alphabetic principle, as accurate phonological representations are required in order to understand the correspondence between letters and phonemes in words (Adams, 1994; Melby-Lervåg et al., 2012).

Evidence supporting the role of phonological representations in learning to read also comes from studies using connectionist models of reading, such as the Triangle model (Seidenberg & McClelland, 1989). Harm and Seidenberg (1999) found that additional training of phonological output units facilitated word reading and also lead to increased generalisation in comparison to earlier model implementations that did not receive phonological pre-training (see also Hulme, Quinlan, Bolt, & Snowling, 1995). This finding is aligned with the proposal that underlying phonemic representations, rather than explicit awareness of these representations is crucial in learning to read. Further evidence for this theory will be discussed in subsequent paragraphs when considering the phonological deficit theory of dyslexia.

In summary, there is strong evidence to suggest that phoneme awareness is causally related to children's early reading development. Performance on measures of phoneme awareness is thought to reflect both the quality of underlying phonemic representations and children's ability to consciously access and manipulate these representations. It is proposed that early reading ability is primarily dependent on the quality of phonological representations in combination with letter-sound knowledge.

Rapid automatized naming (RAN)

Rapid naming tasks measure how quickly children can name a series of familiar stimuli; typically this involves the naming of letters, digits, colours or objects (Wolf & Bowers, 1999). These measures are also referred to as rapid automatized naming (RAN) tasks, as performance is assumed to reflect automatic processing (Denckla & Rudel, 1974). Several decades of research has revealed a strong relationship between performance on measures of RAN and children's reading ability, in particular reading fluency, even when controlling for individual differences in other known predictors (Blachman, 1984; Clarke, Hulme, & Snowling, 2005; Compton, 2003; Cutting & Denckla, 2001; de Jong & van der Leij, 1999; Swanson, Trainin, Necoechea, & Hammill, 2003 for a meta-analysis).

Longitudinal studies have also demonstrated the predictive power of RAN speed upon children's reading outcomes and the changing nature of this relationship across early reading development. While naming speed for colours and objects has been found to predict reading performance across the school years (Catts, Gillispie, Leonard, Kail, & Miller, 2002; Lervåg et al., 2009; Share et al., 1984), performance on *alphanumeric* RAN tasks (naming of digits and letters) typically show a stronger relationship with reading (Badian, 1993; Compton, 2003; Wagner et al., 1994). For example, in one study colour RAN measured in kindergarten predicted 20% of the variance in word recognition at the end of second grade, whereas letter RAN predicted 41% of the variance in reading (Wolf, Bally, & Morris, 1986). As a result it has been suggested that individual differences in naming speed may simply reflect variations in early reading skill, specifically children's letter-name knowledge (Bowey, 2008). Indeed, not all kindergarten children in the aforementioned studies were able to name letters (e.g. Catts et al., 2002; Wagner et al., 1994) and Wagner et al. (1997) found that naming speed was largely mediated by variations in letter-name knowledge.

However a recent study provides good evidence that RAN predicts variance in reading beyond early variations in reading skill and letter knowledge (Lervåg & Hulme, 2009). This three-year longitudinal study with over 200 Norwegian children found that variations in object and colour RAN, measured before the onset of formal literacy instruction, predicted unique variance in children's reading fluency at the end of second grade. Lervåg and Hulme (2009) also report a significant longitudinal relationship between alphanumeric and non-alphanumeric RAN, indicating that performance on different RAN tasks is likely to rely upon the same underlying mechanism. In line with previous research, phoneme awareness and letter knowledge were also unique predictors and, together with RAN, these measures accounted for 50% of the variance in reading (Lervåg & Hulme, 2009). Furthermore, this study found that later in development, after children had started to receive formal literacy instruction, alphanumeric RAN predicted subsequent reading growth, even when controlling children’s earlier reading skills and phoneme awareness. Interestingly, this relationship was not reciprocal: children’s reading ability did not significantly predict growth in rapid automatized naming. This pattern was confirmed by Caravolas, Lervåg, Defior, Málková, and Hulme (2013) with children learning to read in English, Spanish, and Czech.

This finding is in line with research suggesting that performance on rapid automatized naming tasks is fairly inflexible. For example, de Jong and Vrielink (2004) were unable to influence the speed of children’s performance on a letter RAN task following a two-week intervention programme. Thus, while longitudinal research indicates that RAN appears to tap skills that are causally related to learning to read, there is currently no evidence that training RAN enhances children’s naming speed or reading performance.

Despite the large body of evidence demonstrating a relationship between RAN and reading skill, there is no current consensus regarding the underlying processes involved in RAN. As such the predictive relationship between RAN and reading ability has been a topic of recent debate. Initially RAN was considered as a measure of phonological processing, reflecting the speed at which phonological information can be retrieved from long-term memory (Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wagner & Torgesen, 1987). However a number of studies have since shown that performance on RAN tasks account for additional unique variance in reading when phonological abilities have been controlled (for example Compton, 2000; Lervåg & Hulme, 2009; Manis, Seidenberg, & Doi, 1999). Thus, while there is clearly a phonological demand, RAN measures appear to tap additional skills that are relevant to children’s reading ability.

Kail and colleagues have argued that RAN speed is simply an index of children’s global speed of processing (Kail & Hall, 1994; Kail, Hall, & Caskey, 1999). However when individual differences in speed of processing are controlled, RAN continues to predict variance in reading performance (Bowey, McGuigan, & Ruschena, 2005; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007). In addition, the recent discovery that *pause time* (the duration between articulation of the RAN items) and *articulation time* (the time taken to articulate RAN items) form distinct components of rapid automatized naming suggests a specific influence of naming speed, rather than simply differences in global processing (Lervåg & Hulme, 2009; Neuhaus, Foorman, Francis, & Carlson, 2001).

The majority of studies have reported that RAN pause time, rather than articulation time, is a stronger predictor of reading (Georgiou, Parrila, & Kirby, 2006; Neuhaus et al., 2001; Neuhaus & Swank, 2002) however there have been some contradictory findings (e.g. Clarke et al., 2005). This stronger effect of RAN pause time has been interpreted to reflect the speed of phonological retrieval (Neuhaus et al., 2001) and, some have argued, the quality of underlying orthographic representations (Georgiou, Parrila, Kirby, & Stephenson, 2008).

Manis et al. (1999) propose that RAN speed reflects the ability to learn, and subsequently access, visual-verbal associations, a skill that is undoubtedly critical during the early stages of reading development. Evidence that performance on paired-associate learning tasks correlates with reading ability provides support for this proposal, as these tasks also involve forming and accessing visual-verbal associations (Hulme et al., 2007; Windfuhr & Snowling, 2001). However studies have generally found the relationship between RAN and paired-associate learning to be weak (Lervåg et al., 2009) or indeed absent (Poulsen, Juul, & Elbro, 2015). Furthermore, Logan, Schatschneider, and Wagner (2011) found that naming speed for letters and digits presented individually did not mediate the relationship between RAN and reading. Given that this task also requires accessing visual-verbal associations, it seems unlikely that the RAN-reading relationship can be completely explained by visual-verbal processing efficiency.

Following from this, it has been widely reported that discrete naming tasks (where items are presented one at a time) do not correlate with reading as strongly as those that involve serial naming (where items are presented simultaneously) (de Jong, 2011; Logan et al., 2011; Wolf & Bowers, 1999). This finding is intriguing and suggests that the serial aspect of RAN may be important in explaining the RAN-reading relationship. Certainly, both serial RAN and reading (particularly performance on measures of reading fluency) require rapid and accurate visual scanning in order to process information efficiently. In line with this a number of researchers have suggested that visual scanning ability might underpin the relationship between RAN and reading (Jones, Ashby, & Branigan, 2013; Jones, Obregón, Kelly, & Branigan, 2008; Kuperman & Van Dyke, 2011; Logan et al., 2011). Protopapas, Altani, and Georgiou (2013) report that performance on a backwards RAN task (where children are required to process items right-to-left) was also significantly correlated with reading and in fact accounted for a larger amount of variance in reading compared to performance on the standard forward RAN task. This unexpected finding was suggested to indicate the role of cognitive control of visual-attentional processing in RAN and reading.

A further alternative account of the RAN-reading relationship has been put forward by Bowers, Wolf and colleagues (Bowers, Sunseth, & Golden, 1999; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000). This “orthographic account” suggests that RAN speed reflects how automatically orthographic and phonological information can be activated. Specifically, RAN speed indexes the precise timing of various visual and linguistic processes, which they argue is crucial in order for children to abstract orthographic patterns in words.

Poulsen et al. (2015) explored the influence of letter knowledge, phoneme awareness, speed of processing, paired-associate learning and lexical search speed upon the RAN-reading relationship using simultaneous mediation analyses. The authors reported that the relationship between RAN and reading was partially mediated by phonological awareness and letter knowledge (for example, phoneme awareness and letter knowledge accounted for 56% of the relationship between reading and object RAN speed). However, the concurrent design of this study makes it difficult to interpret a causal relationship from these results. In contrast to phonological awareness and letter knowledge, paired-associate learning did not mediate the relationship between RAN and reading. The authors propose that paired-associate learning is likely to reflect the ability to establish associations whereas RAN is more indicative of the automation of visual-verbal associations. In line with de Jong (2011) and Jones et al. (2008), Poulsen and colleagues propose that the automatic processing of alphanumeric (and serially presented) information is likely to underlie the RAN-reading relationship.

Finally, some researchers have proposed that RAN skill may reflect the functioning of a neural circuit evolved primarily for object recognition, which is then recycled to serve an analogous purpose in identifying printed words when children learn to read (Lervåg & Hulme, 2009). The authors speculate that RAN tasks might tap the integrity of this neural naming circuit (thought to be located in the left mid-fusiform (Price et al., 2006)), which in turn constrains the development of children’s reading ability. This theory is consistent with the finding that performance on RAN does not improve with increased reading skill and nor does the training of RAN bring about improvement in children’s reading skill (de Jong & Vrielink, 2004).

To summarise, it is clear that RAN speed is a robust predictor of early reading development. Despite the strong relationship between these two skills, it is not clear which aspect of RAN is most important in the development of reading skill. There are many common processes involved in both reading and RAN, for example Norton and Wolf (2012) describe RAN as being a “mini-circuit of the later-developing reading circuitry” (pp. 430). As such, it is possible that a number of processes, such as rapid phonological retrieval and efficient visual scanning, combine to make RAN a key predictor of early reading success.

Predictors of reading across alphabetic orthographies

As previously acknowledged, the English orthography is somewhat inconsistent in the relationship between letters and the speech-sounds they represent. For example, one letter may represent a number of different speech-sounds depending on its context in a word. This has led some to question whether previously identified predictors of early reading development are also important predictors across other more *transparent* orthographies, where the relationship between letters and speech-sounds is more consistent (Share, 2008). Indeed, children appear to learn to read more easily in alphabetic orthographies with highly consistent letter-sound correspondences, than in less consistent orthographies (Caravolas et al., 2013; Seymour, Aro, & Erskine, 2003).

Although the vast majority of studies have been conducted with English-speaking children, letter knowledge has been reported to predict early reading skills in French (Bruck, Genesee, & Caravolas, 1997), Norwegian (Lervåg et al., 2009), Dutch (de Jong & van der Leij, 1999), Turkish (Öney & Durgunoğlu, 1997), German (Näslund, 1990) and Spanish, Slovakian and Czech children (Caravolas et al., 2012). Such studies have typically reported much lower levels of letter knowledge in pre-school children compared to English children. However, this discrepancy is likely to reflect cultural differences, in particular the age at which children begin to receive formal literacy instruction. For example, in German-speaking countries (Germany, Austria and Switzerland) teaching letters is actively avoided until children begin school (Mann & Wimmer, 2002). Contrastingly, in English-speaking countries children have typically learned a number of letter names and sounds before starting school (Muter, Hulme, Snowling, & Taylor, 1998).

Studies conducted within transparent orthographies have reported that phoneme awareness is also associated with children’s early reading skills (Caravolas, Volín, & Hulme, 2005; Wimmer, Landerl, Linortner, & Hummer, 1991). However, the strength of this relationship has been reported to decrease after the first two years of formal literacy instruction (de Jong & van der Leij, 2002; Lervåg et al., 2009; Wimmer, Mayringer, & Landerl, 2000). This has led some researchers to suggest that phoneme awareness may develop earlier and faster in children learning to read transparent orthographies and therefore may exert less of an influence on learning to read (Anthony & Francis, 2005; Vaessen et al., 2010). In contrast, in orthographies where there is a complex relationship between letters and speech-sounds, learning to read may place greater demands on children's phoneme awareness. In line with this hypothesis, longitudinal research involving direct comparison of predictors across orthographies have typically found that phoneme awareness is a stronger and more stable predictor of reading in less orthographically transparent languages (e.g. English and French) compared to more transparent orthographies (e.g. Greek, German, Norwegian, Swedish and Finnish) (Furnes & Samuelsson, 2010; Georgiou, Parrila, & Papadopoulos, 2008; Mann & Wimmer, 2002; Ziegler, Bertrand, et al., 2010).

In contrast, performance on measures of RAN appears to demonstrate the reverse pattern. In transparent orthographies RAN has been found to predict reading performance throughout the school years (Georgiou, Parrila, & Papadopoulos, 2008; Morfidi, Van Der Leij, De Jong, Scheltinga, & Bekebrede, 2007; Vaessen & Blomert, 2010), whereas in English, the influence of RAN speed upon reading appears to be much shorter (Parrila, Kirby, & McQuarrie, 2004; Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009). However, it is important to note that these studies often use measures of reading fluency, rather than accuracy, as children learning to read more transparent orthographies typically demonstrate greater variability on these measures. Thus, some researchers have suggested the extended influence of RAN in transparent orthographies may reflect the use of reading fluency measures (e.g. Share, 2008). Indeed, Moll et al. (2014) report than RAN performance was a significant predictor of reading accuracy in English-speaking children but not in French, German, Hungarian or Finnish children, whereas, RAN was a strong and consistent predictor of reading fluency across all languages.

A recent large-scale longitudinal study conducted by Caravolas et al. (2013) directly compared the contribution of letter knowledge, phoneme awareness and RAN across three languages varying in orthographic consistency. This study followed a large group of English, Spanish and Czech children for 28 months, beginning just before or, in the case of the English group, at the onset of formal literacy instruction.

The main finding from this study was that early reading ability in all three languages was predicted by individual differences in letter knowledge, phoneme awareness and RAN measured at the beginning of the study. The only difference across the three languages was that letter knowledge played a less important role in English, which the authors suggest may reflect the inconsistency of letter-sound correspondences (Caravolas et al., 2013). Furthermore, while initial letter knowledge and phoneme awareness predicted the amount of growth in reading performance over the first year of school, RAN speed predicted how quickly children's reading improved during this time. Subsequent growth in reading during the second year of school was only predicted by earlier reading performance, indicating the importance and relative stability of early reading skills.

To summarise, early reading development is characterised by increasingly close and automatic links between print and speech. These associations are at first quite arbitrary and following explicit instruction children become increasingly aware of the systematic relationship between individual letters and the speech-sounds they represent. Many studies spanning several decades provide evidence that individual differences in letter knowledge, phoneme awareness and RAN speed are robust and reliable predictors of children's reading performance. Furthermore, a wealth of cross-linguistic research provides good evidence that these three predictors are important in learning to read across a range of alphabetic orthographies.

1.3 Developmental dyslexia

Up to now I have considered the typical development of early reading skills and highlighted the complexity of this process. Despite this complexity, with appropriate instruction the vast majority of children will learn to read with remarkable ease. However a significant minority will struggle to acquire this fundamental skill. This section will now consider such cases, with the aim of summarising current understanding of developmental dyslexia and its causal risk factors.

Developmental dyslexia has been extensively studied and is probably one of the best understood developmental disorders. This review will first give a working definition and brief overview of the biological bases of dyslexia before focusing on the main cognitive theories of this disorder. In particular this section will consider theories implicating the auditory and visual processing systems, in order to evaluate the role of automatic letter-sound integration in dyslexia.

1.3.1 Definition and biological basis of dyslexia

Dyslexia is a neurodevelopmental disorder characterised by a severe difficulty in learning to read and spell in the absence of physical impairment or educational disadvantage (Peterson & Pennington, 2015). Children with dyslexia struggle to achieve accurate and fluent word recognition and typically their slow, effortful reading and poor spelling persists into adulthood (S. E. Shaywitz et al., 1999).

Research suggests that individuals with dyslexia represent the lower end of a continuous distribution of reading ability (S. E Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992) and as such the placement of a diagnostic cut-off is somewhat arbitrary. Typically researchers have set this cut-off at 1.5 or 2 standard deviations below the mean, accounting for children’s age (Peterson & Pennington, 2012). Using such criteria, dyslexia has been estimated to affect between 3-7% of the population, and is thus considered to be a fairly common disorder (S. E Shaywitz, Shaywitz, Fletcher, & Escobar, 1990; Yule, Rutter, Berger, & Thompson, 1974).

Children with dyslexia often experience comorbid difficulties, for example attention-deficit hyperactivity disorder (ADHD), language impairment or mathematics disorder (Bishop & Snowling, 2004; Landerl & Moll, 2010; Rhee, Hewitt, Corley, Willcutt, & Pennington, 2005). Such comorbidities are suggested to be the result of shared neurocognitive risk factors, a topic that will be discussed in subsequent paragraphs (Pennington & Bishop, 2009).

Research has also indicated the strong heritability of dyslexia, for example Snowling, Gallagher, and Frith (2003) report that in their study, 66% of pre-school children at family risk of dyslexia (those with at least one dyslexic family member) went on to experience reading difficulties. While genetic research has identified a number of candidate genes (see Fisher & Francks, 2006 for a review), the precise genetic mechanisms underlying dyslexia remain largely unknown. It is likely that a number of genetic and environmental risk factors interact in the development of reading difficulties (Peterson & Pennington, 2012).

By contrast, much more is known about the neural basis of dyslexia. Extensive evidence suggests that structural and functional abnormalities of a distributed left-hemisphere language network characterise individuals with dyslexia (see Price, 2013; Schlaggar & McCandliss, 2007 for reviews). For example, a recent meta-analysis by Richlan, Kronbichler, and Wimmer (2009) reported that reduced activation in left-hemisphere temporo-parietal and occipito-temporal regions in individuals with dyslexia are likely to reflect impaired phonological processing and visual word recognition, respectively. Through comparison with reading-age and chronological-age control groups, research by Hoeft and colleagues has confirmed that such functional abnormalities are characteristic of dyslexia, rather than simply reflecting limited reading experience (Hoeft et al., 2006; Hoeft et al., 2007). Research investigating structural differences in brain matter mirror those investigating functional activation, reporting reduced grey and white matter density in left-hemisphere sites (Kronbichler et al., 2008; Silani et al., 2005; Steinbrink et al., 2008). Furthermore, Raschle, Chang, and Gaab (2011) report significant differences in grey matter structure between pre-school children with and without family-risk of dyslexia, suggesting reduced grey matter predates learning to read.

1.3.2 Cognitive theories of dyslexia

General processing deficits

A number of theories have proposed that dyslexia results from a deficit in more domain-general learning abilities. For example, some researchers have argued that reading difficulties can be attributed to impairments in associative learning (Gascon & Goodglass, 1970), rule learning (Manis et al., 1987) and difficulties in focusing or shifting attention (Hari & Renvall, 2001; Pelham & Ross, 1977). However, such theories have limited empirical evidence and also fail to account for the specific nature of reading difficulties in dyslexia (Vellutino, Fletcher, Snowling, & Scanlon, 2004).

The most widely studied theory positing a more general processing deficit is the cerebellar deficit theory proposed by Nicolson and Fawcett (1990). This broad theory suggests that impairment of the cerebellum causes a deficit in the automatisation of behaviour, in particular the ability to complete overlearned tasks such as reading. Evidence for this theory comes from studies reporting the poor performance of children with dyslexia on a number of cerebellar tasks such as time estimation (Nicolson, Fawcett, & Dean, 1995), motor control (Fawcett, Nicolson, & Dean, 1996) and dual tasks requiring automatisation of balance (Nicolson & Fawcett, 1990). However, again, this theory does not account for the highly specific difficulties in children with dyslexia. In addition, while some children with dyslexia experience motor impairments, some studies have reported motor problems in only a subgroup of children with dyslexia (Ramus et al., 2003) or not at all (van Daal & van der Leij, 1999). Furthermore, there is evidence to suggest motor/cerebellar impairments in dyslexia are result of comorbidity with ADHD (Raberger & Wimmer, 2003; Rochelle & Talcott, 2006).

Processing deficits specific to the visual and auditory sensory systems

Early accounts of dyslexia suggested that reading difficulties arose from a deficit in visual processing. For example, one of the earliest theories, known as the optical reversibility theory of dyslexia (Orton, 1925) proposed that individuals with dyslexia perceived letters and words in reverse (e.g. commonly mistaking b for d). However, these early studies failed to control for verbal demands of the tasks and subsequent, more carefully controlled, studies were unable to replicate group differences in visual processing (Vellutino, 1987).

A number of theories implicating the visual system have since been put forward, the majority of which propose specific impairment of the magnocellular visual pathway, also referred to as the ‘transient visual system’ (see Ramus et al., 2003 for a review). For example, Lovegrove and colleagues propose a deficit in the transient visual system whereby individuals with dyslexia are unable to inhibit visual traces of words in connected text (e.g. Lovegrove, Martin, & Slaghuis, 1986). However, evidence that the transient visual system is causally related to dyslexia is mixed (Vellutino et al., 2004), and one obvious criticism is that individuals with dyslexia are also impaired when reading individual words as well as connected text (Hulme, 1988).

In recent years there has been renewed interest in visual processing theories of dyslexia, in particular theories implicating the allocation of attention (e.g. Facoetti & Molteni, 2001; Hari & Renvall, 2001; see also Vidyasagar & Pammer, 2010 for a review). One such theory known as the ‘visual attention span deficit hypothesis’ postulates that individuals with dyslexia struggle to narrow their attentional window, and as a result experience difficulty processing letters in the correct order and distinguishing between words that are visually similar (Bosse, Tainturier, & Valdois, 2007; Valdois, Bosse, & Tainturier, 2004). In such studies participants are presented with an array of five letters for 200ms and are required to identify either as many letters as possible or a single cued letter. The authors report that children with dyslexia typically perform poorly on these tasks and suggest this may result from impaired visual-attentional processing.

A subsequent study compared children’s performance on a similar task, using strings of letters, digits and non-alphanumeric symbols (Ziegler, Pech‐Georgel, Dufau, & Grainger, 2010). Importantly this task required a two-alternative forced choice rather than verbal report, thus reducing the phonological STM demands. Ziegler and colleagues report that children with dyslexia were significantly less accurate in selecting the correct letters and digits, however performance with symbols was unimpaired. Thus, results indicated that children with dyslexia exhibited a specific difficulty with symbols that map onto phonological codes, rather than with visual-attentional processing more generally.

In addition to processing deficits in the visual domain, there are a number of theories of dyslexia proposing that reading difficulties arise from impairment in the auditory domain. One of the most widely studied theories is the rapid auditory processing deficit hypothesis (Tallal, 1980). This theory proposes that reading difficulties result from a deficit in the perception of rapid and brief sounds, meaning that children are unable to segment information from the speech stream, resulting in impaired phonological processing in dyslexia.

Evidence for this theory comes from studies reporting impaired performance of individuals with dyslexia on tasks measuring frequency discrimination (Ahissar, Protopapas, Reid, & Merzenich, 2000; Mcanally & Stein, 1996) and temporal order judgement (Nagarajan et al., 1999; Tallal, 1980). However some studies have since failed to replicate these findings (Hill, Bailey, Griffiths, & Snowling, 1999; McArthur & Hogben, 2001) and others suggest that impaired rapid auditory processing may only be found in a subgroup of children with dyslexia (Marshall, Snowling, & Bailey, 2001; Mody, Studdert-Kennedy, & Brady, 1997; Rosen & Manganari, 2001). In addition there is some evidence that a deficit in rapid auditory processing may in fact reflect oral language difficulties in children with dyslexia, rather than reading difficulties (Heath, Hogben, & Clark, 1999; Tallal & Stark, 1982).

A more recent theory proposed by Goswami et al. (2002) concerns the auditory processing of rhythm, or more specifically, the amplitude envelope rise time of speech. Speech contains a range of amplitude modulations, which vary in *rise time* (i.e. the time that is required to reach peak amplitude). One method used to determine rise time sensitivity is a ‘beat detection task’ whereby the steeper the rise time of the amplitude modulation, the more likely it is that participants will perceive a ‘beat’. A number of studies have shown that children with dyslexia are less sensitive to variations in rise time (Goswami et al., 2011; Poelmans et al., 2011; Richardson, Thomson, Scott, & Goswami, 2004) which has led to the suggestion that impaired perception of amplitude envelopes might hamper the development of accurate phonological representations and underlie phonological deficits observed in individuals with dyslexia (Goswami, 2015). A recent comprehensive review has confirmed group differences on measures of low-level auditory processing, including sensitivity to rise time (Hämäläinen, Salminen, & Leppänen, 2013). However the authors also acknowledge a number of inconsistent findings and again suggest that low-level auditory processing deficits may characterise a subgroup of individuals, rather than reflect the main causal risk factor for dyslexia.

In addition to theories positing a deficit in the visual or auditory domain, some researchers have argued that reading difficulties may result from impaired cross-modal integration of vision and audition. For example, Widmann, Schröger, Tervaniemi, Pakarinen, and Kujala (2012) created a symbol-to-sound matching task to measure audio-visual integration. In this task children were presented with a number of rectangles that were positioned either above or below the midline and corresponding auditory tones, which were either high or low in pitch. Children were required to decide if the rectangles and tones were congruent or incongruent using a button response. The authors report that children with dyslexia performed significantly worse on this matching task compared to typically developing (TD) children. Although further replication is clearly required, studies involving the presentation of corresponding light flashes and auditory tones have reported similar group differences (Laasonen, Tomma-Halme, Lahti-Nuuttila, Service, & Virsu, 2000; Laasonen & Virsu, 2001). In addition one training study claims that exercises involving audio-visual matching led to improvements in the reading skills of children with dyslexia (Kujala et al., 2001). However the small sample size (N=24) and substandard design of this training study prevents any firm conclusions from being drawn.

In line with this idea of a cross-modal deficit, a number of paired-associate learning studies have shown that children with dyslexia struggle to form cross-modal associations (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003). However recent research by Litt and Nation (2014) compared paired-associate learning performance across and within verbal and visual modalities and found that children with dyslexia showed a specific deficit in conditions that required verbal learning. Thus, this research provides good evidence that impaired visual-verbal paired-associate learning in children with dyslexia is most likely to reflect an underlying difficulty in learning new phonological information rather than a deficit in general cross-modal learning.

Phonological deficit theory of dyslexia

As discussed earlier in this review, research has shown that phonological language skills, in particular children’s phoneme awareness, are an important predictor of early reading development (e.g. Melby-Lervåg et al., 2012). Furthermore, intervention research has demonstrated that there is likely to be a causal relationship between phoneme awareness and early reading development (Bowyer ‐ Crane et al., 2008; Hulme et al., 2012). In line with this, the proposal of a phonological deficit as the cognitive basis of dyslexia is now also widely accepted, however theorists continue to debate the specific nature of this phonological deficit (Peterson & Pennington, 2015; Ramus, 2014; Ramus & Szenkovits, 2008; Vellutino et al., 2004).

Many studies have demonstrated that, compared to typically developing children, children with dyslexia display impaired performance on a number of phonological tasks, including measures of non-word repetition (Elbro, Borstrøm, & Petersen, 1998; Snowling, Stackhouse, & Rack, 1986), phonological paired-associate learning (Litt & Nation, 2014; Wimmer, Mayringer, & Landerl, 1998), phonemic awareness (Bruck, 1992; Landerl, 2001; Swan & Goswami, 1997) and verbal STM (Griffiths & Snowling, 2002; McDougall, Hulme, Ellis, & Monk, 1994).

In addition, there is evidence to suggest that phonological deficits are present before children learn to read (Pennington & Lefly, 2001; Scarborough, 1990; Snowling et al., 2003). These longitudinal studies recruited children at family risk of dyslexia, allowing researchers to directly compare the early cognitive skills of children who learnt to read normally, versus those who received a later diagnosis of dyslexia. These studies show that high-risk children who go on to experience reading difficulties have significantly lower scores on a wide range of phonological measures, and in addition, a higher incidence of broad oral language difficulties before reading instruction begins. Likewise, it has been shown that children with early language difficulties are at high risk of subsequent reading difficulties (Snowling, Bishop, & Stothard, 2000; Thompson et al., 2015). This research illustrates that spoken language skills provide a critical foundation for the development of reading, and suggest that having strong oral language skills in the presence of familial risk can protect against developing subsequent reading difficulties.

Whereas explicit awareness of the phonological structure of spoken language is believed to play a causal role in typical reading development, it is widely held that the phonological deficit observed in children with dyslexia primarily arises from poorly specified or weak phonological representations (Fowler, 1991; Snowling & Hulme, 1994). Indeed, studies have shown that children with dyslexia have increasingly impaired phonological representations compared to younger typically developing children matched on reading ability (Boada & Pennington, 2006; Bruno et al., 2007; Elbro & Jensen, 2005; Nation, Marshall, & Snowling, 2001). According to this hypothesis, children with inaccurate or “fuzzy” phonological representations struggle to acquire related phonological skills such as phonological awareness and letter-sound decoding (Elbro, 1998; Snowling, 2000). In addition to impaired performance on phonological language tasks, problems storing and retrieving phonological information is likely to make it difficult for children with dyslexia to establish strong associations between spoken and printed words (Vellutino & Fletcher, 2008).

As previously discussed, some researchers propose that impaired auditory processing underlies the phonological deficit observed in children with dyslexia (e.g. Goswami et al., 2002; Tallal, 1980). A variant of this argument is that inaccurate phonological representations are the result of impaired speech perception in children with dyslexia. Evidence for this hypothesis comes from studies of categorical perception, which report that children with dyslexia make significantly more errors when asked to discriminate between two syllables that differ in voice onset time (Chiappe, Chiappe, & Gottardo, 2004; Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004). While it is clear how a deficit in speech perception could lead to the development of inaccurate phonological representations, evidence of this deficit is somewhat inconsistent. It would appear most likely that impaired speech perception might characterise a subgroup of children with dyslexia and may be related to oral language difficulties in this group, rather than specific reading difficulties (Hulme & Snowling, 2009; Joanisse, Manis, Keating, & Seidenberg, 2000).

Over the years a number of researchers have proposed that there are distinct subtypes of dyslexia, which may account for subgroups of children who have reading difficulties in the presence of additional deficits, such as impaired speech perception (see Vellutino & Fletcher, 2008 for a review). One theory, known as the double deficit hypothesis (Bowers & Wolf, 1993) proposes three subtypes of dyslexia that are characterised by deficits in either phonological skills, rapid automatized naming or “double deficits” in both phonological skills and rapid automatized naming. Within this account deficits in RAN are thought to reflect an impaired timing mechanism, which subsequently disrupts the temporal integration of letters during reading and prevents children from detecting and learning orthographic patterns (Bowers, Golden, Kennedy, & Young, 1994; Wolf, Pfeil, Lotz, & Biddle, 1994). As previously discussed, performance on measures of RAN do appear to correlate most strongly with reading fluency rather than accuracy and also predict children’s reading ability beyond differences in phonological skills (Manis, Doi, & Bhadha, 2000). In addition, Wolf et al. (2000) report that children with double deficits are typically worse readers when compared to children with either phonological or RAN deficits.

In line with this idea of distinct subtypes in dyslexia, a number of researchers now consider potential causal influences as multiple independent risk factors, which combine and interact to increase the risk of reading disorder (Bishop, 2006; Pennington, 2006). Within this view, a single phonological deficit is insufficient to account for reading difficulties in dyslexia. Indeed, a number of studies have reported children who have a preschool phonological deficit but who go on to develop normal literacy skills (Bishop, McDonald, Bird, & Hayiou - Thomas, 2009; Peterson, Pennington, Shriberg, & Boada, 2009; Snowling et al., 2003). Rather, a core phonological deficit might vary in severity across individuals, with its influence on reading likely to depend on the presence of additional risk or protective factors, such as broader oral language skills or processing speed (Moll, Loff, & Snowling, 2013; Peterson & Pennington, 2015).

To summarise, research over the past few decades has made good progress in understanding why some children struggle to learn to read. There is good evidence for genetic influences on the development of dyslexia, however environmental factors also play a role. Current understanding of the neural basis of dyslexia is well advanced and implicates reduced activation and structural differences in a left-hemisphere language network. In line with this, recent research has highlighted the importance of early oral language skills in children with family risk of dyslexia.

This necessarily condensed summary of research on dyslexia, reflects the current dominant theory that reading difficulties arise from a core deficit in phonological processing, specifically, poorly specified phonological representations, possibly operating in combination with other cognitive risk factors. While some have argued for a central role of low-level visual and auditory processing deficits, these theories often fail to account for the highly specific nature of dyslexia. Theories positing impaired speech perception offer a plausible account of the origin of observed phonological deficits, however such impairments are not present in all children with dyslexia and therefore appear less likely to reflect a core deficit. Certainly, understanding the cognitive basis of dyslexia is complex and the next goal in this field will be to improve understanding of how various cognitive risk factors might interact in the aetiology of dyslexia.

1.4 Letter-sound integration, reading and dyslexia

The research summarised so far has illustrated the essential role of the auditory and visual systems in learning to read. Creating associations between printed letters and their corresponding speech-sounds is a crucial process in the early stages of reading acquisition. Once children have acquired letter-sound knowledge, these ‘connections’ become increasingly efficient, such that during decoding, the processing of a visual letter appears to automatically activate the corresponding sound. Whilst this would appear to be a crucial skill in learning to read, relatively few studies have investigated how basic (letter-level) associations between script and speech are acquired and subsequently automatized, and the influence this has on reading ability. I will now consider research investigating the integration of letters and speech-sounds in order to determine whether a deficit in this ability may reflect a proximal cause of dyslexia.

1.4.1 Behavioural evidence of automatic letter-sound integration

A number of studies have shown that the visual and auditory systems become highly interactive as a result of learning to read, such that in literate adults, performance on speech processing tasks is influenced by orthographic knowledge. The majority of studies have investigated word-level processing, employing a variety of different paradigms, including rhyme judgement (Donnenwerth-Nolan, Tanenhaus, & Seidenberg, 1981), priming (Chéreau, Gaskell, & Dumay, 2007) and lexical decision (Taft, Castles, Davis, Lazendic, & Nguyen-Hoan, 2008; Ziegler & Ferrand, 1998). Furthermore, there is evidence that phonological and orthographic processes are increasingly interactive in good readers compared to poor readers (Booth, Perfetti, & MacWhinney, 1999; Desroches et al., 2010; Landerl, Frith, & Wimmer, 1996; Snowling, 1980). There are, however, relatively few studies investigating cross-modal interaction at the level of individual letters and speech-sounds.

An early study by Dijkstra, Schreuder, and Frauenfelder (1989) provides evidence of automatic cross-modal associations between letters and speech-sounds. This study found that adult Dutch readers were significantly faster to identify the vowel in an auditory syllable (e.g. /e/ in /se/) when it was primed by the same visually presented letter (e.g. <e>) presented 250 or 100ms before the syllable. Participants in this study were also significantly slower to identify the vowel when primed by an incongruent visual letter (e.g. <a>). Both congruent and incongruent response times were compared to a baseline condition where a non-linguistic visual stimulus preceded the auditory syllable.

The authors argue that the presentation of a congruent letter triggered automatic cross-modal activation of the target vowel, resulting in a facilitating effect on auditory identification. Whereas in the incongruent condition, the competing phonological representation was activated, resulting in slower identification of the target vowel. A further experiment also reported significant priming following the visual presentation of the co-occurring consonant. As the consonant letter prime is not relevant to the participants' target vowel choice, the authors conclude that the priming effect occurred automatically, in the absence of control and attention. Whilst this study did not measure participants' reading skill, the authors propose that this process of cross-modal activation supports visual word recognition.

A similar study, with English-speaking adults, required participants to make a forced-choice auditory discrimination (e.g. "heard /tɑ/ or heard /dɑ/?") following the presentation of either a congruent (e.g. <ta>), incongruent (e.g. <da>) or irrelevant grapheme (e.g. <na>) (Borowsky, Owen, & Fonos, 1999). Participants were more accurate in making this decision following the congruent grapheme prime, compared to both the incongruent and irrelevant prime. Furthermore, the difference in accuracy between the congruent and baseline conditions was significantly greater than the difference between the incongruent and baseline (irrelevant prime) conditions. The authors interpreted this facilitation as evidence for direct connections between visual and phonemic representations, rather than simply a bias or willingness to select the corresponding phoneme (which would presumably provide equal benefit and cost).

In a further experiment, Borowsky and colleagues investigated the effect of an auditory prime on visual discrimination. Again, participants were significantly more accurate in making a visual discrimination (e.g. “saw <ta> or saw <da>?”) following the presentation of a congruent phoneme. However, in this experiment the visual prime showed a symmetrical effect upon accuracy in the congruent and incongruent condition. Thus the authors concluded there was no evidence for direct connections from phonemic to visual representations.

Using a similar behavioural design Blau, Van Atteveldt, Formisano, Goebel, and Blomert (2008) presented participants with visual letters that varied in visual noise (low, medium or high). Letters were followed by an auditory speech-sound which participants had to identify (the speech-sound was either /a/ or /e/). Participants in this study were faster to identify the speech-sound following the presentation of a congruent visual letter, compared to trials where speech-sounds were presented alone. In addition, performance on incongruent trials was slower. Both of these effects were weaker when the visual letter was increasingly masked. Thus results from this study also demonstrate cross-modal activation of letters and speech-sounds in literate adults. However, it is not clear from this study whether such activation was automatic. While the behavioural response was unrelated to the visual letter, this study manipulated the weighting of congruent and incongruent trials (75%: 25%), so in contrast to previous studies, participants were encouraged to attend to the visual information.

Of the limited behavioural studies exploring letter-sound integration, there are even fewer developmental studies. As such, it is not yet clear when letters and speech-sounds become automatically integrated and how this ability relates to reading skill across typical development.

Studies investigating letter-sound integration in children have most commonly compared the performance of children with and without dyslexia. For example, Blau et al. (2010) measured the performance of two groups of 9 year-old Dutch children on a behavioural letter-speech-sound matching task. In this task, children were asked to judge the congruency of letter speech-sound pairs (for example /ui/ and <oe>). The study found that while the two groups did not differ in terms of accuracy, children with dyslexia took significantly longer to decide whether the visual letter and auditory speech-sound were the same or different. This finding suggests that while children with dyslexia may have adequate letter-sound knowledge, the extent to which these representations are automatically integrated is reduced. However, the absence of a baseline condition limits the conclusions that can be drawn from this study as it is not clear whether increased response times in the dyslexic group simply reflect a difficulty processing phonological information.

A more recent study from the same group compared the performance of three groups of 9 year-old children (TD, mildly dyslexic and severely dyslexic) on the same letter-sound matching task, although in this study it is referred to as a letter-speech-sound discrimination task (Žarić et al., 2014). Children with dyslexia were divided into two groups based on a median split of their reading fluency scores.

In line with previous findings, there were no significant differences in terms of accuracy between the typically developing and mildly dyslexic group. However, the accuracy of the TD group was higher compared to the severely dyslexic group. In contrast, there were no significant differences in response time between either group for this task.

This study also included a letter identification task that required children to match a speech-sound to one of four visually presented letters (e.g. /b/ and <b> <d> <t> <p>). There were no significant differences in accuracy between the TD group and the children with mild dyslexia. However children with severe dyslexia were found to be significantly less accurate, compared to the control group. In terms of response speed on this task, the TD group were significantly faster to identify the correct letter, compared to both groups of children with dyslexia. This may indicate reduced integration of letters and speech-sounds in children with dyslexia, however, the absence of a baseline condition prevents this conclusion from being drawn.

It is not clear why findings from these studies are inconsistent, specifically why Blau et al. (2010) but not Žarić et al. (2014) found significant group differences on the same letter-speech-sound discrimination task. However, the primary focus of these studies was to explore the neural correlates of letter-sound integration, where, in contrast to performance on behavioural measures of integration, significant group differences were observed. These inconsistent results suggest there may be a dissociation between behavioural and neural indices of integration, an issue that will be discussed further in subsequent chapters.

A recent training study provided an alternative measure of letter-sound integration through teaching Dutch children with and without dyslexia an artificial script using Hebrew letters and Dutch phonemes (Aravena, Snellings, Tijms, & van der Molen, 2013). In line with results from Blau et al. (2010), both groups demonstrated adequate letter-sound knowledge of the artificial script. However, when tested on a more complex, time-pressured task the dyslexic group made significantly more errors. Furthermore, TD readers were significantly faster than children with dyslexia when required to decode familiar words written using this artificial script. Findings from this study appear to support the notion that simply knowing which letter belongs to which speech-sound differs widely from the ability to use these associations efficiently for fluent reading, and that impairment of the latter is associated with difficulties in decoding words efficiently. A particular advantage of this design is that the authors were able to control the amount of reading experience children received prior to the study. However, given that the phonemes in this artificial script were from the participant’s native language, it is still unclear whether the dyslexic group’s poor performance was attributable to their initially poor phonological representations.

While there is limited behavioural evidence supporting the role of automatic letter-sound integration in typical reading development and dyslexia, there are a number of training studies that report gains in reading following explicit instruction in letter-sound correspondences (Bach, Richardson, Brandeis, Martin, & Brem, 2013; Magnan, Ecalle, Veuillet, & Collet, 2004; Tijms & Hoeks, 2005). Although it has not been experimentally tested, it is possible that frequent and persistent training in letter-sound correspondences leads to automatic integration and subsequently improvements in reading performance.

In a recent longitudinal study, Blomert and Willems (2010) trained a small group of children with and without family risk of dyslexia using a computerised programme designed to improve letter-sound correspondences. Comparing the risk and non-risk children before and after training revealed that the risk group did not show improvements in letter-speech-sound processing, whereas the non-risk group showed significant improvement after training. However, there was no significant relationship between improvements in letter-sound associations following training and first grade reading ability. As the authors acknowledge, this is perhaps due to the relatively short duration of training (six months) and the extended period of time required for automatic associations to develop (Froyen, Bonte, van Atteveldt, & Blomert, 2009). In addition, measures of letter-sound associations were calculated using accuracy scores on a letter-speech-sound discrimination and identification task (as previously described). Therefore, it is possible that differences in accuracy reflect children’s letter-sound knowledge rather than the extent of automatic integration.

To summarise, behavioural studies suggest that the presentation of a congruent visual letter leads faster identification of a corresponding phoneme in literate adults. This indicates that following several years of reading experience letters and speech-sounds have become automatically integrated.

Though researchers have proposed that this skill might underlie visual word recognition, there are currently no studies that have explored the relationship between automatic letter-sound integration and reading ability in adults.

Furthermore, behavioural research assessing the development of letter-sound integration is scarce. The majority of developmental studies in this field have compared the performance of children with and without dyslexia, with mixed results. Early work reported a discrepancy between accuracy and reaction time on behavioural measures of letter-sound integration, suggesting that children with dyslexia have adequate knowledge of correspondences between letters and speech-sounds but that representations are not automatically integrated. However subsequent research was unable to replicate these findings. Studies involving explicit training of letter-sound correspondences have been successful in promoting children's reading skills and there is some evidence to suggest TD children show greater improvement in this skill compared to children with family risk of dyslexia. However it is not clear from these studies whether gains in reading result from enhanced integration or simply improved letter-sound knowledge, or whether underlying differences in phonological processing are driving group differences.

1.4.2 A neural network for the multi-sensory integration of letters and speech-sounds

There is growing evidence of neural differences in individuals with dyslexia, specifically, in the structure and activation of a distributed left-hemisphere language and reading network (Peterson & Pennington, 2012). This section will first examine studies exploring how speech and script are associated in the brain. Understanding the proposed neural marker of letter-sound integration in typically developing readers will serve as a basis for understanding how this mechanism may be impaired in dyslexia.

The influence of letters on speech-sound processing: Evidence for multi-sensory integration and modulatory feedback

Studies using magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) have highlighted the role of the superior temporal sulcus (STS) and superior temporal gyrus (STG) as multi-sensory integration sites for letters and speech-sounds (Raij, Uutela, & Hari, 2000; van Atteveldt, Formisano, Goebel, & Blomert, 2004). The findings from these studies are summarised in Table 1.1. As can be seen from the Table, studies have generally cited two main findings to support claims about multi-sensory integration at the neuronal level. These are;

1) Evidence that a specific brain region responds to both auditory and visual input and critically, that multisensory activation is “super-additive” (Calvert, 2001, i.e. activation is greater than would be expected from the sum of auditory and visual activation)
2) A significant “congruency effect” (i.e. differential activation for corresponding and non-corresponding information) as this implies that information from individual sensory inputs has been integrated successfully

In the van Atteveldt et al. (2004) study, Dutch adults passively attended to letters and speech-sounds presented in isolation or in pairs during fMRI recording. Letter-sound pairs were either congruent or incongruent. As reported in previous studies of single-letter and speech-sound processing, unimodal presentation of letters and speech-sounds led to increased activation in corresponding sensory processing areas (letters - inferior occipito-temporal cortex; speech-sounds - superior temporal cortex) (James & Gauthier, 2006; Jäncke, Wüstenberg, Scheich, & Heinze, 2002; Polk et al., 2002). However, areas in the superior temporal sulcus (STS) and superior temporal gyrus (STG) responded to visual letter stimuli as well as to auditory speech-sounds. In addition, regions of the auditory cortex showed a super-additive response during the simultaneous presentation of letters and speech-sounds, independent of congruency.

Table 1.1 A summary of findings from neuroimaging studies investigating automatic letter-sound integration

Details of the study				**Evidence of multisensory integration**			
Authors/year/journal	**Reading status / age group**	**Sample size**	**Language spoken**	**Increased activation during AV (bimodal) versus A or V (unimodal) presentation of letters and speech-sounds?**	**Increased activation during AV compared to A + V (e.g. super-additivity)?**	**Significant "congruency effect"?**	**Direction of the congruency effect**
van Atteveldt et al. (2004); Neuron	TD adults	16	Dutch	**Yes:** Superior temporal gyrus (STG) and superior temporal sulcus (STS)	**Yes:** Planum temporale (PT) and Heschl's sulcus (HS)	**Yes:** Heschl's sulcus extending to planum temporale (PT) (auditory cortex)	Congruent AV > Baseline (speech-sounds presented alone) > Incongruent AV
Raij et al. (2000); Neuron	TD adults	8	Finnish	**Yes:** Superior temporal lobe	**Yes:** Superior temporal lobe	**Yes:** left and right superior temporal sulcus (STS)	Congruent interaction (congruent AV - A+V) > Incongruent interaction (incongruent AV-A+V)
Herdman et al. (2006); Neuroscience Letters	TD adults	13	Japanese	*Did not record activation to unimodal stimuli*	**-**	**Yes:** Left auditory cortex relative to incongruent condition	Congruent AV > Incongruent AV
Holloway, van Atteveldt, Blomert, and Ansari (2015); Cerebral Cortex	TD adults	18	English	*Not reported*	-	**No:** Auditory association cortex **Yes:** Bilateral temporal gyrus	Incongruent AV > Congruent AV

Blau, van Atteveldt, Ekkebus, Goebel, and Blomert (2009); Current Biology	TD adults	13	Dutch	*Not reported*	**-**	**Yes:** superior temporal gyrus (STG)	Baseline (maximal A or V response) > Incongruent AV
	Dyslexic adults	13	Dutch	**-**	**-**	**No**	Baseline (maximal A or V response) = Incongruent AV
Blau et al. (2010); Brain	TD children (aged 9)	16	Dutch	*Not reported*	-	**Yes:** Planum temporale (PT) / Heschl's sulcus (HS) and superior temporal sulcus (STS)	Congruent AV > Incongruent AV
	Dyslexic children (aged 9)	18	Dutch	-	-	**No**	Baseline A = Congruent AV = Incongruent AV
Kronschnabel, Brem, Maurer, and Brandeis (2014); Neuropsychologica	TD adolescents (aged 15)	22	German	*Not reported*	**No:** Instead evidence of sub-additivity (decreased activation for AV) in superior temporal gyrus (STG)	**Yes:** various locations including left inferotemporal cortex, contralateral superior temporal gyrus (STG), superior temporal sulcus (STS) and parieto-temporal-occipital junction	Incongruent AV > Congruent AV
	Dyslexic adolescents (aged 15)	13	German	-	As above	As above	Congruent AV > Incongruent AV

Raij et al. (2000) report a similar pattern of results with Finnish adults using MEG. In this study, participants were required to detect a target letter during sequential presentation of isolated letters, speech-sounds or letter-speech-sound pairs. Again, participants showed an enhanced neural response in the superior temporal lobe during the presentation of letter-speech-sound pairs compared to isolated letters and speech-sounds. Critically, activation during the presentation of letter-speech-sound pairs was significantly higher than the sum of activation during the presentation of isolated letters and speech-sounds. The authors interpreted this super-additive effect as reflecting multisensory integration.

In addition to multisensory activation in the superior temporal sulcus (STS), van Atteveldt et al. (2004) report that activation in the auditory cortex is modulated by the congruency of letter-sound pairs. Participants demonstrated significantly increased activation in response to congruent letter-sound pairs when compared to activation for speech-sounds presented alone. In contrast, activation in response to incongruent pairs was significantly reduced.

A subsequent MEG study by Herdman et al. (2006) investigated the audio-visual integration of Japanese characters (Hiragana graphemes) and their corresponding speech-sounds in Japanese adults. In line with the previous research, this study reported greater response power for congruent relative to incongruent letter-speech-sound pairs in the left auditory cortex. This difference occurred early during processing of the stimuli (within 250ms) supporting fMRI evidence that the processing of visual letters modulates subsequent processing of the speech-sound in the auditory cortex (Hashimoto & Sakai, 2004; van Atteveldt et al., 2004). In typical literate adults this integration process is thought to be rapid and automatic. In line with studies using a passive paradigm, Blau et al. (2008) report that the presentation of a congruent visual letter modulated activation in the superior temporal and auditory cortex during an active speech identification task where visual letters were not relevant to task performance.

However, there is conflicting evidence for the role of the superior temporal cortex in multisensory integration (Hocking & Price, 2008). For instance, a recent study by Kronschnabel et al. (2014) found evidence of decreased activation in response to letter-speech-sound pairs compared to the sum of activation for letters and speech-sounds presented independently.

In contrast to earlier research in relatively transparent orthographies, a recent study suggests that letters and speech-sounds may not be automatically integrated in English readers (Holloway et al., 2015). In this study participants were presented with audio-visual letter and number pairs. There were three different levels of orthographic transparency; participants were shown letters paired with either speech-sounds (least consistent) or letter names (somewhat consistent), or numbers paired with their names (entirely consistent). Congruent and incongruent pairs were presented and participants simply had to attend to the stimuli while fMRI data was collected.

Whole brain analysis revealed a significant congruency effect for letter-name and number pairs in the auditory association cortex, (specifically, the transverse temporal gyrus) but not in response to letter-sound pairs. The authors interpreted this finding as reflecting the irregularity of letter-sound mappings in the English writing system - where one letter can represent a number of different sounds depending on its context in a word. This finding is particularly striking as the authors of this study selected letter-sound pairings that were identified as being the most regular in English (Berndt, Reggia, & Mitchum, 1987).

In addition, the study reported a reverse congruency effect, whereby the presentation of incongruent letter-sound pairs led to greater activation in English readers. The authors interpreted this reverse congruency effect as indicative of conflict resolution when stimuli are mismatched. However, this ‘incongruency effect’ has been reported elsewhere in studies of multisensory processing (Hocking & Price, 2008; Kronschnabel et al., 2014; Pekkola et al., 2006; van Atteveldt, Formisano, Blomert, & Goebel, 2007) with some proposing that increased activation in response to incongruent letter-sound pairs simply reflects higher-level processing of two different representations, compared to one (Kronschnabel et al., 2014). Thus it is not clear what can be inferred from the direction of these congruency effects. As summarised in Table 1.1, findings have been inconsistent, with some studies comparing congruent and incongruent activation directly and others comparing congruent or incongruent activation with activation in response to speech-sounds presented alone.

Atypical integration of letters and speech-sounds in the dyslexic brain

Subsequent research investigated the neural integration of letters and speech-sounds in 26 adult Dutch readers with varying reading abilities (Blau et al., 2009). As in earlier studies, participants passively attended to individual letters and speech-sounds and letter-speech-sound pairs during fMRI recording. The congruency of letter-sound pairs was manipulated. The study revealed that whilst typical and dyslexic readers activated the same occipito-temporal network during the presentation of isolated letters and speech-sounds, dyslexic readers showed reduced activation in response to isolated speech-sounds. In addition, the authors claim that adults with dyslexia showed evidence of reduced integration of letter-sound pairs. Whereas typical adults suppressed superior temporal gyrus (STG) activation during the presentation of incongruent letter-sound pairs, dyslexic adults showed comparable levels of activation for both congruent and incongruent letter-sound pairs. The absence of a ‘congruency effect’ was interpreted as reflecting a lack of modulatory feedback, preventing dyslexic readers from filtering out inappropriate associations between letters and speech-sounds in favour of processing relevant letter-sound pairs.

As summarised in Table 1.1, the pattern of results in the adult control group from the Blau et al. (2009) study contrast with those from the earlier study by van Atteveldt et al. (2004). In van Atteveldt et al. (2004) letter-sound integration was inferred from increased activation in response to congruent letter-sound pairs compared to activation for isolated speech-sounds presented alone. In contrast, in the Blau et al. (2009) study, letter-sound integration in typical readers is inferred from a significant decrease in activation during the presentation of incongruent letter-speech-sound pairs compared to activation for isolated speech-sounds. Given that a reader does not typically encounter mismatched letter speech-sound pairs and that typical adults and adults with dyslexia show a comparable neural response to matching letter-speech-sound pairs in the Blau et al. (2009) study, it is not clear how group differences in decreased activation in response to incongruent letter-sound pairs can provide an explanation for difficulties in learning to read.

Subsequent research has replicated the group differences reported in the Blau et al. (2009) study with 9-year-old Dutch children (Blau et al., 2010). In this study, children with dyslexia showed comparable levels of activation in response to congruent and incongruent letter-speech-sound pairs, whereas typically developing children of the same age showed reduced activation in response to incongruent letter-speech-sound pairs (Blau et al., 2010). Furthermore, the authors report that the difference in activation between the two conditions correlated significantly with children’s reading performance, suggesting that integration of letters and speech-sounds is associated with the development of efficient decoding.

Differential patterns of activation between individuals with and without dyslexia have been interpreted as showing that a neural deficit in integrating letters and speech-sounds may contribute to reading failure. However, by comparing children with dyslexia to typically developing children of a similar age it is not clear whether the observed differences in brain activation reflect a cause of dyslexia or simply reflect neural changes following a developmental history of reading difficulties. The same argument can be made for group differences reported in adults. Therefore it is not clear from these studies whether abnormal effects reflect the cause or consequence of reading impairment.

One method to control for such an effect is to study pre-literate children at family risk of dyslexia. For instance, a study by Simos et al. (2002) recorded the brain activity of English-speaking children with and without a family risk of dyslexia who were in the early stages of learning to read. The children, aged between five and seven years, were presented with single letters, which they were then required to pronounce. Children in the at-risk group (N=30) made significantly more errors and showed significantly reduced activation in the left posterior superior temporal gyrus (STG) compared to the not-at-risk group (N=15). This reduced activation in the at-risk group also occurred over a shorter duration, which the authors interpreted as preventing access to letter-speech-sound associations. Whilst these results are in line with previous findings, it is possible that differences in brain activity reflect processes involved in executing the pronunciation task. Furthermore as this was not a longitudinal study it is not clear whether the children in the at-risk group eventually went on to experience reading difficulties.

As summarised in Table 1.1, a recent study comparing German adolescents with and without dyslexia has reported the reverse pattern of letter-sound integration in dyslexia (Kronschnabel et al., 2014). In this study adolescents with dyslexia (N=13) demonstrated increased activation for congruent versus incongruent letter-sound pairings, whereas, in contrast to previous findings, typically developing participants (N=22) showed the opposite pattern. The authors suggest that this reverse pattern may reflect the inverted U-shape of activation for readers of differing abilities, whereby activation peaks during the initial stages of learning and subsequently decreases with experience (Price & Devlin, 2011). Thus, reduced activation in response to congruent relative to incongruent stimuli may reflect more efficient processing in non-impaired adolescents compared to those with dyslexia.

To summarise, research has identified regions of the superior temporal cortex that appear to be responsible for the neural integration of visual letters and auditory speech-sounds. In non-impaired readers, these regions are activated in response to speech-sounds and letters and, critically, show enhanced activation during multi-sensory presentation of letter-sound pairs, characteristic of neural integration sites (Calvert, 2001). Such observations suggest that following years of reading experience, the brain adapts to process letters and their corresponding speech-sounds as one audio-visual construct.

In addition, studies have shown that regions in the auditory cortex show differential activation for congruent and incongruent letter-speech-sound pairs. However, as summarised in Table 1.1, there is very little agreement in terms of the direction of this congruency effect and as a result it is not clear what can be inferred from these patterns of differential activation.

Some studies have claimed that this multi-sensory network may be aberrant in adults and children with dyslexia. For example, it has been suggested that the observed differences in activation (specifically, reduced suppression of incongruent letter-speech-sound pairs in individuals with dyslexia) may tap a cause of reading difficulties. However, at present it is not clear how this differential pattern of activation relates to reading performance or, whether differences in integration reflect a cause of reading difficulties or are simply a consequence of limited reading experience.

1.4.3 The sequence and time-course of automatic letter-sound integration in typical and dyslexic readers

A series of electroencephalography (EEG) studies have complemented previously described neuroimaging studies, exploring the time course of letter-sound integration in dyslexic and typically developing readers. Recording event-related potentials (ERPs; voltage fluctuations within cortical neurons in response to a stimulus) at a high temporal resolution provides a means of investigating automatic letter-sound integration (van Atteveldt, Roebroeck, & Goebel, 2009).

These ERP studies have typically used the mismatch negativity (MMN) paradigm to investigate letter-speech-sound integration. The MMN is a negative component of the auditory ERP thought to reflect the neural comparison between a standard stimulus and a deviant stimulus (Näätänen, 2000). Using this paradigm, participants are repeatedly presented with a standard speech-sound (e.g. /a/) during EEG recording. When a deviant speech-sound (e.g. /o/) is then presented, it activates a deviance detection mechanism. In studies of letter-sound integration, a congruent visually presented letter is presented along with the standard speech-sound (e.g. <a>), so that the deviant stimulus (/o/) differs from both the standard speech-sound (/a/) and corresponding letter (<a>). This double cross-modal violation results in an enhanced MMN amplitude compared to the standard auditory deviancy effect, which has been interpreted as evidence that the congruent letter and speech-sound have become automatically integrated prior to the processing of the deviant stimulus (Blomert, 2011).

The developmental transition from late association of letters and speech-sounds to early and automatic integration: Evidence from EEG research

The pattern of results from studies using the cross-modal MMN paradigm to assess automatic letter-sound integration is summarised in Table 1.2. In this paradigm, children are presented with isolated speech-sounds, or letters and the corresponding speech-sounds, during EEG recording. Congruent letters are presented simultaneously or 200 milliseconds (ms) prior to the speech-sound (200ms stimulus onset asynchrony or SOA).

Comparing the structure of the MMN in the auditory and simultaneous audio-visual conditions, Froyen et al. (2009) reported that there was no significant effect of letter-sound integration; visual presentation of corresponding letters did not change the size of the MMN in beginner readers (aged 8 years) or more advanced readers with four years of reading instruction (aged 11), despite complete knowledge of letter-sound correspondences. However, more advanced readers demonstrated a larger MMN when letters were presented 200ms prior to the speech-sounds.

The authors also report that both groups showed significant differences between the auditory and audio-visual conditions 650ms after speech-sound onset, as indicated by the amplitude of ERP difference waves. Beginner readers showed this “late” MMN enhancement when letters were presented 200ms prior to speech-sounds, whereas advanced readers demonstrated late enhancement only when letters and speech-sounds were presented

Table 1.2 Summary of published findings reporting cross-modal MMN enhancement

				Early MMN window		Late negativity	
Authors/year/journal	**Sample size**	**Reading status**	**Age group**	**0ms SOA**	**200ms SOA**	**0ms SOA**	**200ms SOA**
Froyen et al. (2009); Journal of Cognitive Neuroscience	62*	TD	8 years	No	No	No	Yes
Froyen et al., (2009); Journal of Cognitive Neuroscience	23*	TD	11 years	No	Yes	Yes	No
Žarić et al.(2014); PLoS ONE	20	TD	9 years	Yes	Yes	Yes	Yes
Froyen et al.(2008); Neuroscience Letters	67*	TD (adult)	18-33 years	Yes	No	No	No
Froyen, Willems & Blomert (2011); Developmental Science	18	Dyslexic	11 years	No	No	No	Yes
Žarić et al.(2014); PLoS ONE	18	Mildly dyslexic	9 years	Yes	Yes	No	No
Žarić et al.(2014); PLoS ONE	18	Severely dyslexic	9 years	No	Yes	No	No

** These studies used a between-subjects design. Sample sizes for each experiment varied, with N= ~14 in each condition* simultaneously. This late mismatch negativity was interpreted as revealing the development of letter-speech-sound integration or the “late association” (pp.578) of letters and speech-sounds (Froyen et al., 2009).It is important to note that visual presentation differed considerably across the auditory and audio-visual conditions (in the auditory condition participants viewed a silent movie). However, the authors assert that the difference in MMN amplitude was not the result of differences in visual stimulation in these two conditions. They argue the MMN is a robust auditory mechanism, unlikely to be influenced by irrelevant visual processing (Froyen et al., 2009).

These results suggest that integration occurs early for children with four years reading experience (150ms after speech-sound onset) whereas this effect is only observed later (650ms after speech-sound onset) in beginner readers. However, a more recent study from the same research group has reported a different pattern of results. Žarić et al. (2014) employed the same cross-modal MMN paradigm to explore integration of letters and speech-sounds in twenty 9-year-old children. The pattern of results in the early MMN window (100-250ms after stimulus onset) revealed significant cross-modal MMN enhancement during simultaneous presentation of letters and speech-sounds and when letters were presented 200ms prior to the speech-sounds. Children also demonstrated a significant cross-modal enhancement in the late negativity window (600-750ms after stimulus onset), when letters and speech-sounds were presented simultaneously and when the letter preceded the speech-sound.

These results are unexpected and suggest that children aged 9 demonstrate evidence of early cross-modal integration across a broad temporal window (at both 0ms and 200ms SOA). In contrast to these findings, the pattern of results with 8 year-old and 11 year-old children were argued to reflect a developmental shift from simple association of letters and speech-sounds, to early and automatic integration of the two sensory inputs (Froyen et al., 2009). Žarić and colleagues argue that these discrepancies reflect the non-linear progression from simple association to early and automatic integration of letters and speech-sounds in typically developing readers. They also propose that the observed late enhancement may reflect differences in methodology between the two studies, such as improvement of signal-to-noise ratio from increasing trial length from 1250ms to 1700ms. In addition, the most recent study employed a within-subjects design whereas in previous studies the majority of children completed one condition.

In support of the proposed developmental shift from simple association to early and automatic integration, earlier research with adult participants reports clear enhancement of MMN amplitude, but only during the early MMN window and only when letters and speech-sounds were presented simultaneously (Froyen, Van Atteveldt, Bonte, & Blomert, 2008). These results indicate that early integration occurs only during simultaneous presentation for adult readers, whereas for younger readers, integration occurs only after a longer interval between the two stimuli (200ms SOA). The authors hypothesised that, for adults, temporal proximity is crucial for the early integration of letters and speech-sounds, a finding also reported in previous fMRI research (van Atteveldt et al., 2007). This shift in the temporal window for multi-sensory integration was interpreted as reflecting brain maturation and is supported by evidence that temporal proximity becomes a key characteristic of multi-sensory integration over the course of development (Wallace & Stein, 1997).

A subsequent study replicated and extended these findings, providing evidence that letter-sound integration in adults occurs early in the pre-attentive stages of processing (Andres, Cardy, & Joanisse, 2011). In contrast to the passive paradigm used by Froyen and colleagues, participants in this study performed a visual detection task in the context of an unattended MMN paradigm. In this task participants were instructed to ignore the auditory stimulus and respond to the visual letters only, pressing a button if the presented letter was a vowel. Cross-modal enhancement of the MMN in this study suggests that this effect is not simply driven by overt monitoring of the congruency of letter-sound stimuli. Furthermore, this study reported significantly greater cross-modal enhancement when the visual letter was congruent with the auditory phoneme in comparison to when it was incongruent. By making this comparison it is possible to rule out the interpretation that the significant cross-modal MMN enhancement shown in the Froyen et al. (2008) study was simply the result of presenting a visual letter, regardless of the relationship between the stimuli.

Absent early integration of letters and speech-sounds in dyslexia

Subsequent research replicated the cross-modal MMN paradigm with eighteen 11-year-old dyslexic children, the same age as the advanced readers in the previous study (Froyen, Willems, & Blomert, 2011). Children with dyslexia did not demonstrate any influence of letters on the processing of speech-sounds; the structure of the MMN did not differ across auditory and audio-visual conditions implying a lack of early integration of letters and speech-sounds. Results did reveal a late effect, but only in a wide temporal window (200ms SOA). Thus, the pattern of results for dyslexic children with four years reading instruction resembled the pattern of results found for beginner readers, characterised by the absence of early integration of letters and speech-sounds (Froyen et al., 2009). While this review is primarily focused on letter-sound integration, it is of interest to note that evidence of impaired cross-modal integration in children and adults with dyslexia has also been reported during the presentation of syllable pairs (Mittag, Thesleff, Laasonen, & Kujala, 2013) and also during word reading tasks (Hasko, Bruder, Bartling, & Schulte-Körne, 2012; Savill & Thierry, 2011).

However, again the results from Žarić et al. (2014) are inconsistent with earlier studies, which complicates the current interpretation. As previously described, this study employed the same cross-modal MMN paradigm as in previous studies to explore integration of letters and speech-sounds in 9-year-old children. The main aim of this additional study was to investigate the relationship between ERP indices of integration and individual differences in reading fluency. As such, the children with dyslexia were divided into two further groups; mildly dyslexic (N=18) and severely dyslexic (N=18) based on a median split of their reading fluency scores.

The pattern of results in the early MMN window revealed that, during simultaneous presentation of letters and speech-sounds, the mildly dyslexic group demonstrated significant cross-modal MMN enhancement compared to the auditory only condition. The severely dyslexic group did not show a significant difference, which the authors interpreted as indicating the absence of early and automatic integration of letters and speech-sounds. However, when the visual letter preceded the speech-sound by 200ms, both groups of children with dyslexia demonstrated an enhanced cross-modal MMN. In the late negativity window (600-750ms after stimulus onset), both dyslexic groups demonstrated non-significant cross-modal enhancement in both conditions.

These findings are at odds with previous results. Most strikingly, results from the most recent study clearly demonstrate evidence of early integration of letters and speech-sounds in children with dyslexia. The authors argue that the crucial difference between the three groups lies in the latency of the MMN. Specifically, they report that the severely dyslexic group show a significantly shorter MMN latency when letters and speech-sounds are presented simultaneously, both compared to the TD group and the less-impaired dyslexic group. Thus, the authors suggest that reduced integration in this study is reflected in a shorter onset of the peak cross-modal MMN response.

It is important to note that the use of the MMN paradigm in the study of developmental disorders of language has previously been criticised for providing inconsistent results (Bishop, 2007). Thus, it is possible that inconsistent findings in the MMN for beginner and dyslexic readers reflect the poor reliability of the auditory MMN, rather than the absence of automatic integration between letters and speech-sounds.

A subgroup of the children with dyslexia in this study took part in a further training study that involved twice-weekly sessions of explicit instruction on letter-sound correspondences alongside standard school reading instruction (Žarić et al., 2015). Seventeen children from the original study completed the same EEG and reading measures following six months of training. Whilst children did not show significant improvement on behavioural measures of letter-speech-sound identification and discrimination, differences in ERP measures of integration were apparent between Time 1 (T1) and Time 2 (T2).

Specifically, following letter-sound training children demonstrated significant late cross-modal enhancement in both the 0ms and 200ms SOA condition. In contrast, in the case of the early cross-modal MMN, the pattern remained the same at T1 and T2. At both time points children with dyslexia demonstrated significant cross-modal enhancement when letters and speech-sounds were presented asynchronously but not when presented simultaneously. The authors propose that early integration may be less malleable and as a result may place constraints on the improvements that children with dyslexia are able to make in reading. This hypothesis is supported by the finding that the timing of the early MMN response predicted gains in reading fluency across the six month period. This finding is in line with previous work reporting that children with the most severe reading impairments show a shorter-lasting and reduced MMN response (Žarić et al., 2014). However, whilst training appears to bring about differential effects in neural integration, without a control group it is not clear whether the training of letter-sound correspondences led to the observed changes, or whether this was simply the result of maturation or practice effects.

There are few electrophysiological studies investigating letter-sound integration with alternative measures to the MMN. One study by Lemons et al. (2010) explored the effectiveness of ERPs in predicting the reading growth of 29 beginner readers. Patterns of ERPs over frontal and parietal regions during a task involving matching letters and their corresponding speech-sounds were reported to predict reading change over 19 weeks (R^2 change = .22).

Children with different levels of reading ability completed three reading-related tasks (letter-sound matching, non-word rhyming and non-word reading) during EEG recording. In the matching task, children were presented with a printed letter followed by an auditory speech-sound; the congruency of the speech-sound was manipulated and children were required to indicate if the pairs matched or did not match. Controlling for other reading measures, amplitudes in the 400-600ms temporal window during this task were enhanced in children who showed improvement on subsequent measures of reading, suggesting that neural responses during this letter-sound matching task provided a unique measure of reading ability. The authors hypothesised that this correlation between late ERP response during letter-sound matching and early reading ability may reflect enhanced memory processes responsible for learning the correspondences between letters and speech-sounds.

However, late auditory ERPs have been reported to show large individual differences and effects of cortical maturation making it difficult to identify task-related differences with certainty (Wunderlich, Cone-Wesson, & Shepherd, 2006). Given the small sample size and the age of the participants in the current study, this limitation restricts the conclusions that can be drawn from these findings. Furthermore, Lemons et al. (2010) compared the congruent condition with conditions where the same letter was followed by different incongruent speech-sounds; this comparison does not rule out the possibility that poor readers show a generally reduced response to the speech-sound, independent of the visually presented letter.

Subsequent work by Nash et al. (submitted) has built upon this paradigm, however the results provide an increasingly complex picture. This study compared the performance of 13 English-speaking children with dyslexia aged between 9 and 13 years to two groups of typically developing children: a group matched on chronological age (N = 17) and an additional younger group matched on reading ability (N = 17) aged between 7 and 9 years.

Children in this study completed a priming task, which involved the presentation of a visual letter prime followed by an auditory speech-sound target. The prime and target were either the same letter (congruent condition) or different (baseline condition). Importantly, the visual prime in the baseline condition was a Greek letter, which for this group of children would presumably have no associated speech-sound. Children completed a behavioural version of the priming task, which simply required the categorisation of the target as speech or not speech, and also a passive version of the task during which children simply attended to the stimuli while EEG data was collected.

Behavioural data revealed that all three groups were significantly faster to identify the auditory target following presentation of a congruent letter prime, compared to the Greek letter. This suggests that the typically developing and dyslexic children automatically activated speech-sounds from printed letters. However, comparing the ERP data across the two conditions revealed subtle group differences. While the older TD group showed a significant early effect (namely a larger left frontal-central P1 amplitude in the congruent condition), the younger group showed a later congruency effect in the P2 window. The authors interpreted the early P1 congruency effect in the older children as indicative of early sensory processing of the visual letter, whereas the later P2 effect in the younger children was suggested to reflect more effortful attentional processing. These findings are in line with the age-related differences reported by Froyen and colleagues using the MMN paradigm (Froyen et al., 2009; Froyen et al., 2011).

In contrast, the dyslexic group in this study showed evidence of both an early and late congruency effect, however the early P1 effect was located in a different region to that of the older typically developing group (more frontal and centrally located in children with dyslexia). The authors propose that greater amplitude in the frontal region during the presentation of congruent letters may reflect increasing cognitive effort in the children with dyslexia. It is acknowledged, however, that further replication is necessary before firm conclusions can be drawn, particularly given the poor spatial resolution of EEG.

Altogether, findings from electrophysiological research suggest that neural indicators of letter-sound integration vary with differing levels of reading ability. By measuring activity at a higher temporal resolution, this research provides some evidence that letter-sound integration in non-impaired readers occurs early during stimulus processing and becomes fully automatic with increasing reading experience. However there have been some contradictory findings.

Dyslexic readers appear to associate letters and speech-sounds, as indicated by the late enhancement of the MMN. However, some researchers have reported patterns of response that resemble those of beginner readers with less than one year reading instruction, suggesting that despite reading practice, letter-sound pairs are not integrated into fully automated audio-visual objects in dyslexic readers. Again, there have been some inconsistent findings and at present there is little agreement regarding the neural signature of letter-sound integration in children with dyslexia. One feature of work in this area is that it is plagued by small sample sizes and the reliability of the measures used is typically not known.

1.5 The present thesis: A behavioural investigation into automatic letter-sound integration

This thesis investigates the automatic integration of letters and speech-sounds in typically developing and dyslexic readers. The research originates from a series of recent studies by Blomert and colleagues, which propose that problems learning to read arise from a specific deficit in establishing automatic associations between letters and speech-sounds. While this theory may represent a novel account of dyslexia, the ideas underlining this proposal are not new. As summarised earlier, it is widely accepted that the task of learning to read is fundamentally the process of mapping print onto phonology.

Evidence that individual differences in letter knowledge, phoneme awareness and rapid automatized naming speed reliably predict children's reading performance is also consistent with the proposal that automatic associations between letters and speech-sounds are implicated in early reading development. For instance, it is possible that early variations in children's letter-sound knowledge influences the extent to which these associations become automatically integrated during the early stages of learning to read. Similarly, it has been proposed that the relationship between reading and RAN speed reflects how automatically orthographic and phonological information can be activated (e.g. Wolf & Bowers, 1999; Wolf et al., 2000).

The well-established role of phonological skills in learning to read is perhaps more difficult to reconcile with the proposal of a specific deficit in automatic letter-sound integration. At present it is not clear whether a core phonological deficit could in fact account for difficulties establishing automatic associations between letters and speech-sounds in children with dyslexia. If phonological representations are impaired it seems likely that children with dyslexia would struggle to form automatic associations between letters and their corresponding speech-sounds.

In summarising the evidence for a deficit in automatic letter-sound integration this Chapter has highlighted a number of inconsistent findings. In addition, many of these studies have failed to recruit adequate control groups. As such it is not clear whether a deficit in automatic letter-sound integration is characteristic of children with dyslexia or simply reflects a developmental history of limited reading experience.

Above all, there is limited behavioural support for this theory. The majority of studies investigating automatic letter-sound integration have used neuroimaging techniques and it is not often clear from these studies how differences in neural integration provide an explanation for difficulties in learning to read. It is therefore timely to investigate automatic letter-sound integration using behavioural techniques in order to determine whether differences in automatic letter-sound integration contribute to reading skill above and beyond current established predictors of reading ability.

Chapter 2 Automatic integration of letters and speech-sounds in literate adults

2.1 Introduction

This chapter reports a priming study designed to assess whether a priming task can provide evidence of automatic letter-sound integration in adult readers.

It is expected that adults with a number of years of formal reading instruction and several years of reading experience should automatically associate visual letters with their corresponding speech-sounds. As a result of repeated co-occurrence, letter-sound pairs in literate adults might be considered overlearned paired associates and as such the visual representation of a letter should automatically evoke the corresponding auditory information (van Atteveldt et al., 2007). In line with this prediction, behavioural studies have reported evidence of automatic cross-modal associations between letters and speech-sounds in Dutch adults (Blau et al., 2008; Dijkstra et al., 1989).

However, a recent study investigating the neural signature of audio-visual integration suggests that the processing of letter-sound pairs may not be automatized in English-speaking adult readers. Holloway et al. (2015) aimed to replicate previous fMRI research with Dutch adults, which reported activation in the superior temporal cortex (STC) that was sensitive to the congruency of letter-sound pairs (van Atteveldt et al., 2004). In contrast, Holloway et al. (2015) did not find evidence of neural integration for letter-sound pairs in an English-speaking sample. The authors interpreted this finding as reflecting the irregularity of letter-sound mappings in the English writing system, where, one letter can represent many different sounds depending on the context of other letters in the word. In line with this hypothesis, participants did demonstrate neural integration for letter-name and number pairs, where cross-modal associations are increasingly consistent.

While there have been relatively few studies investigating cross-modal integration of letters and speech-sounds, one behavioural study by Borowsky et al. (1999) reports evidence of automatic associations between letters and speech-sounds in English-speaking adults. This study found that adults' auditory discrimination (e.g. “heard /ta/ or heard /da/?”) was more accurate following the presentation of congruent visual information (e.g. <ta>) compared to the presentation of irrelevant information (e.g. <na>). Furthermore, this difference was significantly greater than the difference between incongruent (e.g. <da>) and baseline (e.g. <na>) conditions. The authors therefore interpreted this facilitation as demonstrating direct connections between visual and phonemic representations, rather than simply a bias to select the corresponding phoneme.

Given the somewhat conflicting results in English-speaking adult readers it is of interest to investigate behavioural measures of integration. In addition, this study also aimed to explore the relationship between performance on the priming task with different aspects of reading and spelling performance. Whilst previous behavioural studies did not measure participants reading skill, the authors propose that this process of cross-modal activation supports visual word recognition.

It is difficult to predict the relationship between reading and automatic letter-sound integration in adults. On the one hand, as previously outlined, Blau et al. (2009) found that Dutch adults with dyslexia showed reduced neural integration of letters and speech-sounds, as indexed by the absence of a significant congruency effect in the superior temporal cortex (STC). Furthermore, this congruency effect was significantly correlated with reading ability across the whole sample. Based on these findings it may be predicted that the extent of automatic letter-sound integration will correlate with variations in reading ability in a sample of English adults.

However, if it is the case that neural associations between letters and speech-sounds are weaker in less transparent orthographies such as English, it may be that the extent to which letters and speech-sounds are automatically integrated does not contribute to reading performance in the same way as in more transparent languages, such as Dutch for example. Ziegler and Goswami (2006) suggest that learning to read in English is likely to involve employing a number of strategies to deal with inconsistent letter-sound mappings, in particular learning to recognise letter patterns for larger written units such as rimes or even whole words.

Furthermore as this is the first behavioural study investigating letter-sound integration in adults, it is not clear whether individual differences in the automaticity of letter-sound integration will be sufficiently large to predict variance in reading ability, particularly in adults whose reading is likely to rely on recognition of words as familiar wholes (Share, 2008).

To assess letter-sound integration a priming task was used. The idea underlining this task is that if participants are automatically integrating letters with their corresponding speech-sound, they should be quicker to identify a speech-sound following the presentation of a congruent letter prime versus the presentation of an incongruent letter or a symbol with no associated speech-sound.

2.2 Method

2.2.1 Participants

Forty student volunteers (12 male, 28 female) with a mean age of 22 years (range = 27 years) from University College London participated in the experiment in compliance with a course requirement. All participants whose native language was not English were fluent in both spoken and written

English. The University College London Ethics Committee granted ethical approval for this study.

2.2.2 Design and materials

Letter-sound integration measure

The measure of letter-sound integration was a priming task involving the successive presentation of a visual letter prime and an auditory phoneme target. Participants were required to decide on each trial whether the auditory target was a “real” speech-sound. Participants were familiarised with the stimuli in an initial learning trial.

Stimuli. Stimuli were phonemes /pə/ (283ms), /tə/ (293ms), /də/ (263ms), /kə/ (304ms), /və/ (428ms), /zə/ (413ms) and /dʒə/ (357ms) recorded by a female native English speaker in a sound attenuated booth and the corresponding lower case letters presented in Ariel (pixel size 90 x 80). Novel letters (adapted from Taylor, Plunkett, & Nation, 2011) and scrambled phonemes (nonverbal <z> (413ms), nonverbal <d> (262ms), nonverbal <j> (357ms), nonverbal <k> (303ms), nonverbal <p> (282ms), nonverbal <t> (292ms) and nonverbal <v> (428ms)) served as non-letter stimuli. Scrambled phonemes were created using Matlab (Ellis, 2010). The script was modified for use with short sound files. Each phoneme was divided into 5ms overlapping hanning windows. The order of these windows was then randomised within a 250ms radius. The randomly overlapping windows were then combined to form the scrambled speech-sound. The length, overall power and frequency spectrum remained identical to the original speech-sound recording.

Apparatus. Stimulus presentation and recording of response speed and accuracy were accomplished using E-Prime Software (version 2.0) and a Psychology Software Tools Serial Response Box (SRB; model 200a) with a

Dell laptop (Latitude E5520) running Windows 7. Auditory stimuli were presented through Beyer Dynamic headphones (DT 770).

Design. In the task a letter prime was presented prior to an auditory phoneme target. On each trial, a centrally located fixation point was presented for 1000ms followed by the presentation of the letter or non-letter stimulus, presented in black and appearing on the white screen for 500ms. The auditory target was then presented over headphones. Each trial was followed by the visual prompt “Real sound?” Participants were instructed to attend to both the visual letter and auditory speech-sound and decide whether the sound was a ‘real’ speech-sound using “YES” and “NO” response keys. The experimenter monitored the participants’ performance, controlling the presentation of trials. Figure 2.1 shows the structure of a trial.

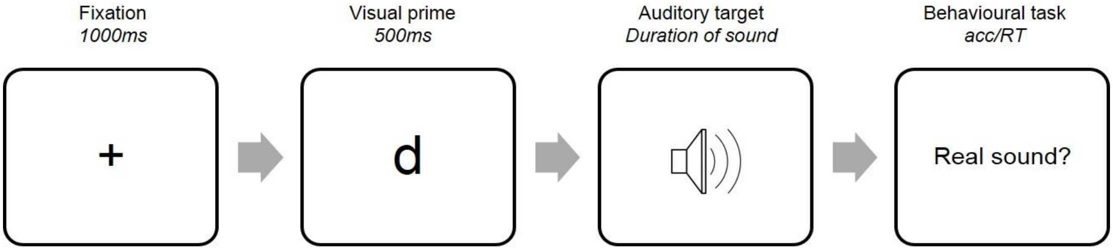


Figure 2.1 The structure of a letter-sound priming trial

There were three experimental conditions in the letter-sound priming task. In the congruent condition, the visual letter prime and auditory target matched (for example, letter p followed by the phoneme /pə/). In the incongruent condition the prime and target were not the same letter/speech-sound. In the baseline condition, the prime was a novel letter and the target was a real speech-sound.

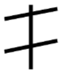
In addition, there were 3 control conditions to prevent participants detecting the relationship between primes and targets and generating expectancies about the up-coming target. These conditions are shown in Table 2.1, along with examples. In the incongruent and control conditions visual stimuli were always paired as shown in Table 2.2. Each stimulus pairing was presented three times. The order of trials within the letter-sound priming task was randomized.

There were 144 experimental trials in the priming task, including 18 ‘catch’ trials to ensure participants were paying attention to the screen. Catch trials consisted of a visually presented traffic light where participants were required to press the “GO” response key. The priming task took approximately 10 minutes to complete and participants were allowed to pause the experiment and take a short break at any time.

Table 2.1 Experimental conditions for letter-sound priming task

Condition	Prime (visual stimulus)	Target (auditory stimulus)	Response required
Congruent	Letter <p>	Phoneme /pə/	Is it a speech-sound? (YES)
Baseline	Novel letter <  >	Phoneme /pə/	Is it a speech-sound? (YES)
Incongruent	Letter <t>	Phoneme /pə/	Is it a speech-sound? (YES)
Control	Letter <p>	Scrambled phoneme / pə^s/	Is it a speech-sound? (NO)
Control	Novel letter <  >	Scrambled phoneme /pə^s/	Is it a speech-sound? (NO)
Control	Letter <p>	Scrambled phoneme /pə^s/	Is it a speech-sound? (NO)

Table 2.2 Novel stimulus and letter pairings

Letter	Novel symbol
t	
d	
k	
v	
j	
p	
z	

Literacy measures

Rapid Automatized Naming. Participants completed the alphanumeric RAN subtests from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999). These subtests required participants to name two 4 x 9 arrays of letters/digits as quickly and accurately as possible. Practice trials ensured participants understood the instructions. The time taken (in seconds) to read both arrays was recorded.

Reading. Participants completed the Sight Word reading Efficiency (SWE) and Phonemic Decoding Efficiency (PDE) subtests from the Test of Word Reading Efficiency (TOWRE 2; Torgesen, Wagner, & Rashotte, 1999). These subtests required participants to read as many words/non-words as possible in 45 seconds. Practice items were administered prior to test items. The number of items read correctly was recorded.

Decoding. Participants were asked to read two short nonsense passages (taken from the York Adult Assessment Battery; J. Hatcher & Snowling, 2002). The first passage contained 16 non-words in the context of 36 words. The second passage contained 13 non-words in the context of 31 words. The total number of errors and the time taken to read the two passages (in seconds) were recorded. Passage reading rate was calculated by dividing the total number of words read correctly by the total time taken to read the passages.

Spoonerisms. Participants completed a spoonerism task (taken from the York Adult Assessment Battery - Revised; Warmington, Stothard, & Snowling, 2013) where they were required to exchange the beginning sounds of well-known names, for example ‘John Lennon’ would become ‘Lohn Jennon’. Practice trials ensured participants understood the instructions. The total number of errors and the time taken to complete each item was recorded. Spoonerism rate was calculated by dividing the total number of correct items by the total response time for correct items for each participant.

Spelling. Participants were required to complete the spelling subtest from the Wide Range Achievement Test (WRAT; Wilkinson, 1993). The total number of words spelt correctly was recorded.

2.3 Results

Means and standard deviations for the measures of reading related skills and letter-sound integration are presented in Table 2.3 and Table 2.4. A RAN composite score was calculated by summing z-scores from the digit and letter subtests. A reading composite score was calculated by summing z-scores for timed measures of word and non-word reading and participant’s passage reading rate as these scores were highly correlated.

Raw scores on the PDE subtest of the TOWRE were not normally distributed and so were transformed by examining the results of transformations from Tukey’s ladder of powers (using the “ladder” command in Stata v 13.0). Scores were transformed using a cubic transformation however analyses of untransformed data yielded essentially identical patterns of results. The reading composite score was calculated using untransformed scores and subsequent composite scores were not transformed.

2.3.1 Effects of priming in the letter-sound integration task

Before analyses were conducted, outliers were removed from the raw reaction time (RT) data. Only correct responses were included in the analysis. Responses that were over 5000ms were first removed as this was considered to reflect a lapse in attention rather than accurate performance on the task. A non-recursive outlier removal procedure was then used, as recommended by Selst and Jolicoeur (1994). Data from two participants was excluded from the analysis due to excessively long average response times.

The percentage of RT data that was excluded, as both response errors and outliers, is shown in Table 2.5. As shown in the table, over 95% of the possible RT data were available for analysis. The mean correct RTs in each condition of the letter-sound priming experiment, together with 95% within-subject confidence intervals (Morey, 2008) are shown in Figure 2.2. Compared to the baseline condition the data show facilitation in the congruent priming condition and interference in the incongruent condition. To assess the reliability of these differences, response times for the baseline, congruent and incongruent condition were compared using a mixed effects linear regression model treating participants and items as crossed random effects (xtmixed in Stata 13.1) in order to account for variability across participants and target items (see Baayen, Davidson, & Bates, 2008 for an explanation). Whilst there are a small number of levels of target item to be treated as a random effect, comparison of models with target items as fixed and as random effects were found to be almost identical.

Table 2.3 Characteristics of the sample (N=38)

	Mean (SD)	**Min.**	**Max.**
Age (years)	21.24 (4.70)	17	37
Passage reading error (/30)	3.61 (2.99)	0	11
Passage reading total time (secs; s)	44.92 (9.91)	31	67
Passage reading rate (items/sec)	2.15 (0.46)	1.30	3.10
Spoonerism accuracy (/24)	20.61 (3.74)	8	24
Spoonerism total time (s)	33.41 (16.63)	11.60	66.37
Spoonerism rate (item/sec)	0.47 (.25)	0.12	1.04
TOWRE-SWE (raw score /104)	93.42 (8.61)	69	104
TOWRE-SWE (standard score)	97.45 (11.08)	75	113
TOWRE-PDE (raw score /63)	56.47 (6.50)	40	63
TOWRE-PDE (standard score)	105.87 (11.71)	83	120
RAN Digits (s)*	23.79 (5.69)	12	39
RAN Digits (standard score)	9.84 (2.66)	4	14
RAN Letters (s)	23.63 (4.35)	16	33
RAN Letters (standard score)*	10.38 (2.71)	6	17
WRAT Spelling (raw score/ 57)	48.97 (3.39)	40	57
WRAT Spelling (standard score)	117.61 (13.07)	92	145
RAN composite*	0.01 (1.87)	-3.83	4.14
Reading composite	0.01 (2.71)	-7.21	3.61

**N=37 for RAN Digits and Letters and RAN composite*

Table 2.4 Performance on letter-sound priming task (N=38)

	Mean (SD)	Min.	Max.
Baseline accuracy (/21)	20.55 (0.76)	18	21
Congruent accuracy (/21)	20.71 (0.61)	18	21
Incongruent accuracy (/21)	20.68 (0.53)	19	21
Baseline average RT (ms)	581.07 (99.98)	415.40	767.48
Congruent average RT (ms)	548.82 (99.30)	401.30	797.67
Incongruent average RT (ms)	595.06 (112.60)	410.43	814.52

Table 2.5 Percentage RT data not available for analysis in the letter-sound priming task

	Response error (%)	Outliers (%)
Baseline	0.75	0.83
Congruent	1.07	0.44
Incongruent	0.48	0.95
Total	2.30	2.22

This model predicted participant's target response times as a function of experimental condition, using two dummy coded variables (baseline vs. congruent (0, 1) and baseline vs. incongruent (0, 1)). Results showed that the difference in target response time between the baseline and congruent condition was significant (estimated difference = -31.61, z = -5.03, 95% confidence interval = [-43.94, -19.28], $p < .001$). The effect size of this difference (ignoring participant and item variability) is d = .32. The difference between response times in the baseline and incongruent condition was also significant (estimated difference = 14.20, z = 2.26, 95% confidence interval =

[1.88, 26.52], p =. 024). The effect size here (ignoring participant and item variability) is d = .13.

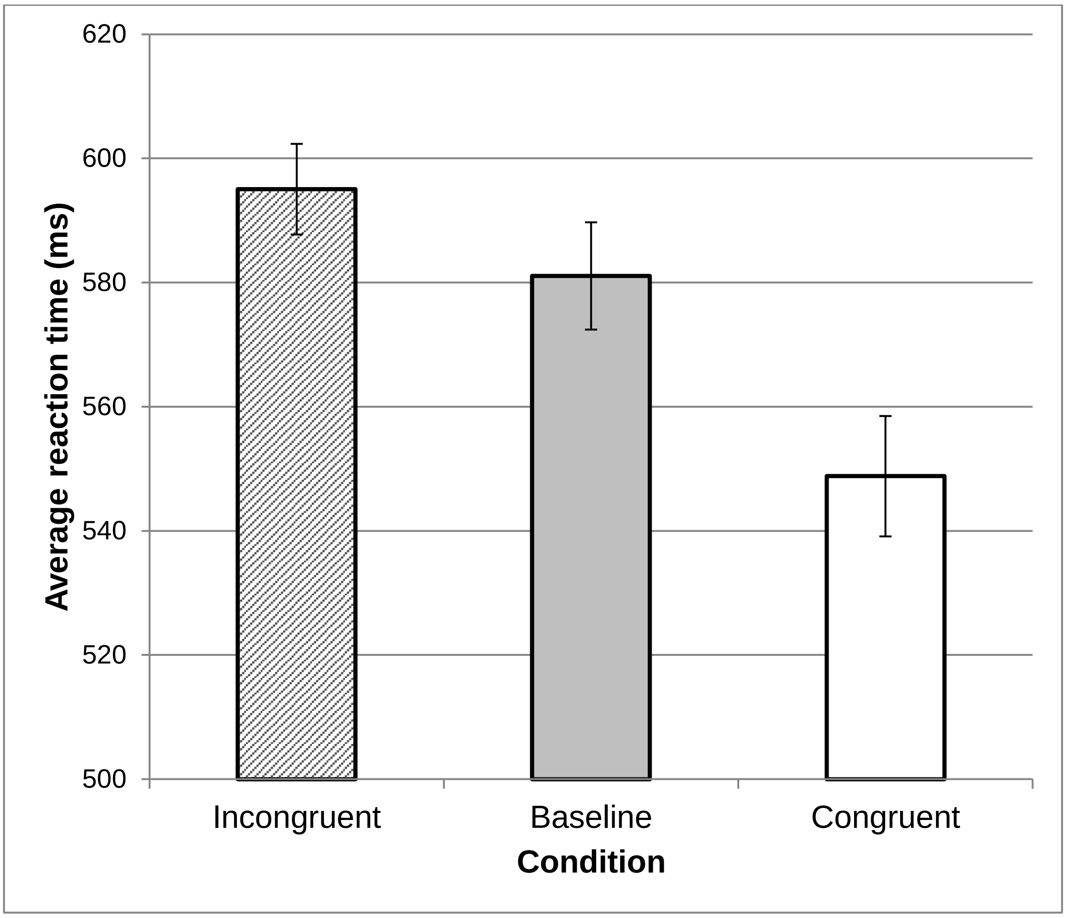


Figure 2.2 Average response times (and 95% CIs) for each condition of the letter-sound priming task

2.3.2 Relationship between letter-sound integration and measures of reading

Measures of facilitation and interference were used to investigate the relationship between letter-sound integration and reading. Facilitation was calculated for the letter-sound priming task by subtracting each participant's average response time in the baseline condition from their average response time in the congruent condition, a negative score indicated facilitation.

Interference was calculated by subtracting baseline response times from incongruent response times, a positive score indicated interference.

Table 2.7 shows the simple correlations among reading and letter-sound integration measures. As shown, there were no significant correlations between measures of reading and letter-sound integration.

Hierarchical regression analyses were used to explore predictors of reading. A two stage hierarchical multiple regression model was conducted with the reading composite score as the dependent variable. Table 2.8 displays the results of the regression analyses predicting reading performance. Baseline response time was not a significant predictor of reading ability (F (1, 36) = .03, p = .865). Congruent response time was then added to the model to provide an estimate of the specific effect of letter-speech-sound integration on reading performance. However adding congruent response time did not account for additional unique variance (F (1, 35) = .64, p = .430) indicating the extent to which participants were facilitated by the letter prime did not predict variance in reading performance.

Similarly, adding participants average response time for the incongruent condition to this model did not account for additional unique variance (F (1, 35) = .80, p = .377) indicating the extent to which participants were inhibited by the letter prime did not predict variance in reading performance.

2.3.3 Accounting for differences between native English speakers and those with English as an additional language (EAL)

There were a number of participants in this study for whom English was an additional language (N = 18). As this represents almost half the sample the effect of EAL upon reading ability and performance on the phoneme awareness, rapid naming and letter-sound priming task was further investigated.

Performance on the letter-sound priming task

Analyses were conducted to determine whether response times in the baseline, congruent and incongruent condition differed between native English and EAL participants. Means and standard deviations describing the two groups' performance on the letter-sound priming task are presented in Table 2.9.

A mixed effects regression model predicting participant's target response times as a function of experimental condition and language status (using dummy coded variables 0 = native speaker, 1 = EAL) showed that language status did not significantly predict participant's response times on the letter-sound priming task (estimated difference = -14.15, z = -.43, 95% confidence interval = [-79.18, 50.88], p = .670). Furthermore the interaction between experimental conditions and language status was not significant indicating that the size of the priming effect (identified in prior analyses) does not differ between groups.

The difference in target response time between the baseline and congruent condition did not differ significantly between native and EAL groups (estimated difference = 8.96, z = .71, 95% confidence interval = [-15.73, 33.64], p = .447). Similarly, the difference between response times in the baseline and incongruent condition did not differ significantly between native and EAL groups (estimated difference = -.68, z = -.05, 95% confidence interval = [-25.35, 23.98], p =. 957).

The relationship between letter-sound integration and reading ability

Table 2.10 shows the simple correlations among these measures for native English speakers and participants with EAL separately. There were no significant correlations between reading performance and measures of letter-sound integration for either the native English speakers or participants with

EAL suggesting that performance on the letter-sound priming task was not related to reading ability in either group.

Further inspection of the correlations between the various reading measures does however highlight differences between native English and EAL participants. In particular, in the EAL sample spoonerism rate and spelling performance are significantly correlated with reading (r= .68 and .64 respectively, p < .01). Scatterplots below (Figure 2.3 and Figure 2.4) illustrate the differences between these groups in terms of the strength of relationship between reading ability and phoneme awareness and spelling.

As shown in Figure 2.5, though the correlation between rapid naming and reading is stronger in the native speakers (r= -.59, p < .01) than the EAL group (r=-.44, p < .01); these 2 correlations do not differ significantly in size (z = 0.58; p = .56 two tailed).

Table 2.6 Simple correlations between measures of reading

	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. RAN Digit	.75**	.44**	.28	-.47**	.48**	.01	-.37*	-.52**	-.35*	-.31†
2. RAN Letter		.33*	.26	-.35*	.21	.23	-.15	-.34*	-.19	-.20
3. Passage Reading TT			.53**	-.97**	.60**	-.41*	-.45**	-.72**	-.82**	-.60**
4. Passage Reading Error				-.63**	.29	-.36*	-.28	-.38*	-.69**	-.58**
5. Passage Reading Rate					-.58**	.41**	.44**	.68**	.81**	.63**
6. Spoonerism TT						-.51**	-.86**	-.61**	-.57**	-.40*
7. Spoonerism Accuracy							-.50**	.36*	0.55**	.45**
8. Spoonerism Rate								.54**	.48**	.21
9. TOWRE-SWE									.69**	.31†
10. TOWRE-PDE										.52**
11. Spelling										

*Note: ** = p <.01, * = p <.05. † = p <.06 TT = Total time. Correlations were computed with the subsample that completed each task: rapid naming tasks N=37, all other tasks N=38.*

Table 2.7 Simple correlations between measures of reading and performance on the letter-sound priming task

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. RAN composite		-.43**	-.28	-.28	-.18	.04	.17	.08	.17
2. Reading composite			.53**	.54**	.12	.15	.03	.09	.08
3. Spoonerism rate				.21	.15	.10	-.02	.05	.01
4. Spelling					.15	.15	.00	.08	.05
5. Facilitation						.51**	-.29	.21	-.10
6. Interference							.14	.40*	.45*
7. Baseline								.87**	.95**
8. Congruent									.92**
9. Incongruent									

*Note: ** = p <.01, * = p <.05. Correlations were computed with the subsample that completed each task: rapid naming composite N=37, all other tasks N=38.*

Table 2.8 Hierarchical regression analysis predicting performance on measures of reading from continuous measures of performance on the letter-sound priming task

	β	t	Unique R^2	df
Model 1				
Baseline RT	.001	.17		1, 36
Model 2				
Baseline RT	-.006	-.61		
Congruent RT	.007	.80	.018	1, 35
Model 3				
Baseline RT	-.011	-.79		
Incongruent RT	.011	.89	.023	1, 35

*Note: ** = p <. 01, * = p < .05*

Table 2.9 Performance on the letter-sound priming task for Native English (N=20) and EAL participants (N=18)

	Native English			**EAL**		
	Mean (SD)	**Min.**	**Max.**	**Mean (SD)**	**Min.**	**Max.**
Baseline RT (ms)	587.27 (165.08)	321	1416	602.11 (175.58)	267	1539
Congruent RT (ms)	552.65 (163.47)	257	1339	546.72 (142.69)	233	985
Incongruent RT (ms)	602.11 (175.58)	267	1539	588.14 (156.60)	279	1308

Table 2.10 Simple correlations between reading and performance on the letter-sound priming task for Native and EAL participants

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. RAN composite		-.59**	-.46*	-.11	-.16	-.03	.26	.17	.22
2. Reading composite	-.44		.33	.34	.15	.41	.01	.09	.03
3. Spoonerism rate	-.45	.68**		.01	.37	.27	-.08	.12	.03
4. Spelling	-.42	.64**	.54*		.15	.16	-.13	-.04	-.05
5. Facilitation	-.22	.21	.11	.19		.51*	-.19	.35	.02
6. Interference	.15	-.05	-.41	.14	.52*		.16	.42	.50*
7. Baseline RT	.09	-.01	-.21	.11	-.42	.12		.85**	.93**
8. Congruent RT	-.00	-.09	-.18	.21	.01	.38	.90**		.90**
9. Incongruent RT	.12	-.03	-.31	.14	-.25	.38	.96**	.94**	

*Note: ** = p <.01, * = p <.05. Correlations above the diagonal using Native English participants only (N=20) and below the diagonal using only EAL participants (N=18).*

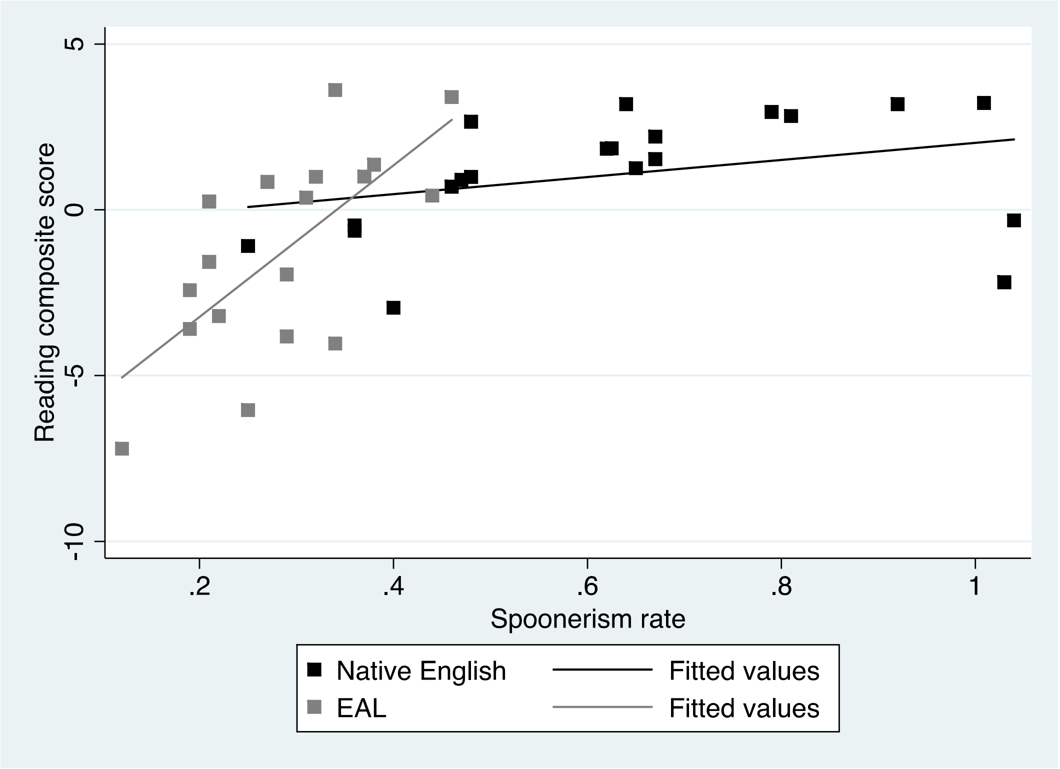


Figure 2.3 Two-way linear plot with regression slope predicting reading performance from performance on spoonerism task for Native English speakers and EAL participants

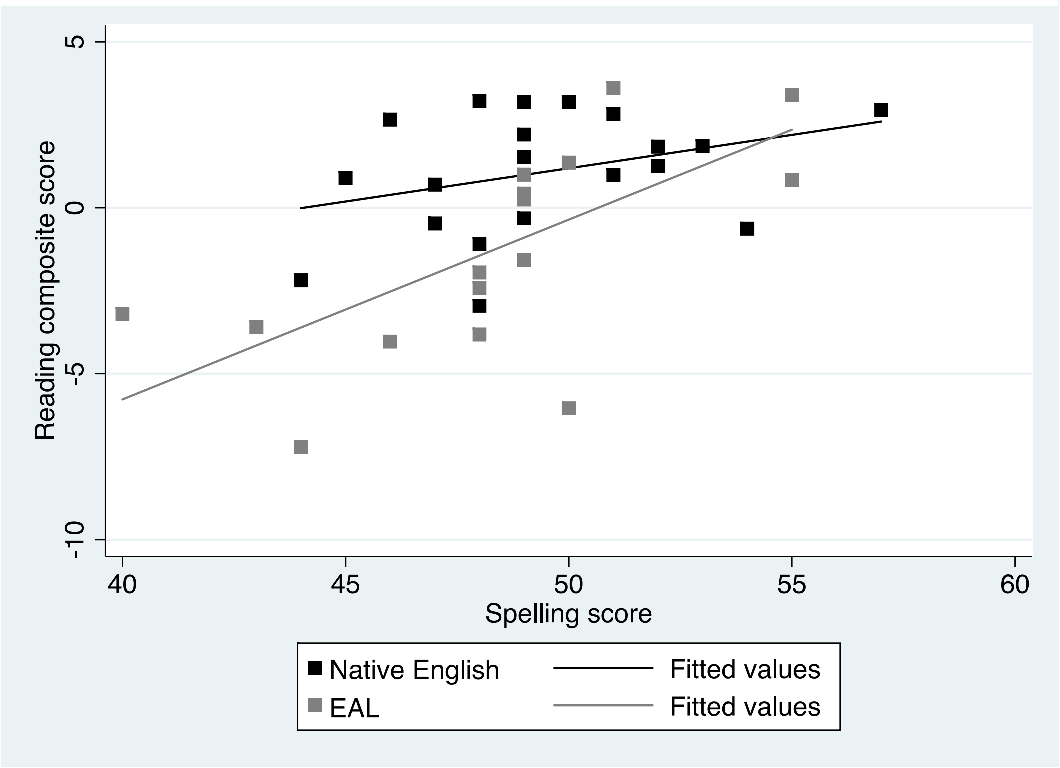


Figure 2.4 Two-way linear plot with regression slope predicting reading performance from spelling scores for Native English speakers and EAL participants

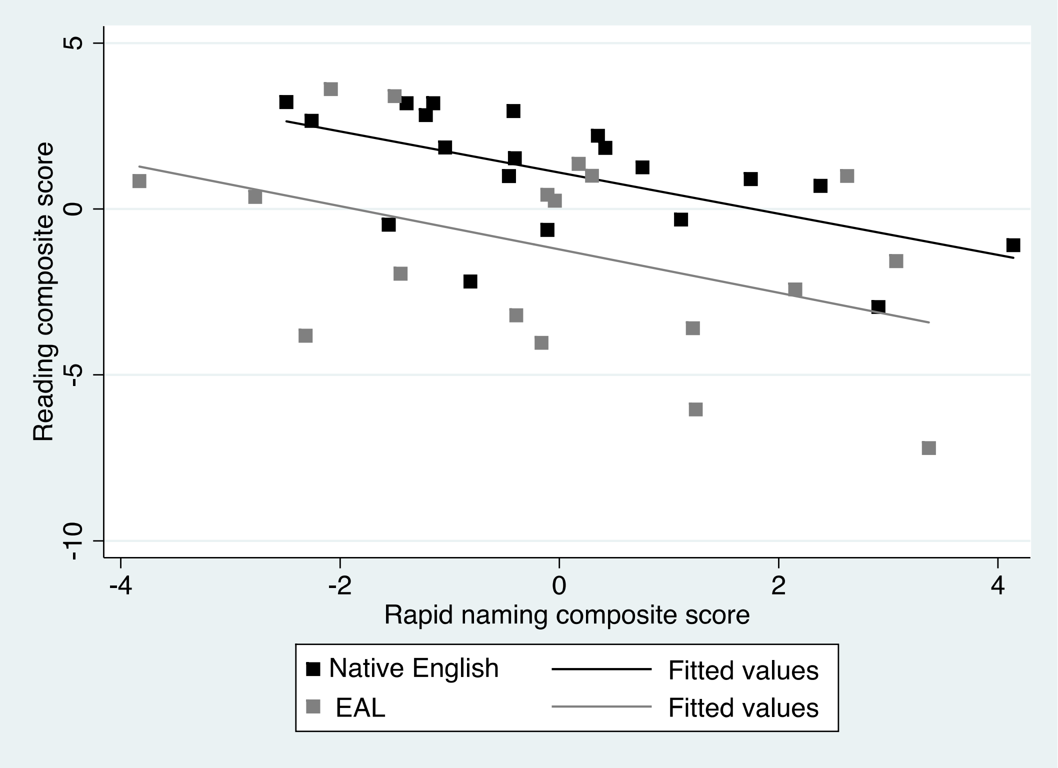


Figure 2.5 Two-way linear plot with regression slope predicting reading performance from rapid naming composite scores for Native English speakers and EAL participants

2.4 Discussion

This study aimed to provide behavioural evidence for automatic letter-sound integration in English-speaking adults and to assess whether variations in this skill are associated with individual differences in reading skill. While it was clear that, as a group, adults in this study showed evidence of automatic letter-sound integration, individual differences in the automaticity of letter-sound integration did not predict variance in reading skill.

2.4.1 Evidence of automatic letter-sound integration in English-speaking adults

The data reported here provide support for the existence of automatic mappings between printed letters and the speech-sounds they represent. In line with previous findings (Borowsky et al., 1999), participants in this study demonstrated facilitation in the congruent condition, relative to the incongruent and baseline condition, and inhibition in the incongruent condition, relative to the congruent and baseline condition. This finding indicates that after several years of reading experience English-speaking adults automatically integrate letters with their corresponding speech-sound, providing support for the view that letters become increasingly multi-modal as a result of repeated exposure over time (Blomert, 2011).

Holloway et al. (2015) argue that individuals who have learnt to read in a transparent orthographic system, such as Dutch, demonstrate neural sensitivity to the congruency of letter-speech-sound pairs, whereby the brain responds differently to congruent and incongruent letter-sound pairs. Furthermore, they suggest that the processing of speech is only modulated by visual information for highly regular and overlearned audio-visual pairs, such as transparent letter-sound associations in Dutch. However, the results from the priming experiment reported here clearly demonstrate that English-speaking adults are sensitive to letter-speech-sound congruency. These results therefore provide important evidence that speech processing is modulated by visual information, even in English where letter-sound correspondences are less consistent.

One other possibly notable effect is that there was an inhibitory effect in the incongruent condition. This inhibition effect however was smaller than the facilitation effect. This effect can be taken as further evidence of automatic letter-sound integration. However, the main focus of the present study was on finding behavioural evidence of facilitation from congruent letter-sound pairings since such pairings are overwhelmingly the ones that occur in reading.

2.4.2 Automatic letter-sound integration is not a concurrent predictor of reading ability in English-speaking adults

Individual differences in reading skill were not associated with variations in the extent to which letters and speech-sounds were automatically integrated. There were no significant correlations between any of the measures of letter-sound integration and reading in the current sample. This finding is inconsistent with previous research suggesting that variations in letter-sound integration are associated with reading ability. For example, research has reported that neural indices of automatic letter-sound integration are significantly correlated with reading ability in both dyslexic and typically developing children (Froyen et al., 2011) and that reading-impaired adult readers demonstrate reduced neural integration compared to non-impaired readers (Blau et al., 2009).

However, it is possible that individual differences in reading ability and/or letter-sound integration in the present study were not sufficiently large to detect a relationship between the two. In particular, the EAL analyses revealed that the distribution of reading ability differs quite substantially between native English and second language speakers, with native English participants demonstrating less variability in their reading scores. The present investigation was a pilot study designed to evaluate the use of a priming paradigm as a behavioural measure of letter-sound integration. In future studies investigating automatic letter-sound integration in adults and its relation to reading ability, it might be preferable to select only native English speaking participants and to ensure participants demonstrated a wide range of reading performance.

Subsequent studies investigating the relationship between automatic letter-sound integration and reading ability will therefore measure these skills in typically developing children during the early stages of reading development. It is likely that this age group will show considerably larger variations in reading performance and it is also possible that variations in the extent to which automatic letter-sound integration skills have been developed will be predictive of early variations in reading skills.

2.4.3 Concluding remarks

The findings from this pilot study indicate that following several years of reading experience, English-speaking adults have developed an audio-visual representation of a letter that can be measured using a priming task. As a group, participants demonstrated clear effects of priming, indicating that they were automatically integrating the visual letter with the auditory speech-sound. This study therefore provides support for the use of a priming task as a behavioural measure of automatic letter-sound integration.

Although the present study did not find a relationship between letter-sound integration and reading performance it was arguably not well suited to investigating individual differences. It seems plausible for example to argue that the range of variation in letter-sound integration skills amongst the highly educated adults in the present study might be too small to be a reliable predictor of variations in reading ability. Further research with typically developing children will aim to assess the relationship between automatic letter-sound integration and reading ability in an age range where it is plausible to expect that variations in the ability to establish automatic connections between letters and their corresponding sounds may operate to place constraints on learning basic word reading skills.

Chapter 3 A cross-sectional study investigating the relationship between letter-sound priming and reading performance in typically developing children

3.1 Introduction

The primary aim of this study was to investigate whether typically developing children with approximately two years of reading experience show evidence of automatic letter-sound integration using a behavioural priming paradigm. A secondary aim was to explore whether measures of automatic letter-sound integration are associated with individual differences in early reading ability or variation in other known predictors of reading: letter knowledge, phoneme awareness and RAN.

Previous research has reported atypical neural integration of letters and speech-sounds in children with dyslexia compared to age-matched controls (Blau et al., 2010; Froyen et al., 2011). This has led to the novel hypothesis that a deficit in letter-sound integration reflects a proximal cause of reading difficulties (Blomert, 2011). However, at present it is not clear how these reported neural differences relate to reading performance or, whether differences in integration reflect a cause of dyslexia or simply the consequence of limited reading experience.

Behavioural experiments investigating letter-sound integration in children have been reported alongside neuroimaging results. These studies have involved comparing the performance of children with dyslexia to an age-matched control group. For example, a recent study by Žarić et al. (2014) found that children with dyslexia were significantly slower to match a speech-sound to one of four visually presented letters (e.g. /b/ with either <b>, <d>, <t> or <p>) compared to age-matched controls. This finding was interpreted as evidence for reduced integration of letters and speech-sounds in children with dyslexia. However, the absence of a baseline condition in this task prevents this conclusion from being drawn. It is possible that underlying differences in phonological processing skills in children with dyslexia resulted in impaired letter-sound matching performance.

Blau et al. (2010) reported similar findings using a letter speech-sound matching task where children were asked to judge the congruency of letter speech-sound pairs (for example /ui/ and <oe>). While the two groups did not differ in terms of accuracy, children with dyslexia took significantly longer to decide whether the visual letter and auditory speech-sound were the same or different. However, again, without controlling for differences in phonological processing it is not possible to conclude that impaired performance on this task indicates a specific deficit in letter-sound integration. Furthermore, a subsequent replication using the same letter-sound matching task found no group differences in reaction time, and instead reported subtle differences in accuracy (Žarić et al., 2014).

In addition, it is not currently clear how automatic letter-sound integration relates to established predictors of early reading ability such as letter-sound knowledge and RAN. While it seems likely that early variations in letter-sound knowledge might influence the extent to which associations become automatically integrated, some researchers have suggested that simple knowledge of letter-sound correspondences differs from the ability to use these associations efficiently for fluent reading (Aravena et al., 2013; Blomert, 2011). Furthermore, it is plausible that RAN speed might be related to automatic letter-sound integration as performance on RAN tasks relies upon rapid retrieval of phonological information from a visual code (Hulme & Snowling, 2014).

Research investigating performance on measures of letter-sound integration has involved children learning to read Dutch, a language with highly consistent letter to speech-sound mappings, but has yet to extend these findings to an English-speaking sample. It is possible that automatic letter-sound integration would take longer to emerge, or indeed may never emerge in English as letter-sound mappings are much less consistent. However, the pilot study with adults reported in Chapter 2 revealed that English-speaking adults demonstrate clear effects of priming, indicating that they were automatically integrating visual letters with their corresponding speech-sound. This suggests that, despite the relatively complex relationship between English letters and speech-sounds, at some point literate English speakers develop an audio-visual representation of a letter. It is therefore of interest to investigate automatic letter-sound integration in children during the early stages of reading development to explore when this skill may emerge.

It is predicted that children with approximately two years of reading instruction will demonstrate evidence of automatic letter sound integration in the priming task. It is expected that children will demonstrate a similar pattern to adults; specifically children will be quicker to identify a speech-sound following the presentation of a congruent letter prime versus the presentation of an incongruent letter or a symbol with no associated speech-sound.

It is widely agreed that the reading ability of children with dyslexia represents the lower end of a continuous distribution (S. E Shaywitz et al., 1992). As such, if a lack of automatic letter-sound integration is a cause of reading impairment, as Blomert (2011) asserts, then variations in the extent to which letters and speech-sounds are integrated should be associated with individual differences in children’s reading ability more generally. It is therefore predicted that typically developing children who demonstrate increased letter-sound integration (as indexed by a larger priming effect) will also score better on measures of reading ability. Similarly, it is hypothesised that children who demonstrate enhanced letter-sound integration will also perform well on measures of letter-sound knowledge and RAN.

Furthermore, if a deficit in automatic letter-sound integration represents a proximal cause of dyslexia, it is expected that performance on the letter-sound priming task should correlate with reading ability when controlling for individual differences in phonological processing (as measured by performance on a phoneme awareness task).

In summary, the main focus of the present study was to investigate children's performance on the letter-sound priming task and to explore whether performance on this task is associated with individual differences in early reading ability. The present study therefore aimed to answer the following research questions:

1. Do English-speaking children aged between 5 and 7 years show behavioural evidence of automatic letter-sound integration as assessed by a letter-sound priming task?

2. Does performance on the letter-sound priming task correlate with individual differences in reading ability (when controlling for individual differences in phonological processing)?

3. Does performance on the letter-sound priming task correlate with other known predictors of reading: letter knowledge, phoneme awareness and RAN?

4. Does the letter-sound priming task provide a reliable measure of automatic letter-sound integration?

3.2 Method

3.2.1 Participants

Two hundred and nineteen children (101 male, 118 female) with a mean age of 6 years and 6 months (range = 36.50 months) from schools in North Yorkshire and Greater London participated in this experiment. Children were unselected for reading ability. All children whose native language was not English were fluent in both spoken and written English. Written consent was gained from parents and the children were given a sticker for their participation. The University College London Ethics Committee granted ethical approval for this study.

3.2.2 Design and materials

Letter-sound integration measure

The letter-sound priming task used in the pilot study with adults was adapted for use with children. The task involved the successive presentation of a prime and a target. The prime was a visually presented letter; followed shortly after by the target which was a spoken phoneme presented over headphones. Children were required to decide on each trial whether the second stimulus (the ’target’) was a ‘real’ speech-sound or not. Children were familiarised with the stimuli and task in an initial learning trial.

Stimuli. Stimuli in this task were the phonemes /tə/ (293ms), /də/ (263ms), /və/ (428ms), /zə/ (413ms) and /dʒə/ (357ms) recorded by a female native English speaker in a sound attenuated booth and the corresponding lower case letters presented in Ariel (pixel size 90 x 80). Novel letters (adapted from Taylor et al., 2011) and scrambled phonemes (nonverbal /zə/(413ms), nonverbal /də/(262ms), nonverbal /dʒə/(357ms), nonverbal /tə/(292ms) and nonverbal /və/(428ms)) served as non-letter stimuli. Scrambled phonemes were created using a Matlab script modified for use with short sound files (Ellis, 2010). Each phoneme was divided into 5ms overlapping hanning windows. The order of these windows was then randomised within a 250ms radius. The randomly overlapping windows were then combined to form the scrambled speech-sound. The length, overall power and frequency spectrum remained identical to the original speech-sound recording.

Apparatus. As in the adult experiment, stimuli were presented and responses recorded (speed and accuracy) using E-Prime Software (version 2.0) and a

Psychology Software Tools Serial Response Box (SRB; model 200a) with a Dell laptop (Latitude E5520) running Windows 7. Auditory stimuli were presented through Beyer Dynamic headphones (DT 770).

Design. In the priming task a letter prime was presented prior to an auditory phoneme target. A centrally located fixation point was presented for 1000ms followed by the presentation of the letter or non-letter stimulus, presented in black and appearing on the white screen for 500ms. The auditory target was then presented over headphones and was synchronous with the offset of the visual letter. Each trial was followed by the visual prompt "Real sound?" Children were instructed to attend to both the visual letter and auditory speech-sound and decide whether the sound was a 'real' speech-sound using "YES" and "NO" response keys. The experimenter monitored the child's performance, controlling the presentation of trials. Figure 3.1 displays the structure of a trial.

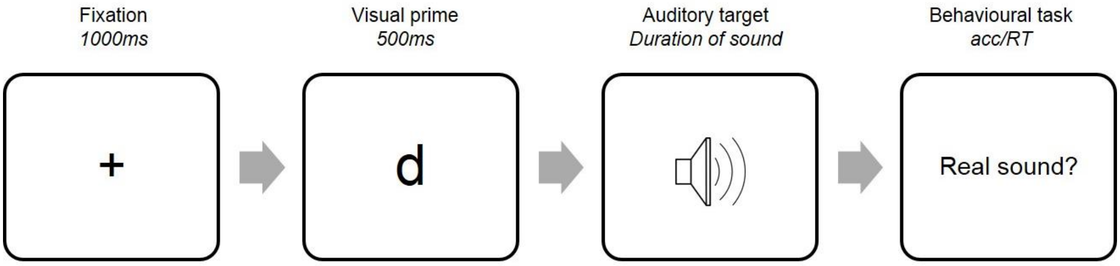


Figure 3.1 The structure of a letter-sound priming trial

As in the adult priming task, there were 6 conditions. In the congruent condition, the prime and target were the same letter/sound. In the unrelated (or incongruent) condition the prime and target were not the same letter/sound. In the baseline condition, the prime and target were not the same; the prime was a novel symbol and the target was a real speech-sound. There were 3 control conditions to prevent participants detecting the relationship between primes and targets and generating expectancies about the up-coming target.

These conditions are shown in Table 3.1, along with examples. In the control conditions visual stimuli were always paired as shown in Table 3.2.

There were 20 trials for each condition and each condition included 4 trials of each pairing, apart from the incongruent condition where each letter prime was presented once and paired with all of the other speech-sounds. There were 135 trials in total, including 15 ‘catch’ trials to ensure children were paying attention to the screen. On catch trials the same letters were presented but rather than presented in black, these stimuli were covered in a black and white animal print (for example, zebra stripes). Children were instructed to press the “GO” response key to catch the animal letters for the zookeeper. A cartoon picture of a zookeeper was presented for 500ms after each catch trial response.

The order of trials was randomized. The priming task took approximately 10 minutes to complete and children were allowed to pause the experiment and take a short break at any time.

Literacy related measures

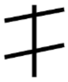
Rapid automatized naming. Children completed RAN subtests from the CTOPP (Wagner et al., 1999). These subtests required children to name two 9 x 4 arrays of 6 letters/digits/objects as quickly and accurately as possible. Practice trials ensured children understood the instructions. The time taken (in seconds) to name all items in both arrays was recorded.

Reading. Children completed the word and non-word reading subtests from the Test of Word Reading Efficiency (TOWRE 2; Torgesen et al., 1999). These subtests required children to read as many words/non-words as possible in 45 seconds. Practice items were administered prior to test items. The number of items read correctly was recorded. The word-reading subtest provided a measure of single word reading fluency whereas the non-word subtest

Table 3.1 Experimental conditions for the letter-sound priming task.

Condition	Prime (Visual stimulus)	Target (Auditory stimulus)	Response required
Congruent	Letter <z>	Phoneme /zə/	Is it a speech-sound? (YES)
Baseline	Novel letter <  >	Phoneme /zə/	Is it a speech-sound? (YES)
Incongruent	Letter <t>	Phoneme /zə/	Is it a speech-sound? (YES)
Control	Letter <z>	Scrambled phoneme /zəˢ/	Is it a speech-sound? (NO)
Control	Novel letter <  >	Scrambled phoneme /zəˢ/	Is it a speech-sound? (NO)
Control	Letter <t>	Scrambled phoneme /zəˢ/	Is it a speech-sound? (NO)

Table 3.2 Novel and real letter pairings

Letter	Novel symbol
t	
d	
v	
j	
z	

provided an additional measure of decoding skill and fluency. Children also completed the Single Word Reading Test (SWRT 6-16; Foster, 2007) where they were asked to read aloud a list of words that became increasingly difficult. This test provided a measure of word reading skill.

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 what sound letters and digraphs make, providing an untimed measure of the child’s knowledge of letter-sounds. The number of correctly identified letter-sounds was recorded (maximum=32).

Phoneme awareness. Children completed the phoneme deletion subtest from the YARC (Hulme et al., 2009). In this test children heard a word (and saw an accompanying picture) and were required to repeat this word but to ‘take away a sound’ from it (for example “Can you say seesaw? Can you say it again but this time don’t say saw?”). Practice trials ensured children understood the instructions. The number of items answered correctly was recorded to provide a measure of phoneme awareness.

3.2.3 Assessing reliability of the letter-sound priming task

Fifty-four children (23 male, 31 female) with a mean age of 6 years and 6 months (range = 22.52 months) completed the letter-sound priming task twice in order to provide an estimate of test re-test reliability.

Children completed the letter-sound priming task, as previously described. This task was completed a second time the following day. There were nine children who completed the follow up session two days after the first session.

3.3 Results

Means and standard deviations for measures of reading related skills and performance on the letter-sound priming task are presented in Table 3.3. A reading composite score was calculated by summing z-scores for timed and untimed measures of word and non-word reading as these scores were highly correlated.

Raw scores on the letter-sound knowledge test were at ceiling (47% of children achieved the maximum score) and so this measure was excluded from subsequent regression analyses. Furthermore, RAN measures were not normally distributed and so were transformed by examining the results of transformations from Tukey’s ladder of powers (using the “ladder” command in Stata v 13.0). Scores were transformed using an inverse root transformation however analyses of untransformed data yielded essentially identical patterns of results (correlations using transformed data are included in appendix 1).

Table 3.3 Performance on letter-sound priming task (N=212)

	Mean (SD)	**Min.**	**Max.**
Baseline accuracy (/20)	19.11 (1.34)	13.00	20.00
Congruent accuracy (/20)	19.05 (1.23)	13.00	20.00
Incongruent accuracy (/20)	19.17 (1.26)	12.00	20.00
Baseline average RT (ms)	1243.81 (333.69)	673.47	2267.15
Congruent average RT (ms)	1128.45 (297.84)	640.42	2230.94
Incongruent average RT (ms)	1229.58 (314.85)	732.63	2584.29

3.3.1 Effect of priming

Before analyses were conducted, outliers were removed from the raw reaction time (RT) data. Only correct responses were included in the analysis. Responses that were over 5000ms were first removed as this was considered to reflect a lapse in attention rather than accurate performance on the task. A non-recursive outlier removal procedure was then used, as recommended by Selst and Jolicoeur (1994). Reaction time data from two participants was excluded from the analysis due to below chance accuracy on the priming task.

The percentage of RT data that was excluded, as both response errors and outliers, is shown in Table 3.5. As shown in the table, over 90% of the possible RT data were available for analysis.

The mean correct response times in each condition of the letter-sound priming experiment, together with 95% within-subject confidence intervals (Morey, 2008) are shown in Figure 3.2. Compared to the baseline condition the data show facilitation in the congruent priming condition and also facilitation in the incongruent condition. To assess the reliability of these differences, response times for the baseline, congruent and incongruent condition were compared using a mixed effects linear regression model treating participants and items as crossed random effects (xtmixed in Stata 13.1) in order to account for variability across participants and target items. Whilst there are a small number of levels of target item to be treated as a random effect, comparison of models with target items as fixed and as random effects were found to be almost identical.

Table 3.4 Descriptive statistics for performance on literacy-related measures

Measure	N	Mean (SD)	Min.	Max.
Age (months)	219	78.03 (7.68)	56.94	93.43
LSK raw score /32	112	31.06 (1.18)	26	32
LSK standard score		111.39 (9.87)	84	130
SWRT raw score /60	217	26.13 (11.58)	2	51
SWRT standard score		111.10 (12.86)	75	141
TOWRE SWE raw score /104	158	43.83 (18.31)	3	78
TOWRE SWE standard score		115.82 (11.57)	91	145
TOWRE PDE raw score /63	156	22.62 (12.26)	0	48
TOWRE PDE standard score		116.59 (10.23)	95	140
RAN Digits total time (seconds;s)	166	47.74 (15.25)	26	139
RAN Digits scaled score		10.73 (2.23)	3	16
RAN Letters total time (s)	136	58.49 (19.03)	32	138
RAN Letters scaled score		10.04 (1.94)	4	15
RAN Objects total time (s)	163	84.40 (19.23)	52	163
RAN Objects scaled score		10.85 (2.43)	4	19
Phoneme Deletion raw score /24	113	14.65 (5.75)	3	24
Phoneme Deletion standard score		110.42 (12.05)	70	137
RAN Objects No Repetition (s)	82	52.12 (14.35)	29	100
Reading composite score	156	.05 (2.89)	-5.79	5.57

Table 3.5 Percentage RT data excluded for each experimental condition

	Response error (%)	Outliers (%)
Baseline	1.41	1.37
Congruent	1.26	1.28
Incongruent	1.14	1.30
Total	3.81	3.95

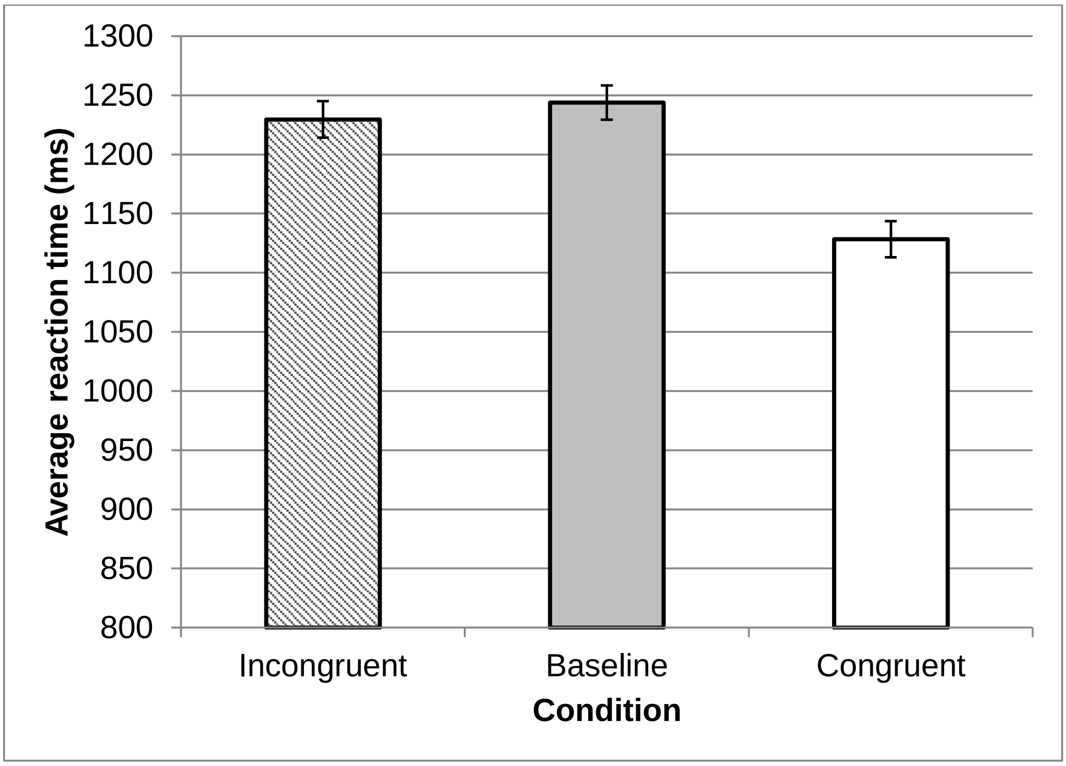


Figure 3.2 Average response times (and 95% CIs) for each condition of the letter-sound priming task (N=212)

This model predicted participant's target response times as a function of experimental condition, using two dummy coded variables (baseline vs. congruent (0, 1) and baseline vs. incongruent (0, 1)). Results showed that the difference in target response time between the baseline and congruent condition was significant (estimated difference = -114.16, z = -11.14, 95% confidence interval = [-134.25, -94.08], p < .001). The effect size of this difference (ignoring participant and item variability) is d = .36. However, the difference between response times in the baseline and incongruent condition was not significant (estimated difference = -13.05, z = -1.28, 95% confidence interval = [-33.11, 7.00], p =. 202). The effect size here (ignoring participant and item variability) is d = .04.

3.3.2 Age analyses

Children in this study were recruited from different year groups. As there were a large number of children in each age group, the effect of age upon performance on the letter-sound integration task was further investigated. As there were only 3 children in the 4-year-old group these children were removed from the sample for age-related analyses.

Means and standard deviations for performance on the letter-sound priming task in each age group are presented in Table 3.6. The mean correct response times in each condition of the letter-sound priming experiment for each age group, together with 95% within-subject confidence intervals (Morey, 2008) are shown in Figure 3.3.

For 5 year-old children, both the congruent and incongruent condition show facilitation compared to the baseline condition. The 6-year-old group show clear facilitation in the congruent condition compared to the baseline condition, while response times in the incongruent condition also show slight facilitation compared to the baseline condition. Data for the 7-year-old group show facilitation in the congruent priming condition and interference in the incongruent condition compared to the baseline condition. To assess the reliability of these differences, response times for the baseline, congruent and incongruent condition were compared for each age group using a mixed effects linear regression model, again treating participants and items as crossed random effects.

As before, each model predicted participant’s target response times as a function of experimental condition, using two dummy coded variables (baseline vs. congruent (0, 1) and baseline vs. incongruent (0,1)). Results for

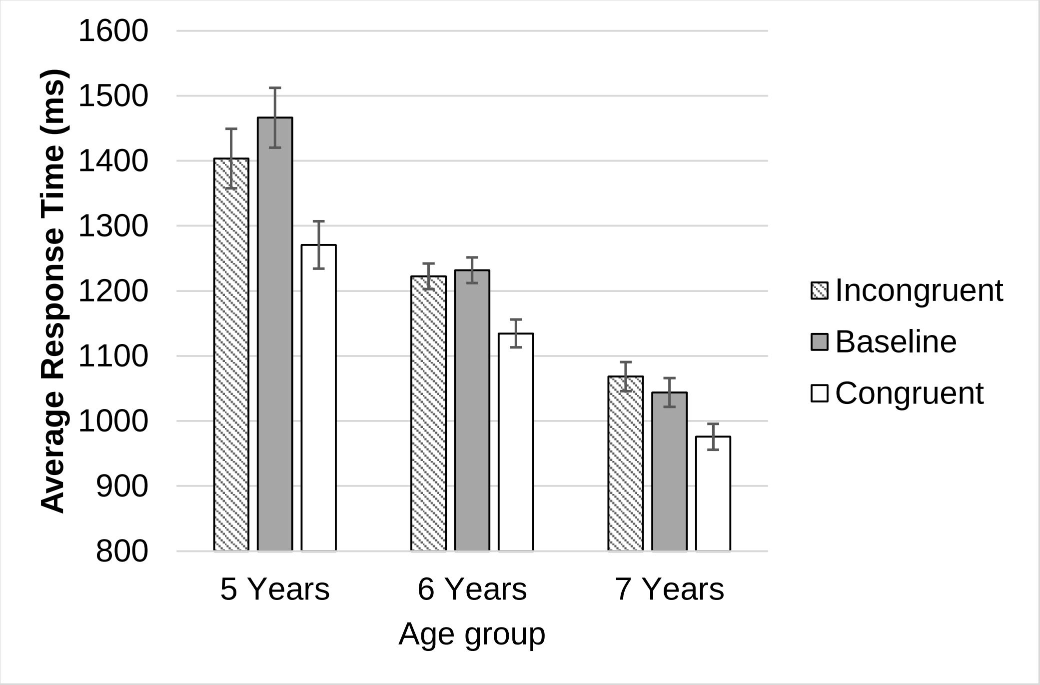


Figure 3.3 Average response times (and 95% CIs) for each condition of the letter-sound priming task across the three age groups

the 5-year-old group showed that the difference in target response time between the baseline and congruent condition was significant (estimated difference = -191.94, z = -7.18, 95% confidence interval = [-244.36, -139.52], p < .001). The effect size of this difference (ignoring participant and item variability) is d = .56. The difference between response times in the baseline and incongruent condition was also significant (estimated difference = -62.02, z = -2.32, 95% confidence interval = [-114.44, -9.60], p =. 020). The effect size of this difference (ignoring participant and item variability) is d = .17.

Results for the 6-year-old group also showed a significant difference between the baseline and congruent condition (estimated difference = -95.62, z = -6.79, 95% confidence interval = [-123.22, -68.02], p < .001). The effect size of this difference (ignoring participant and item variability) is d = .33. However the difference between response times in the baseline and incongruent condition was not significant (estimated difference = -9.44, z = -0.67, 95% confidence interval = [-36.96, 18.08], p = .501). The effect size here is d = .03.

Table 3.6 Descriptive statistics for performance on the letter-sound priming task for each age group

	Mean (SD)	**Min.**	**Max.**
5 Years (N=50)			
Baseline accuracy (/20)	18.98 (1.38)	13	20
Congruent accuracy (/20)	18.84 (1.42)	15	20
Incongruent accuracy (/20)	18.80 (1.71)	12	20
Baseline average RT (ms)	1466.33 (371.21)	806.00	2267.15
Congruent average RT (ms)	1270.57 (326.44)	643.78	2230.94
Incongruent average RT (ms)	1403.55 (349.46)	809.41	2584.29
6 Years (N=105)			
Baseline accuracy (/20)	19.01 (1.52)	13	20
Congruent accuracy (/20)	19.01 (1.23)	13	20
Incongruent accuracy (/20)	19.22 (1.18)	13	20
Baseline average RT (ms)	1225.92 (296.07)	673.47	2043.44
Congruent average RT (ms)	1130.81 (281.70)	640.42	2144.29
Incongruent average RT (ms)	1215.16 (291.64)	761.16	2298.40
7 Years (N=54)			
Baseline accuracy (/20)	19.42 (.81)	17	20
Congruent accuracy (/20)	19.30 (1.02)	16	20
Incongruent accuracy (/20)	19.37 (.81)	17	20
Baseline average RT (ms)	1043.85 (200.78)	763.79	1643.40
Congruent average RT (ms)	975.81 (205.57)	663.63	1470
Incongruent average RT (ms)	1068.29 (210.38)	732.63	1721.80

Results for the 7-year-old group followed the same pattern as the 6-year-old group, showing a significant difference between response times on the baseline and congruent condition (estimated difference = -67.49, z = -4.55, 95% confidence interval = [-96.54, -38.44], p < .001). The effect size of this difference (ignoring participant and item variability) is d = .33. The difference between response times in the baseline and incongruent condition was not significant (estimated difference = 24.09, z = 1.62, 95% confidence interval = [-4.98, 53.17], p = .104). The effect size associated with this difference is d = -.12.

A mixed effects regression model predicting children's target response times as a function of experimental condition and age (using the 6-year-old group as the reference group) revealed significant effects of age upon response times. Children's response times in the 5-year-old group were significantly slower compared to those in the 6-year-old group (estimated difference = 239.32, z = 5.02, 95% confidence interval = [145.88, 332.77], p < .001). Response times in the 7-year-old group were significantly faster compared to the 6-year-old group (estimated difference = -181.54, z = -3.91, 95% confidence interval = [-272.49, -90.59], p < .001).

Furthermore there was a significant interaction between experimental condition and age indicating that the size of the priming effect (as identified in prior analyses) differed between groups.

The difference in target response time between the baseline and congruent condition was significantly larger in the 5-year-old group compared to the 6-year-old group (estimated difference = -96.21, z = -3.76, 95% confidence interval = [-146.30, -46.12], p < .001). This difference was not significant between the 6-year-old and 7-year-old group (estimated difference = 28.23, z = 1.14, 95% confidence interval = [-20.10, 76.56], p = .252).

Similarly, the difference between response times in the baseline and incongruent condition was significantly larger in the 5-year-old group compared to the 6-year-old group (estimated difference = -52.12, z = -2.04, 95% confidence interval = [-102.16, -2.08], p < .001). This difference was not significant between the 6-year-old and 7-year-old group (estimated difference = 33.78, z = 1.37, 95% confidence interval = [-14.53, 82.08], p = .171).

Taken together, these results demonstrate that the 5-year-old children showed a significantly greater priming effect compared to the 6 and 7-year-old children in this sample. This effect was present when comparing response times in the baseline and congruent conditions and also, unexpectedly, when comparing response times in the baseline and incongruent conditions. It is possible this pattern of results was caused by elevated response times in the baseline condition in the 5-year-old group, an issue that will be discussed further.

Table 3.7 Correlations between age and performance on the letter-sound priming task (N=209)

	1.	2.	3.	4.	5.
1. Age (months)					
2. Facilitation	.22**				
3. Interference	.17*	.45***			
4. Baseline Ave RT	-.45***	-.46***	-.39***		
5. Congruent Ave RT	-.37***	.10	-.16*	.84***	
6. Incongruent Ave RT	-.38***	-.21**	.20**	.82***	.79***

3.3.3 Relationship with reading

Measures of facilitation and interference were used to investigate the relationship between letter-sound integration and reading. Facilitation was calculated for the letter-sound priming task by subtracting each participant’s average response time in the baseline condition from their average response time in the congruent condition, a negative score indicated facilitation. Interference was calculated by subtracting baseline response times from incongruent response times, a positive score indicated interference. These measures will be referred to as indices of integration. Correlations between children's average response times for each condition of the letter-sound priming task were also included in the analyses.

Table 3.8 shows the simple correlations among reading measures and age. As shown, age was significantly correlated with all reading measures (with the exception of letter-sound knowledge where scores were at ceiling). As expected, the different measures of reading-related skills were also significantly correlated, again with the exception of letter-sound knowledge.

Rapid automatized naming

Table 3.9 shows the simple correlations among the various RAN tasks and letter-sound integration measures, partial correlations controlling for age are shown below the diagonal. The subsequent analysis will focus on these partial correlations as performance on reading-related and letter-sound integration measures were both significantly correlated with age.

Considering first the correlations between integration indices and RAN; performance on digit RAN was significantly correlated with average response times for each condition of the priming task (r = .21, .24 and .23, p = .0090, .0022 and .0033 for baseline, congruent and incongruent conditions). However the only other correlation that was significant when controlling for age, was between response times in the congruent condition and letter RAN (r = .18, p = .0350). Significant correlations may reflect the speeded element of both tasks, performance on which may also be influenced by age; hence not all partial correlations remain significant.

Hierarchical regression analyses were used to test this hypothesis. A two stage hierarchical multiple regression model was conducted with digit RAN score as the dependent variable. Together children's age and response times in the baseline condition predicted 21.80% of the variance in RAN performance ((F 2, 159) = 22.16, p < .001).

Congruent response time was then added to the model to provide an estimate of the specific effect of letter-speech-sound integration on RAN performance. However, adding congruent RT did not account for additional variance ((F 1, 158) = 1.24, p = .267, R^2 change < .01) indicating the extent to which children were facilitated by the letter prime did not predict variance in the RAN of digits. Similarly adding incongruent RT did not account for additional variance ((F 1, 158) = 1.88, p = .172, R^2 change < .01).

Reading

Table 3.10 shows the simple and partial correlations among reading and letter-sound integration measures. As shown, there were no significant correlations between any indices of integration and reading (see also Figure 3.4 illustrating the absence of a relationship between children's reading and facilitation). However, performance on both subtests of the TOWRE and also the reading composite measure were significantly correlated with performance on each condition of the letter-sound priming task (r's between -.21 and -.27, p between .0007 and .0103). The only other correlations that were significant when controlling for age was the correlation between scores on the SWRT and average response times in the incongruent condition (r = -.16, p= .0178) and between performance on the Phoneme Deletion measure and average response times in the congruent condition (r = -.20, p = .0428).

These results suggest that reading ability (measured by performance on the TOWRE) is negatively correlated with the speed of response on the priming task (deciding whether a presented sound is a real speech-sound or a scrambled phoneme) but that the degree of facilitation or inhibition produced in this task by a preceding letter is not related to reading ability. Thus it is not the speed of the letter-sound integration process that is related to reading but rather the speed with which a speech-sound can be identified in isolation. Arguably, speed of response in the priming task (how quickly a child can identify an auditory stimulus as being a speech-sound) reflects a measure of phonological processing speed.

It is possible that the discrepancy between correlations with the SWRT and TOWRE reflect the speeded aspect of the two tasks; the TOWRE is a timed measure of reading whereas the SWRT is not. However, there were also differences in the sample of children that completed these two measures. The SWRT was completed by nearly all the children in the study (N= 217) whereas the TOWRE-SWE and PDE subtests were completed by a subset of these children (N = 158 and 156 respectively).

Hierarchical regression analyses were used to explore predictors of reading. A two stage hierarchical multiple regression model was conducted with reading composite score as the dependent variable. Together children's age and response times in the baseline condition predicted 44.41% of the variance in reading performance ((F 2, 149) = 59.51, $p < .001$).

Congruent response time was then added to the model to provide an estimate of the specific effect of letter-speech-sound integration on reading performance. However, adding congruent RT did not account for additional variance ((F 1, 148) = 0.03, $p = .869$, R^2 change < .01) indicating the extent to which children were facilitated by the letter prime did not predict variance in reading performance. Similarly adding incongruent RT did not account for additional variance ((F 1, 148) = 2.46, $p = .119$, R^2 change < .01).

Given that response times in the baseline condition significantly predicted reading performance in this model, a further regression model was used to explore whether baseline performance on the letter-sound identification task was a unique predictor of reading ability above and beyond established predictors of reading.

Again, a two stage hierarchical multiple regression model was conducted with the reading composite score as the dependent variable. Together children's age and performance on measures of phoneme deletion and RAN predicted 74.74% of the variance in reading performance ((F 3, 104) = 102.57, $p < .001$).

Baseline response time was then added to the model to provide an estimate of the effect of performance on the letter-sound identification task. Adding baseline response time significantly improved the model, accounting for an additional 1.27% of the variance in reading performance and this change in R^2 was significant ((F 1, 103) = 5.47, p = .021).

Two further regression models were used to explore relationships between performance on the SWRT and incongruent response time and performance on the Phoneme Deletion task and congruent response time. Simultaneous regression analyses revealed that response times in the incongruent condition did not significantly predict performance on the SWRT when controlling for children's age and response times in the baseline condition (β = -.005, t = -1.61, p = .110). Similarly, average response times in the congruent condition did not significantly predict performance on the Phoneme Deletion task when controlling for age and baseline response time (β = -.001, t = -.59, p = .559).

Table 3.8 Simple correlations between age and performance on literacy tasks

	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Age	.16 112	.58*** 217	.64*** 158	.57*** 156	-.41*** 166	-.39*** 136	-.39*** 163	.61*** 113	.63*** 156
2. LSK		.24** 112	.18 112	.24** 112	-.09 111	-.15 87	-.21* 109	.24** 112	.23* 112
3. SWRT			.94*** 158	.91*** 156	-.60*** 166	-.58*** 136	-.49*** 163	80*** 113	.97*** 156
4. TOWRE SWE				.91*** 156	-.71*** 112	-.62*** 87	-.59*** 109	.75*** 113	.98*** 156
5. TOWRE PDE					-.68*** 112	-.64*** 87	-.51*** 109	.74*** 113	.97*** 156
6. RAN Digits						.67*** 136	.70*** 160	-.56*** 112	-.70*** 112
7. RAN Letters							.56*** 132	-.55*** 87	-.63*** 87
8. RAN Object								-.52*** 109	-.55*** 109
9. Phoneme Deletion									.78*** 113
10. Composite Reading Score									

*Note: *** = p <.001, ** = p <.01, * = p <.05. N for each correlation reported beneath coefficient*

Table 3.9 Simple and partial correlations between measures of RAN and letter-sound integration.

	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
1. RAN Digits		.67*** 136	.70*** 160	-.10 162	-.02 162	.36*** 162	.36*** 162	.36*** 162
2. RAN Letters	.60*** 136		.56*** 132	.05 133	.03 133	.25** 133	.31*** 133	.27** 133
3. RAN Objects	.64*** 160	.48*** 132		-.18* 159	-.14 159	.31*** 159	.25** 159	.24** 159
4. Facilitation	.00 162	.15 133	-.09 159		.44*** 212	-.46*** 212	.12 212	-.22** 212
5. Interference	.05 162	.10 133	-.09 159	.42*** 212		-.38*** 212	-.15* 212	.19** 212
6. Baseline Ave RT	.21** 162	.08 133	.15 159	-.41*** 212	-.35*** 212		.83*** 212	.83*** 212
7. Congruent Ave RT	.24** 162	.18* 133	.12 159	.23*** 212	-.09 212	.79*** 212		.788*** 212
8. Incongruent Ave RT	.23** 162	.13 133	.09 159	-.14* 212	.30*** 212	.79*** 212	.75*** 212	

*Note: *** = p <.001, ** = p <.01, * = p <.05. Simple correlations above the diagonal and partial correlations controlling for age below the diagonal. N for each correlation reported beneath coefficient.*

Table 3.10 Simple and partial correlations between measures of reading and letter-sound integration.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. SWRT		.94***	.91***	.97***	.80***	.15*	.04	-.36***	-.36***	-.36***
		158	156	156	113	211	211	211	211	211
2. TOWRE-SWE	.90***		.91***	.98***	.75***	.19*	.07	-.45***	-.40***	-.44***
	158		156	156	113	153	153	153	153	153
3. TOWRE-PDE	.86***	.86***		.97***	.74***	.18*	.04	-.43***	-.38***	-.43***
	156	156		156	113	152	152	152	152	152
4. Reading composite	.96***	.96***	.95***		.78***	.20*	.07	-.46***	-.41***	-.45***
	156	156	156		113	152	152	152	152	152
5. Phoneme Deletion	.69***	.59***	.60***	.64***		.15	.05	-.40***	-.38***	-.38***
	113	113	113	113		109	109	109	109	109
6. Facilitation	.02	.05	.05	.06	-.00		.44***	-.46***	.12	-.22**
	211	153	152	152	109		212	212	212	212
7. Interference	-.06	-.05	-.06	-.05	-.06	.42***		-.38***	-.15*	.19**
	211	153	152	152	109	212		212	212	212
8. Baseline Ave RT	-.12	-.21***	-.21**	-.23**	-.15	-.41***	-.35***		.83***	.83***
	211	153	152	152	109	212	212		212	212
9. Congruent Ave RT	-.13	-.21***	-.21**	-.23**	-.20*	.23***	-.09	.79***		.788***
	211	153	152	152	109	212	212	212		212
10. Incongruent Ave RT	-.16*	-.25**	-.26**	-.27***	-.18	-.14*	.30***	.79***	.75***	
	211	153	152	152	109	212	212	212	212	

*Note: *** = p <.001, ** = p <.01, * = p < .05. Simple correlations above the diagonal and partial correlations controlling for age below the diagonal. N for each correlation reported beneath coefficient.*

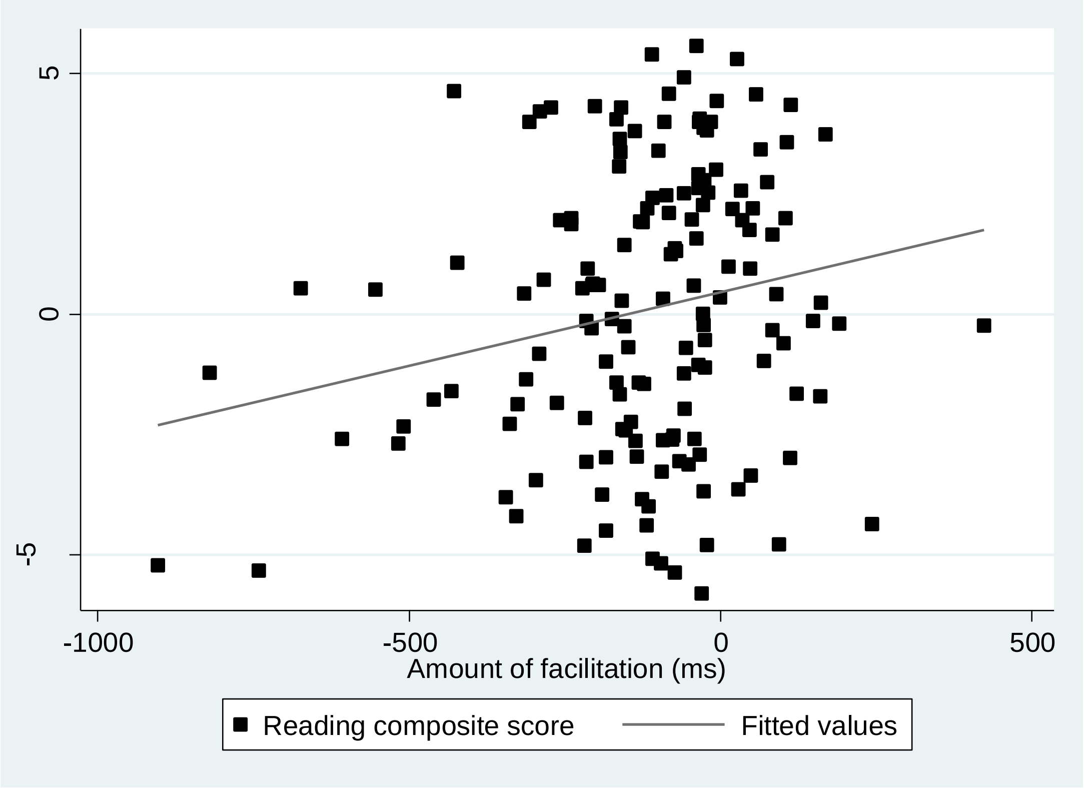


Figure 3.4 One-way linear plot with regression slope predicting reading performance from amount of facilitation on the letter-sound priming task

3.3.4 Reliability of the priming task

Means and standard deviations for performance on both sessions of the letter-sound priming tasks are presented in Table 3.11.

Before analyses were conducted, outliers were removed from the raw reaction time (RT) data. Only correct responses were included in the analysis. Responses that were over 5000ms were first removed as this was considered to reflect a lapse in attention rather than accurate performance on the task. A non-recursive outlier removal procedure was then used, as recommended by Selst and Jolicoeur (1994). Reaction time data from one participant was excluded from the analysis due to below chance accuracy on the priming task.

The percentage of RT data that was excluded, as both response errors and outliers for each session, is shown in Table 3.12. As shown in the table, over 90% of the possible RT data were available for analysis for each experiment.

Performance across the two testing sessions were significantly correlated in each of the three experimental conditions; baseline (r = .54, p < .0001), congruent (r = .70, p < .0001) and incongruent (r = .54, p < .0001).

The mean correct response times in each condition of the letter-sound priming experiment for each session, together with 95% within-subject confidence intervals (Morey, 2008) are shown in Figure 3.5. In both sessions, the data show facilitation in the congruent priming condition compared to the baseline condition. In session 1, the data also show facilitation in the incongruent condition compared to the baseline condition. Whereas in session 2 the data show interference in the incongruent compared to the baseline condition.

To assess the reliability of these differences, response times for the baseline, congruent and incongruent condition in session 1 and 2 were compared using a mixed effects linear regression model treating participants and items as crossed random effects (xtmixed in Stata 13.1) in order to account for variability across participants and target items. Whilst there are a small number of levels of target item to be treated as a random effect, comparison of models with target items as fixed and as random effects were found to be almost identical.

Both models predicted participant's target response times as a function of experimental condition, using two dummy coded variables (baseline vs. congruent (0, 1) and baseline vs. incongruent (0, 1)). Results for session 1 showed that the difference in target response time between the baseline and congruent condition was significant (estimated difference = -107.80, z = -5.57, 95% confidence interval = [-145.71, 69.89], p < .001). The effect size of this difference (ignoring participant and item variability) is d =.46. However, the difference between response times in the baseline and incongruent condition was not significant (estimated difference = -15.45, z = -.80, 95% confidence interval = [-53.23, 22.32], p =. 423). The effect size here is d =.07.

Table 3.11 Descriptive statistics from performance on the letter-sound priming task from Sessions 1 and 2

	Mean (SD)	Min.	Max.
Session 1			
Baseline accuracy (/20)	19.43 (.82)	17	20
Congruent accuracy (/20)	19.13 (1.04)	16	20
Incongruent accuracy (/20)	19.42 (1.00)	15	20
Baseline average RT (ms)	1211.00 (249.02)	757.11	2009.70
Congruent average RT (ms)	1103.46 (214.44)	699.68	1555.21
Incongruent average RT (ms)	1193.86 (239.45)	768.30	1813.50
Session 2			
Baseline accuracy (/20)	18.96 (1.26)	15	20
Congruent accuracy (/20)	19.09 (1.10)	16	20
Incongruent accuracy (/20)	19.09 (1.47)	13	20
Baseline average RT (ms)	1253.07 (296.76)	720.22	1921.47
Congruent average RT (ms)	1201.40 (263.93)	734.85	1837.11
Incongruent average RT (ms)	1276.58 (331.99)	711.58	1985.10

Results for session 2 show a significant difference in target response time between the baseline and congruent condition (estimated difference = -47.45, z = -1.97, 95% confidence interval = [-94.65, -.25], p = .049). The effect size of this difference (ignoring participant and item variability) is d =.18. Whereas the difference in response times in the baseline and incongruent condition were not significant (estimated difference = 22.20, z = .92, 95% confidence interval = [-24.98, 69.39], p = .356). The effect size here is d = -.07.

The data in Figure 3.5 suggest that children were slower in the second session of the priming task compared to the first session. Analyses were therefore conducted to determine whether children’s response times in the three conditions differed across sessions.

Table 3.12 Percentage RT data excluded for each experimental condition for Sessions 1 and 2 of the letter-sound priming task

	Response error (%)	**Outliers (%)**
Session 1		
Baseline	1.05	1.14
Congruent	1.54	1.02
Incongruent	1.02	1.08
Total	3.61	3.24
Session 2		
Baseline	1.76	1.27
Congruent	1.54	1.27
Incongruent	1.54	1.54
Total	4.84	4.08

A mixed effects regression model predicting children’s target response times as a function of experimental condition and session using dummy coded variables (session 1 vs. session 2, (0,1)) revealed there was no significant effect of session upon overall response time in the baseline condition (estimated difference = 40.72, z = 1.84, 95% confidence interval = [-2.70, 84.14] p =. 066). However, children’s response times in congruent condition were significantly slower in the second session compared to the first session (estimated difference = 100.68, z = 4.53, 95% confidence interval = [57.11, 144.25] p < .001). This was also the case for response times in the incongruent condition (estimated difference = 77.61, z = 3.51, 95% confidence interval = [34.23, 121.00] p < .001).

The interaction between experimental condition and session was not significant, indicating that the difference between target response times in the baseline and congruent conditions and the difference between target response times in the baseline and incongruent conditions did not differ across the two sessions.

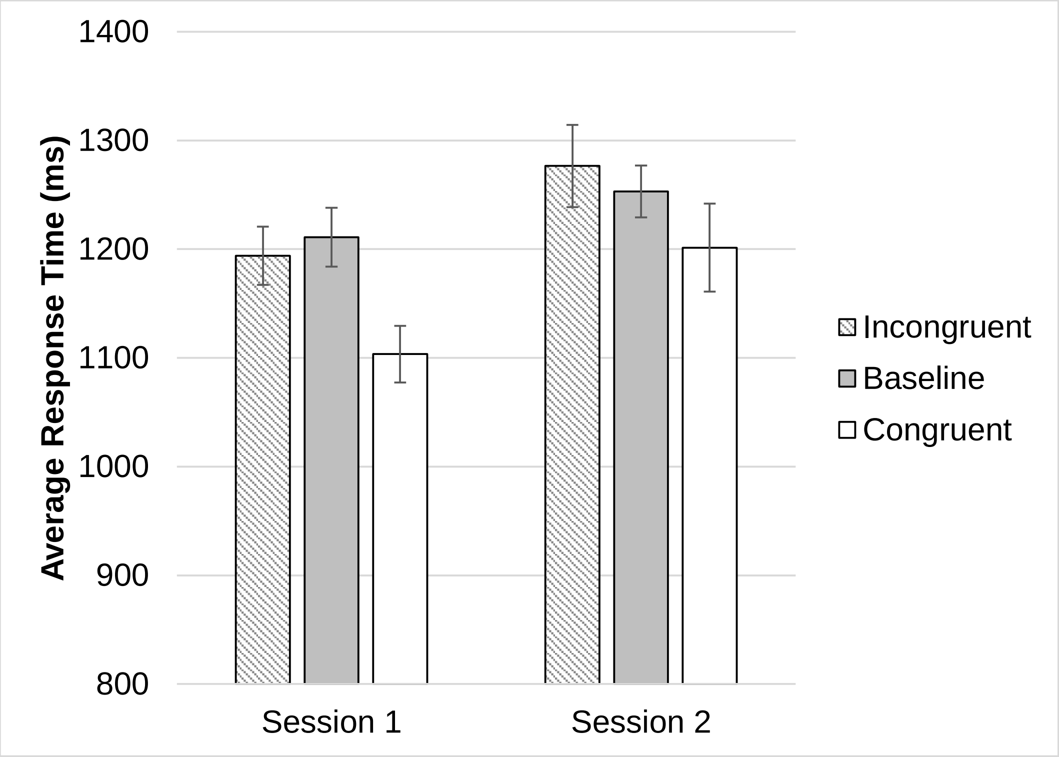


Figure 3.5 Average response times (and 95% CIs) for each condition of the Session 1 and 2 letter-sound priming task (N=53)

3.4 Discussion

This study aimed to provide behavioural evidence of automatic letter-sound integration in a large sample of English-speaking children and to assess whether variations in this skill are associated with individual differences in reading ability. The results suggest that typically developing children with approximately two years of reading experience demonstrate clear evidence of automatic letter-sound integration. However, individual differences in the extent to which letters and speech-sounds are integrated do not appear to predict variance in reading skill.

3.4.1 Evidence of automatic letter-sound integration in typically developing children

The data reported here provide support for the existence of strong associative links between printed letters and the speech-sounds they represent. As predicted, in the letter-sound priming task children demonstrated facilitation in the congruent condition, relative to the incongruent and baseline condition. This finding indicates that after approximately two years of reading experience children automatically integrate letters with their corresponding speech-sound, providing support for the view that letters become multi-modal as a result of repeated exposure over time (Blomert, 2011).

In contrast to results reported in Chapter 2 with adults, children do not show evidence of interference when presented with an incongruent letter. On average, children were in fact slightly quicker to identify the speech-sound following the presentation of an incongruent letter compared to a novel symbol, though this difference was not significant. The amount of facilitation, on the other hand, was relatively large, as indicated by the small to medium effect size of the difference between baseline and congruent response times (Cohen’s d = .36). The inclusion of a baseline condition in the present study extends existing research, with data indicating that the congruency effect reported in previous studies is likely to be driven by facilitation, i.e. faster responses following congruent visual information.

This study also compared performance across age groups in order to investigate when automatic letter-sound integration emerges and how this skill changes with increasing reading experience. As expected, there were age-related differences in overall reaction time: reaction times in the older groups were significantly shorter. However, the pattern of reaction times across conditions was broadly comparable across the three groups. All three age groups demonstrated a significant priming effect, indicating that children aged between 5 and 7 years old automatically integrate letters with their corresponding speech-sound. The size of this priming effect was similar in the 6 and 7-year-old groups, however the 5-year-old group displayed a significantly larger priming effect. This is somewhat surprising as it might be expected that children with increased reading experience and years of formal reading instruction might display a larger priming effect (show greater letter-sound integration).

However, it should be noted that while older children may have more reading experience, the learning of letters and their corresponding speech-sounds often begins before children start school and is typically the focus of pre-school literacy education (Muter et al., 1998). In line with this, 36% of the 5-year-old group scored at ceiling on a measure of letter-sound knowledge and the minimum score was 29 letters and digraphs correct out of a possible 32. It is possible that increased facilitation in the younger age group reflects this “overlearning” of letter-sound associations. In older children, associations may be more fluid (or flexible) in order to accommodate for the inconsistent nature of letter-sound associations in the English language.

An alternative interpretation is that RTs in the baseline condition were significantly longer in the 5-year-old group, resulting in an exaggerated priming effect. This interpretation is supported by the observation that the 5-year-old group also demonstrated significant facilitation in the incongruent condition. While it is plausible that RTs in the incongruent and baseline condition might be similar, it is difficult to explain why the presentation of an incongruent letter might speed up the processing of a speech-sound relative to the presentation of a novel symbol. One possible interpretation for elevated response times in the baseline condition is the novelty of the symbols, which may have been increasingly distracting for younger children. In addition, novel symbols were presented on a third of all trials meaning that the likelihood of a visual letter appearing was greater than that of a novel symbol.

3.4.2 Relationship between performance on the priming task and reading ability

Rapid automatized naming

Measures of letter-sound integration (facilitation and interference) were not significantly correlated with performance on any of the RAN tasks, indicating that the extent to which children automatically integrate letters and corresponding speech-sounds is not associated with naming speed for digits, letters or objects. This was confirmed using regression analyses, which found that, when controlling baseline response times, neither congruent nor incongruent response times predicted children’s RAN speed. It was hypothesised that children’s performance on these two tasks would be related as both tasks are assumed to involve the rapid retrieval of phonological information from a visual code. While it is still plausible that this skill underlies performance on both tasks, the present results could indicate that performance on measures of RAN involves additional processes beyond simply the rapid retrieval of phonological information from visually presented items. In line with this, research has shown that performance on discrete naming tasks (where items are presented one at a time) and serial naming tasks (where items are presented simultaneously) are differentially related to reading (de Jong, 2011; Logan et al., 2011; Wolf & Bowers, 1999). This suggests that efficient visual scanning and processing of serial information are also important processes underlying performance on RAN tasks.

On the other hand, there were significant correlations between RAN performance and average response times on the priming task indicating there may be some common processes involved in these tasks. A number of significant correlations disappeared when age was controlled, suggesting this relationship may reflect the speeded element of both tasks which is also likely to be influenced by children’s age.

Reading

As with performance on the RAN tasks, measures of facilitation and interference were not significantly correlated with performance on any of the reading measures. This finding was also confirmed using regression analyses, which demonstrated that, when controlling baseline response times, neither congruent nor incongruent response times predicted children's reading. These results indicate that the degree of facilitation or inhibition produced in this task by a preceding letter is not related to reading ability. This finding is inconsistent with the hypothesis that automatic letter-sound integration should be a correlate of reading ability and with previous research suggesting that difficulties learning to read result from weakened associations between letters and speech-sounds (Aravena et al., 2013; Blau et al., 2010; Froyen et al., 2011).

In contrast, average response times on all conditions of the priming task were significantly correlated with children's reading performance. These correlations indicate that children who were quicker to identify the speech-sound were also better readers. The present results therefore suggest that it is not the speed of the letter-sound integration process that is associated with reading but rather the speed with which a speech-sound can be identified in isolation. This is in line with a wide literature supporting the role of phonological skills in reading acquisition, as arguably, speed of response in the priming task (how quickly a child can identify an auditory stimulus as being a speech-sound) reflects a measure of phonological processing speed.

Further regression analyses revealed that baseline performance on the letter-sound priming task was a unique predictor of reading ability above and beyond established predictors of reading (namely: children's age, phoneme awareness and RAN speed). While this measure predicted less than 2% additional variance in reading, it is of interest that baseline performance predicts additional variance in reading when controlling for performance on a measure of phoneme deletion, which is widely considered a robust and reliable measure of phonological processing skill. This finding was unexpected and warrants further investigation in order to confirm whether the phonological processing demands of the priming task are driving the observed relationship with reading ability.

3.4.3 Reliability of the letter-sound priming task

The test-retest-reliability coefficient for the letter-sound priming task indicates that children's performance on the task is not particularly reliable (r = .54 for the baseline/incongruent conditions and .70 for the congruent condition). Correlations between .5 and .6 are generally considered to indicate poor reliability. These findings indicate that baseline and incongruent conditions have 29% true score variance, with the remaining 71% of variance being error variance. The congruent condition has 49% true score variance. The improved reliability of performance in the congruent condition may reflect the fact that children were less variable in their performance on this condition, which may reflect increased confidence in their decision when primed by a congruent letter.

Comparison of children's performance on the priming task in session 1 and 2 revealed that children were significantly slower to make a response during the second session, perhaps indicating decreased motivation. However, this difference was not significant for RTs in the baseline condition, which may reflect the increased novelty of the visual symbols in this condition. It is possible that children took longer to respond on the baseline condition during session 1 and subsequently in session 2 RTs did not increase significantly.

Furthermore, in light of the relatively poor reliability of the priming task, it is possible that the present analysis underestimates the contribution of baseline response time in children's reading ability.

3.4.4 Concluding remarks

The findings from this study indicate that children with approximately two years of reading experience demonstrate clear behavioural evidence of automatic letter-sound integration. However, contrary to Blomert’s novel hypothesis, the present results suggest that individual differences in the extent to which letters and speech-sounds are integrated do not appear to predict variance in reading skill.

Rather, performance on the baseline condition of the letter-sound priming task were predictive of children’s reading performance, which may provide additional support for the role of phonological processing skills in learning to read. The finding that baseline response times predicted variance in reading above and beyond established predictors of reading (including a measure of phoneme awareness) is intriguing and warrants further investigation.

Chapter 4 A behavioural study comparing performance on different measures of automatic letter-sound integration in typically developing children

4.1 Introduction

This chapter reports a behavioural study with typically developing children. In this study children completed two measures of automatic letter-sound integration: the letter-sound priming task as described in Chapter 3 and an additional letter-sound matching task. This matching task was designed to be comparable to the task used in previous studies (for example Blau et al., 2010; Žarić et al., 2014) and simply requires children to judge the congruency of letter speech-sound pairs (for example /d/ and <d> = "same").

Previous studies investigating behavioural performance on the letter-sound matching task have compared the reaction times of children with and without dyslexia when making this congruency judgement. For example, Blau et al. (2010) report that children with dyslexia took significantly longer to decide whether pairs of letters and speech-sounds were the same or different, when compared to an age-matched control group. The authors interpreted this finding as evidence for reduced integration of letters and speech-sounds in children with dyslexia. However, a subsequent replication by Žarić et al. (2014) found no group differences in reaction time using the same letter-sound matching task.

This study aimed to clarify these inconsistent results, using a letter-sound matching task to investigate whether the ability to judge the congruency of letter-sound pairs is associated with individual differences in reading ability. Previous studies have reasoned that children with increasingly automatic associations between letters and speech-sounds will be more sensitive to letter-sound congruency and therefore quicker to judge the congruency of letter-sound pairs. Following this logic, if a deficit in automatic letter-sound integration represents a proximal cause of dyslexia, it is expected that performance on the letter-sound matching task should correlate with reading ability in a typically developing sample (i.e. children who are slower in making their response will also have lower reading scores). However, the study reported in the previous chapter found that while children demonstrated evidence of letter-sound integration, individual differences in this skill were not significantly correlated with reading ability. It is therefore of interest to measure performance using an alternative paradigm in order to confirm this finding and investigate whether the two different tasks are measuring the same skill.

In addition, this study measured performance on two versions of the letter-sound matching task: one version where the letter and speech-sound were presented simultaneously and the second where there was a 500ms delay between the letter and speech-sound. Previous research has shown the importance of temporal proximity for cross-modal integration of letters and speech-sounds. For example, evidence from EEG studies suggests that automatic integration occurs only during simultaneous presentation for adult readers, whereas for younger readers aged 11 years, automatic integration occurs only after a longer interval between the two stimuli (Froyen et al., 2009; Froyen et al., 2008). Given the young age of the children in the present study, it is predicted that children will take longer to judge the congruency of the letter-sound pairs when they are presented simultaneously, compared to when there is a 500ms delay.

While performance on the letter-sound priming task provides evidence to suggest that children were automatically integrating letters and their corresponding speech-sounds, performance on the matching task is more difficult to interpret. Studies investigating the neural integration of letters and speech-sounds have typically used what is known as the ‘congruency effect’ as a measure automatic letter-sound integration. This congruency effect is determined by comparing activation during the presentation of congruent letters and speech-sounds versus the presentation of incongruent letters and speech-sounds. The logic behind this comparison is that reliable differences in activation between congruent and incongruent conditions would not be expected unless the auditory and visual information had been successfully integrated (McNorgan, Randazzo-Wagner, & Booth, 2013; van Atteveldt et al., 2007). Previous studies have reported a significant difference in activation between congruent and incongruent conditions for typical readers but not for those with dyslexia (Blau et al., 2010; Blau et al., 2009). This finding has been interpreted as evidence for a deficit in automatic letter-sound integration in children with dyslexia.

However, it is not particularly informative to make the same comparison between congruent and incongruent conditions using behavioural data. For example, there is evidence for ‘same-different disparity’ (Chen & Proctor, 2012) whereby participants are reliably faster in making a same-judgment compared to a different-judgment (see Farell, 1985 for a review). Furthermore, from a theoretical viewpoint, it is likely that children who have formed automatic and efficient associations between letters and speech-sounds would be equally advantaged in determining whether pairs match or do not match, as both conditions require efficient use of this knowledge. It is therefore predicted that, as a group, children will be significantly faster to decide that the letter and speech-sound are the same compared to when they are different.

In summary, the main focus of the present study was to investigate children’s performance on the letter-sound matching task and to evaluate the usefulness of this paradigm as a measure of letter-sound integration. The present study aimed to answer the following questions:

1. Are children quicker to identify congruent letter speech-sound pairs than incongruent letter speech-sound pairs?
2. Does the temporal proximity of letters and speech-sounds influence children’s ability to judge the congruency of letters and speech-sounds?
3. Does performance on a letter-sound matching task correlate with individual differences in reading ability in typically developing children aged between 6 and 7 years?
4. Does performance on the letter-sound matching task correlate with performance on the letter-sound priming task, and therefore provide evidence that the two tasks are measuring the same skill?

4.2 Method

4.2.1 Participants

Forty-nine children (24 male, 25 female) with a mean age of 7 years (range = 20.45 months) from schools in North Yorkshire and Greater London participated in this experiment. All children whose native language was not English were fluent in both spoken and written English. Children were unselected for reading ability. Parents gave written consent and the children were given a sticker for their participation. The University College London Ethics Committee granted ethical approval for this study.

4.2.2 Design and materials

Letter-sound integration measures

Children in this study completed the letter-sound priming task, as described in Chapter 3. Children also completed a matching task that involved the presentation of letter-sound pairs, which were either congruent or incongruent. Children were required to decide whether the letter and speech-sound were the same (congruent). There were two versions of the matching task; 0ms stimulus onset asynchrony (SOA) where the letter and speech-sound were presented simultaneously and 500ms SOA where the letter was presented prior to the sound for 500ms.

Stimuli. Stimuli in this task were the same as those used in Chapter 3; the phonemes /tə/ (293ms), /də/ (263ms), /və/ (428ms), /zə/ (413ms) and /dʒə/ (357ms) and the corresponding lower case letters presented in Ariel (pixel size 90 x 80).

Apparatus. As before, stimuli were presented and responses recorded (speed and accuracy) using E-Prime Software (version 2.0) and a Psychology Software Tools Serial Response Box (SRB; model 200a) with a Dell laptop (Latitude E5520) running Windows 7. Auditory stimuli were presented through Beyer Dynamic headphones (DT 770).

Design. In the 0ms SOA matching task, a centrally located fixation point was presented for 1000ms followed by the simultaneous presentation of a visually presented letter and auditory speech-sound. The letter was presented in black on a white screen and the auditory speech-sound was presented over headphones. The letter remained on the screen until a response was made. Children were instructed to decide whether the letter and the speech-sound were the same using “YES” and “NO” response keys.

In the 500ms SOA version of the task, a centrally located fixation point was presented for 1000ms followed by the presentation of the letter, presented in black and appearing on the white screen for 500ms. The auditory target was then presented over headphones. The letter remained on the screen until a response was made. Children were instructed to decide whether the letter and the speech-sound were the same using “YES” and “NO” response keys. The experimenter monitored the child’s performance during this task, controlling the presentation of trials.

There were 2 conditions. In the congruent condition, the letter and speech-sound were the same letter/sound. In the unrelated (incongruent) condition, the letter and speech-sound were not the same letter/sound. There were 20 trials for each condition. The congruent condition included 4 trials of each pairing, in the incongruent condition each letter prime was presented once and paired with all of the other speech-sounds.

The order of trials within each task was randomized and the order of the two matching tasks (0ms and 500ms SOA) was counterbalanced. Each version of the matching task took approximately 3 minutes to complete and children were allowed to pause the experiment and take a short break at any time. Figure 4.1 displays the structure of a trial.

Literacy Related Measures

Children completed all of the literacy measures, as described in Chapter 3.

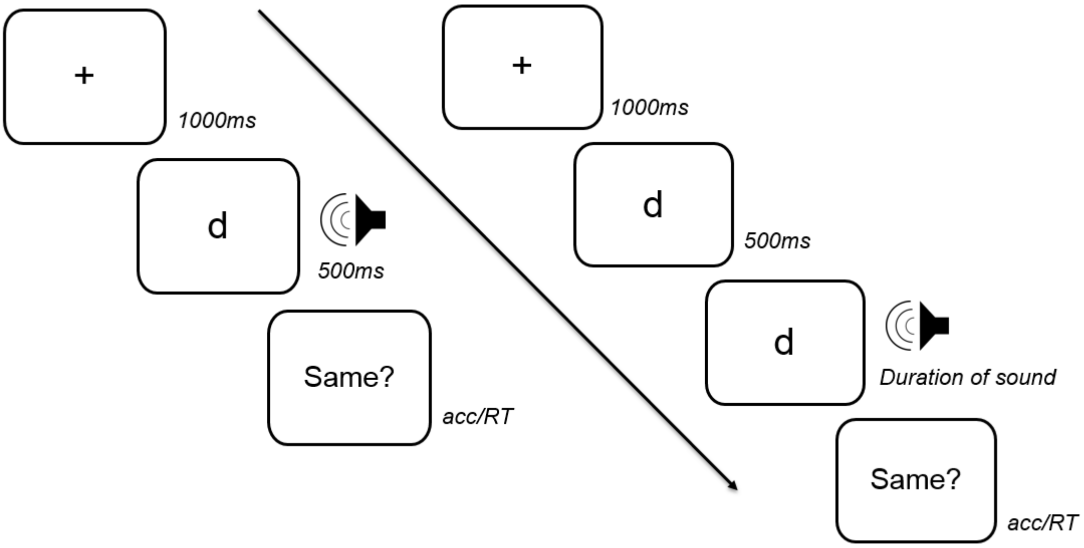


Figure 4.1 The structure of a letter-sound matching trial with 0ms SOA (left) and 500ms SOA (right)

4.3 Results

Means and standard deviations for measures of reading related skills and performance on the letter-sound matching and priming tasks are presented in Table 4.1 and Table 4.2. A reading composite score was calculated by summing z-scores for timed and untimed measures of word and non-word reading as these scores were highly correlated.

Raw scores on the letter-sound knowledge test were at ceiling (60% of children achieved the maximum score) and so this measure was excluded from subsequent regression analyses. Furthermore, measures of RAN and congruent response times were not normally distributed and so were transformed by examining the results of transformations from Tukey's ladder of powers (using the "ladder" command in Stata v 13.0). Congruent average response times and RAN object scores were transformed using inverse root transformation, and RAN letters and digits were transformed using an inverse transformation. However, analyses of untransformed data yielded essentially identical patterns of results (correlations using transformed data are included in appendix 2 and 3).

Table 4.1 Performance on both versions of the letter-sound matching task and the letter-sound priming task (N=48)

	Mean (SD)	Min.	Max.
0ms SOA Matching Task			
Congruent accuracy (/20)	18.90 (1.19)	15	20
Incongruent accuracy (/20)	18.27 (1.45)	15	20
Congruent average RT (ms)	1550.31 (441.96)	724.47	2569.83
Incongruent average RT (ms)	1689.18 (455.62)	784.95	2948.56
500ms SOA Matching Task			
Congruent accuracy (/20)	18.90 (1.36)	14	20
Incongruent accuracy (/20)	18.35 (1.68)	13	20
Congruent average RT (ms)	1376.06 (394.14)	584.42	2210.55
Incongruent average RT (ms)	1549.53 (429.36)	657.85	2383.33
Priming Task (N=46)			
Baseline accuracy (/20)	19.35 (1.25)	14	20
Congruent accuracy (/20)	19.17 (0.97)	16	20
Incongruent accuracy (/20)	19.33 (0.94)	17	20
Baseline average RT (ms)	1085.78 (238.11)	763.79	1668.11
Congruent average RT (ms)	1041.77 (266.78)	684.63	2028.33
Incongruent average RT (ms)	1101.74 (228.95)	732.63	1655.05

Table 4.2 Descriptive statistics for performance on literacy-related measures

Measure	N	Mean (SD)	Min.	Max.
Age (months)	49	84.27 (5.15)	72	92
LSK raw score /32	48	31.42 (0.82)	29	32
LSK standard score		110.98 (7.89)	91	120
SWRT raw score /60	48	33.19 (9.04)	14	47
SWRT standard score		113.06 (11.78)	88	132
TOWRE SWE raw score /104	48	54.38 (14.85)	16	78
TOWRE SWE standard score		119.10 (12.94)	92	145
TOWRE PDE raw score /63	48	28.69 (11.83)	5	48
TOWRE PDE standard score		118.00 (12.51)	95	140
RAN Digits total time (s)	48	43.56 (10.98)	27	85
RAN Digits standard score		11.19 (1.85)	6	15
RAN Letters total time (s)	34	57.03 (18.90)	34	127
RAN Letters standard score		10.09 (1.82)	5	14
RAN Objects total time (s)	47	78.45 (15.05)	52	127
RAN Objects standard score		10.70 (2.41)	4	16
Phoneme Deletion raw score /24	48	17.04 (4.35)	5	24
Phoneme Deletion standard score		111.29 (10.67)	86	129
RAN Objects No Repetition (s)	20	47.95 (10.62)	29	75
Reading composite	48	-.02 (2.51)	-6	4

Table 4.3 Percentage RT data excluded for each experimental condition for each version of the letter-sound matching task

	Response error (%)	**Outliers (%)**
0ms SOA		
Congruent	2.25	1.85
Incongruent	4.20	2.00
Total	6.45	3.85
500ms SOA		
Congruent	2.45	1.25
Incongruent	2.92	2.45
Total	5.37	3.70

4.3.1 Effect of congruency

Before analyses were conducted, outliers were removed from the raw reaction time (RT) data. Only correct responses were included in the analysis. Responses that were over 5000ms were first removed as this was considered to reflect a lapse in attention rather than accurate performance on the task. A non-recursive outlier removal procedure was then used, as recommended by Selst and Jolicoeur (1994). Reaction time data from one participant was excluded from the analysis due to missing data. The percentage of reaction time (RT) data that was excluded, as both response errors and outliers, for both versions of the matching task, is shown in Table 4.3. As shown in the table, approximately 90% of the possible RT data were available for analysis for each version of the letter-sound matching task.

The mean correct response times in each condition of both versions of the letter-sound matching experiment, together with 95% within-subject confidence intervals (Morey, 2008) are shown in Figure 4.2. The data show that children were quicker in the congruent compared to the incongruent condition in both versions of the task. To assess the reliability of these differences, response times for the congruent and incongruent condition in the two versions of the task were compared using mixed effects linear regression models, treating participants and items as crossed random effects (xtmixed in Stata 13.1) in order to account for variability across participants and target items. Whilst there are a small number of levels of target item to be treated as a random effect, comparison of models with target items as fixed and as random effects were found to be almost identical.

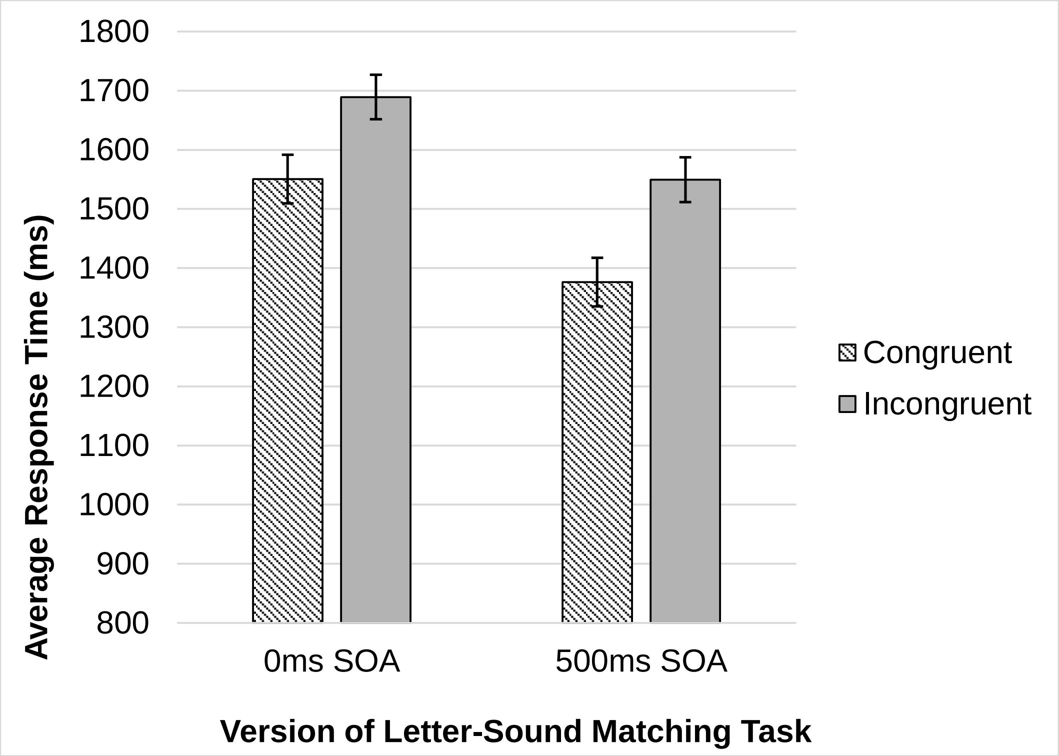


Figure 4.2 Average response times (and 95% CIs) for each condition of the letter-sound matching task (N=48)

The first model predicted participant’s target response times on the 0ms SOA version of the task as a function of experimental condition, using dummy coded variables (congruent vs. incongruent (0, 1). Results showed that the difference in target response time between the congruent and incongruent condition was significant (estimated difference = 137.15, z = 5.09, 95% confidence interval = [84.38, 189.91], p < .001). The effect size of this difference (ignoring participant and item variability) is d = -.31.

The second model predicted target response times on the 500ms SOA version of the task. This model showed that the difference between response times in the congruent and incongruent condition was also significant (estimated difference = 176.14, z = 5.92, 95% confidence interval = [117.81, 234.48], p < .001). The effect size of this difference (ignoring participant and item variability) is d = -.42.

4.3.2 Effect of SOA

The data in Figure 4.2 suggest that children are slower in the 0ms SOA version of the task compared to the 500ms SOA version. Analyses were therefore conducted to determine whether children's response times in the two conditions differed across the 0ms SOA and 500ms SOA version of the task.

A mixed effects regression model predicting children's target response times as a function of experimental condition and SOA duration revealed significant effects of SOA duration upon response times. Children's response times in the congruent condition of the 0ms SOA experiment were significantly slower compared to those in the 500ms SOA experiment (estimated difference = -178.45, z = -6.19, 95% confidence interval = [-234.91, -121.99], p < .001). This difference was also significant for response times in the incongruent condition which again were slower in the 0ms SOA experiment compared to those in the 500ms SOA experiment (estimated difference = -140.93, z = -4.81, 95% confidence interval = [-198.35, -83.51], p < .001).

However, the interaction between experimental condition and SOA duration was not significant, indicating that the size of the difference between the two conditions (as identified in prior analyses) does not differ across the two matching experiments.

4.3.3 Relationship with reading

Average response times in the congruent condition were used to investigate the relationship between letter-sound integration and reading. Table 4.4 shows the simple correlations among reading measures and age. As expected, the different measures of reading-related skills were significantly correlated, with the exception of letter-sound knowledge (where scores were at ceiling). In this smaller sample, age was not significantly correlated with the reading measures (with the exception of phoneme deletion which was weakly correlated with age r = .32, p = .0280).

Table 4.5 shows the simple correlations among the various RAN tasks and performance on the letter-sound matching tasks, partial correlations controlling for age are shown below the diagonal. The subsequent analysis will focus on these partial correlations.

As shown in Table 4.5, response times on both versions of the matching task were significantly correlated with performance on measures of rapid digit and letter naming, with the exception of response times in the congruent condition of the 0ms SOA matching task and digit naming (r = .29, p = .0510). Correlations between response times in the matching task and rapid object naming were not significant.

Table 4.6 shows the simple and partial correlations among reading and performance on the letter-sound matching tasks. As shown in the table, response times on both versions of the matching task were significantly correlated with children’s composite reading scores (r between-.34 and -.42, p between .0051 and .0425).

However, correlations between the individual reading subtests and performance on the matching task were not all significant. Correlations between response times in the congruent condition of the matching task and performance on the SWRT were not significant (r = -.23 and -.26, p = .1213 and .0772 for the 0ms and 500ms SOA version of the task). The correlation between performance on the 500ms SOA congruent condition and TOWRE-SWE was significant (r = -.30, p = .0410), however the correlation with performance on the 0ms SOA congruent condition was not. Furthermore, correlations between response times in the matching task and performance on the phoneme deletion task were not significant.

4.3.4 Comparing different measures of integration

Analyses were conducted to explore the relationship between the two different measures of letter-sound integration. As shown in Table 4.7, average response times on conditions of the two tasks were all significantly correlated (r's between .54 and 84, all p < .0001). However, measures of integration (facilitation and interference) were not significantly correlated with performance on the congruent (or incongruent) condition of the matching tasks.

Table 4.4 Simple correlations between age and performance on literacy tasks

	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Age	.09 48	.22 48	.12 48	.09 48	.04 48	-.14 34	-.11 47	.32* 48	.20 48
2. LSK		.21 48	.19 48	.23 48	-.17 48	.20 34	.00 47	.29* 48	.22 48
3. SWRT			.89*** 48	.87*** 48	-.58*** 48	-.71*** 34	-.32* 47	.73*** 48	.96*** 48
4. TOWRE SWE				.90*** 48	-.71*** 48	-.80*** 34	-.42** 47	.61*** 48	.97*** 48
5. TOWRE PDE					-.71*** 48	-.71*** 34	-.32* 47	.62*** 48	.94*** 48
6. RAN Digits						.62*** 34	.62*** 47	-.33* 48	-.69*** 48
7. RAN Letters							.33 33	-.46** 34	-.79*** 34
8. RAN Object								-.37** 47	-.38** 47
9. Phoneme Deletion									.69*** 48
10. Reading composite score									

*Note: *** = p <.001, ** = p <.01, * = p <.05. N for each correlation reported beneath coefficient.*

Table 4.5 Simple and partial correlations between measures of RAN and performance on the letter-sound matching task.

	1.	2.	3.	4.	5.	6.	7.
1. RAN Digits		.62*** 34	.62*** 46	.28 47	-.25 47	.38** 47	.34* 47
2. RAN Letters	.63*** 34		.33 33	.55*** 34	-.14 34	.47** 34	.54*** 34
3. RAN Objects	.62*** 46	.31 33		.14 46	-.30* 46	.12 46	.11 46
4. 0MS Congruent Ave RT	.29 47	.54** 34	.11 46		.06 48	.71*** 48	.73*** 48
5. 0MS Incongruent Ave RT	.37* 47	.63*** 34	.11 46	.80*** 48		.08 48	-.07 48
6. 500MS Congruent Ave RT	.40** 47	.45** 34	.09 46	.69*** 48	.60*** 48		.80*** 48
7. 500MS Incongruent Ave RT	.34* 47	.54** 34	.10 46	.74*** 48	.63*** 48	.82*** 48	

Note: *** = p <.001, ** = p <.01, * = p <.05. Simple correlations above the diagonal and partial correlations controlling for age below the diagonal. N for each correlation reported beneath coefficient

Table 4.6 Simple and partial correlations between measures of reading and performance on the letter-sound matching task.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. SWRT		.89*** 47	.87*** 47	.96*** 47	.73*** 47	-.27 45	-.35* 47	-.31* 47	-.34* 47
2. TOWRE-SWE	.89*** 47		.90*** 47	.97*** 47	.61*** 47	-.28 47	-.41** 47	-.32* 47	-.38** 47
3. TOWRE-PDE	.87*** 47	.90*** 47		.94** 47	.63*** 47	-.35* 47	-.43** 47	-.40** 47	-.41** 47
4. Reading composite	.96*** 47	.97*** 47	.94*** 47		.69*** 47	-.34* 47	-.42** 47	-.38** 47	-.40** 47
5. Phoneme Deletion	.71*** 47	.60*** 47	.63*** 47	.67*** 47		-.15 47	-.19 47	-.18 47	-.12 47
6. 0MS Congruent Ave RT	-.23 47	-.26 47	-.34* 47	-.30* 47	-.08 47		.06 48	.71*** 48	.73*** 48
7. 0MS Incongruent Ave RT	-.32* 47	-.39** 47	-.42** 47	-.41** 47	-.16 47	.80*** 48		.08 48	-.07 48
8. 500MS Congruent Ave RT	-.26 47	-.30* 47	-.39** 47	-.34* 47	-.11 47	.69*** 48	.60*** 48		.80*** 48
9. 500MS Incongruent Ave RT	-.34* 47	-.37* 47	-.40** 47	-.40** 47	-.11 47	.74*** 48	.63*** 48	.82*** 48	

*Note: *** = p <.001, ** = p <.01, * = p <.05. Simple correlations above the diagonal and partial correlations controlling for age below the diagonal. N for each correlation reported beneath coefficient.*

Table 4.7 Simple correlations between different measures of letter-sound integration

	2.	3.	4.	5.	6.	7.	8.	9.
1. Priming: Facilitation	.34*	-.12	.46**	.07	-.07	.06	-.08	-.13
2. Priming: Interference		-.34*	-.11	.21	-.20	-.03	-.18	-.20
3. Priming: Baseline Ave RT			.83***	.84***	.66***	.57***	.71***	.62***
4. Priming: Congruent Ave RT				.80***	.55***	.54**	.59**	.48***
5. Priming: Incongruent Ave RT					.57***	.57***	.64***	.54***
6. Matching: Congruent 0ms SOA Ave RT						.80***	.71***	.73***
7. Matching: Incongruent 0ms SOA Ave RT							.61***	.63***
8. Matching: Congruent 500ms SOA Ave RT								.80***
9. Matching: Incongruent 500ms SOA Ave RT								

*Note: *** = p <.001, ** = p <.01, * = p <.05. N = 46*

4.4 Discussion

This study investigated children's performance on a letter-sound matching task to evaluate the utility of this paradigm as a measure of automatic letter-sound integration. In line with initial predictions, the results suggest that children with approximately two years of reading experience are quicker to identify congruent versus incongruent letter-sound pairs and take longer to make congruency judgements when auditory and visual stimuli are presented simultaneously. In addition, individual differences in the speed at which children are able to judge the congruency of letter-sound pairs appears to be associated with differences in children's reading ability.

4.4.1 Congruency and temporal proximity of letter speech-sound pairs

Results from the letter-sound matching task suggest that children were quicker to identify that the letter and speech-sound were the same than to identify that the pair were different. This was true for both the 0ms and 500ms SOA version of the task. There was no significant interaction between condition and SOA indicating that differences in RT between congruent and incongruent conditions did not differ significantly across the two versions of the matching task.

This congruency effect is likely to reflect the facilitating effect of responding to congruent information (i.e. making a 'same' judgment), a phenomenon that has been widely reported in experimental research (e.g. Bamber, 1969; Farell, 1985; Posner & Snyder, 2004). One account of this phenomenon is that when a stimulus is presented, pathways in the nervous system become activated, therefore when stimuli are congruent; the same pathway is activated resulting in a faster response (Posner & Snyder, 2004). The significant congruency effect in the present study could therefore be interpreted as tentative evidence of shared pathways between corresponding letters and speech-sounds. However, according to dual-process accounts, there are separate processes involved in making same and different judgements (Farell, 1985) and as such it is challenging to interpret the difference between conditions.

In addition to significant congruency effects, the results from this study show that children were significantly slower on the 0ms SOA version of the task compared to the 500ms SOA version. Longer reaction times in the 0ms SOA version of the task suggests that children found it more challenging to judge the congruency of letter-sound pairs when presented simultaneously, compared to when presented separately (in close succession). However, children were still able to make this decision with relative ease, as indicated by the high levels of accuracy on both versions of the task.

It is possible that differences in reaction time between the two versions of the task may reflect differences in the optimal time window for letter-sound integration. Previous studies investigating the time course of letter-sound integration have reported that the cross-modal MMN (interpreted as evidence of letter-sound integration) is only present in younger children when letters and speech-sounds are presented asynchronously (200ms apart) (Froyen et al., 2009). However, given that the letter-sound matching task requires children to actively reflect on the relationship between the two inputs, it is perhaps more likely that this difference reflects the increased demand on working memory (and phonological processing) when information is presented simultaneously.

4.4.2 The relationship between performance on the letter-sound matching task and children’s reading skill

Average response times on both versions of the letter-sound matching task were significantly correlated with children’s naming speed for digits and letters. This finding indicates that children who are quick to judge the congruency of letter-sound pairs are also quick to name a series of letters and digits. Children’s naming speed for objects was not significantly correlated with performance on the letter-sound matching task.

In addition, average response times were significantly correlated with children’s reading composite scores. This suggests that children who were quick to decide if the letter and speech-sound were congruent were better readers. In contrast, children’s phoneme deletion scores were not significantly correlated with performance on the matching task.

It therefore appears that performance on the letter-sound matching task correlates with individual differences in reading ability (and naming speed) in typically developing children aged between 6 and 7 years. However, given the absence of a baseline condition in this task it is difficult to interpret this relationship. For example, performance on the letter-sound matching task may reflect underlying differences in the processing of the visual letter, the auditory speech-sound or indeed the relationship between the two stimuli. Furthermore, it is not possible to rule out the more domain-general influence of reaction time or processing speed. Without a baseline condition to control for the various demands of the task, it is not possible to conclude that performance reflects variation in automatic letter-sound integration. As a result it is not clear why performance on the task is associated with children’s reading ability. This is also true of previous studies. For example, group differences in reaction time on the letter-sound matching task reported by Blau et al. (2009) may have reflected impaired phonological processing skills in children with dyslexia, rather than a deficit in automatic letter-sound integration.

4.4.3 Comparing the two measures of letter-sound integration

Average response times for the letter-sound matching and priming tasks were significantly correlated, indicating that children who were quick to judge the congruency of letter-sound pairs were also quick to identify whether the auditory target was a speech-sound. This suggests that the tasks have a shared component, however this relationship may simply reflect the speeded response or the speech processing demands common to both tasks.

In contrast, measures of facilitation and interference from the priming task were not significantly correlated with average response times on the letter-sound matching task. Facilitation and interference scores provide a specific index of automatic integration as these scores control for children’s baseline performance on the letter-sound priming task (the time taken to respond to the auditory target). Whereas the letter-sound matching task involves a number of different processes, measures of facilitation and interference are reliable indicators of the relationship between the letter-prime and speech-sound (as all other aspects of the task are kept constant). Therefore, the absence of a relationship between these measures suggests that performance on the letter-sound matching task is not measuring the same construct and therefore is unlikely to measure letter-sound integration.

4.4.4 Concluding remarks

The findings from this study indicate that individual differences in the speed at which children are able to judge the congruency of letter-sound pairs is associated with differences in children's reading ability. However, without a baseline condition it is not possible to conclude that performance on the letter-sound matching task reflects variation in automatic letter-sound integration. Performance on the letter-sound matching task does not, therefore, provide a useful measure of automatic letter-sound integration.

Average response times for the letter-sound matching and priming tasks were significantly correlated and were also both associated with children's reading performance. It is therefore possible that a shared component of these tasks may relate to children's reading performance.

Chapter 5 Automatic integration of letters and speech-sounds in children with dyslexia

5.1 Introduction

The primary aim of this study was to investigate whether children with dyslexia show evidence of automatic letter-sound integration using a priming task. A secondary aim was to explore whether measures of automatic letter-sound integration are associated with individual differences in reading ability in a reading impaired group.

As discussed earlier, previous research has claimed that children with dyslexia display evidence of deficient letter-sound integration when compared to typically developing children of a similar age (Blau et al., 2010; Froyen et al., 2011; Žarić et al., 2014). This has led to the novel hypothesis that a deficit in automatic letter-sound integration reflects a proximal cause of reading failure (Blomert, 2011). While the focus of previous research has been on the neural integration of letters and speech-sounds, studies have also reported group differences on behavioural measures of letter-sound integration. For instance, Blau et al. (2010) found that children with dyslexia were significantly slower to decide whether letter-speech-sound pairs were congruent or incongruent compared to an age-matched control group. However a subsequent study failed to replicate this finding using the same letter-sound identification task (Žarić et al., 2014). Instead, Žarić et al. (2014) report group differences using a letter-sound matching task, whereby children with dyslexia were slower to match a speech-sound to one of four visually presented letters, when compared to age-matched controls.

The results from these studies have been interpreted as evidence of impaired letter-sound integration in children with dyslexia. However, the absence of a baseline condition in these tasks does not rule out the possibility that the dyslexic group were overall slower, perhaps due to the phonological processing demands of the tasks. In addition, the authors have argued that a deficit in automatic letter-sound integration reflects a proximal cause of dyslexia. However, without comparing the performance of typically developing children equated for reading ability, it is not possible to conclude whether impaired performance on these tasks is specifically associated with reading difficulties in children with dyslexia or whether difficulties arise from the dyslexic groups' reduced reading experience.

A recent study by Nash et al. (submitted) addressed these issues by comparing the performance of children with dyslexia to a chronological age (CA) matched control group and a reading age (RA) matched group. Children in this study completed a behavioural priming task designed to measure automatic letter-sound integration. This task was similar to the task used in the present research, and involved the presentation of a visual letter prime followed by an auditory speech-sound target. The prime and target were either the same letter (congruent condition) or different (baseline condition). In the baseline condition, the visual prime was a Greek letter, which for this English-speaking group of children would presumably have no associated speech-sound. Contrary to Blomert's hypothesis, this study reported behavioural evidence of automatic letter-sound integration in all three groups. Thus, even for children with dyslexia, the presentation of a visual letter facilitated processing of the corresponding speech-sound.

The study reported in Chapter 3 showed that typically developing children with approximately two years of reading experience demonstrate clear evidence of automatic letter-sound integration. In this typically developing group, the presentation of a visual letter led to rapid and automatic activation of its corresponding speech-sound. However, individual differences in the extent to which letters and speech-sounds were integrated were not found to predict variance in reading skill. This study involved a large sample of children with a wide range of reading ability. The logic behind this is that if dyslexia represents the lower end of a continuous distribution of reading ability, then individual differences in this large sample should be great enough to detect a relationship between letter-sound integration and reading, if one exists. For example, there is evidence that phoneme awareness is an important predictor of reading achievement in typically developing children (Lervåg et al., 2009) and also that this skill is impaired in children with dyslexia (Wagner & Torgesen, 1987).

Given that the study reported in Chapter 3 did not find evidence of a relationship between automatic letter-sound integration and reading it is difficult to predict whether children with dyslexia will show evidence of letter-sound integration. While it is possible that a deficit in letter-sound integration might reflect a specific abnormality in children with dyslexia, it is generally accepted that dyslexia is a continuous, rather than categorical disorder (Peterson & Pennington, 2015; Vellutino et al., 2004). Therefore, the absence of a relationship with reading ability in previous chapters might suggest that children with dyslexia will also demonstrate evidence of letter-sound integration. It is therefore important to determine whether automatic letter-sound integration is present in children with dyslexia and if so, whether this skill is associated with individual differences in reading ability. A tentative prediction is that children with dyslexia will show behavioural evidence of automatic letter-sound integration that is comparable to that seen in typically developing children matched for reading ability.

In summary, this study aimed to address the following questions:

1) Do children with poor reading skills (dyslexia) show evidence of automatic letter-sound integration?
2) Does the extent of reading difficulty correlate with individual differences in letter-sound integration?

5.2 Method

5.2.1 Participants

Twenty-four children with dyslexia (11 male, 13 female) with a mean age of 9 years 6 months (range = 36.86 months) participated in the experiment. Children were recruited from specialist primary schools for children with dyslexia and/or specific learning difficulties in North London and Surrey. Twenty-one children in this group had received a formal diagnosis of dyslexia from an Educational Psychologist and all of the children had reading and/or spelling standard scores 1.5 SD below average.

A typically developing control group was selected from the sample described in Chapter 3. Children that matched the dyslexic participants on both gender and reading age were selected. Data from seventy-eight typically developing children (45 male, 33 female) were used in the analyses; this group had a mean age of 6 years 6 months (range = 25.56 months)

Children whose native language was not English were fluent in both spoken and written English. Written consent for children to participate in the experiment was obtained from parents and the children were given a sticker for their participation. The University College London Ethics Committee gave ethical approval for this study.

5.2.2 Design and materials

Letter-sound integration measure

The measure of letter-sound integration was the same priming task as described in Chapter 3. This task involved the successive presentation of a prime and a target. The prime was a visually presented letter; followed by a target which was a spoken phoneme presented over headphones. Children were required to decide on each trial whether the second stimulus (the ‘target’) was a ‘real’ speech-sound or not. Children were familiarised with the stimuli and task in an initial learning trial.

Stimuli. As before, stimuli in the task were the phonemes /tə/ (293ms), /də/ (263ms), /və/ (428ms), /zə/ (413ms) and /dʒə/ (357ms) recorded by a female native English speaker in a sound attenuated booth and the corresponding lower case letters presented in Ariel (pixel size 90 x 80). The same novel letters (adapted from Taylor et al., 2011) and scrambled phonemes (nonverbal /zə/(413ms), nonverbal /də/(262ms), nonverbal /dʒə/(357ms), nonverbal /tə/(292ms) and nonverbal /və/(428ms)) served as non-letter stimuli.

Apparatus. Stimuli were presented and responses recorded (speed and accuracy) using E-Prime Software (version 2.0) and a Psychology Software

Tools Serial Response Box (SRB; model 200a) with a Dell laptop (Latitude E5520) running Windows 7. Auditory stimuli were presented through Beyer Dynamic headphones (DT 770).

Design. In this task a letter prime was presented prior to an auditory phoneme target. A centrally located fixation point was presented for 1000ms followed by the presentation of the letter or non-letter stimulus, presented in black and appearing on the white screen for 500ms. The auditory target was then presented over headphones. Each trial was followed by the visual prompt “Real sound?” Children were instructed to attend to both the letter and auditory speech-sound and decide whether the sound was a ‘real’ speech-sound using “YES” and “NO” response keys. The experimenter monitored the child’s performance, controlling the presentation of trials.

As before, there were 6 conditions. In the congruent condition, the prime and target were the same letter/sound. In the unrelated (or incongruent) condition the prime and target were not the same letter/sound. In the baseline condition, the prime and target were not the same; the prime was a novel letter and the target was a real speech-sound. In addition, 3 control conditions were included to prevent participants detecting the relationship between primes and targets and generating expectancies about the up-coming target. As in the original design, scrambled phonemes were used as auditory targets in the control conditions.

There were 20 trials for each condition and each condition included 4 trials of each pairing, apart from the incongruent condition where each letter prime was presented once and paired with all of the other speech-sounds. There were 135 trials in total, including 15 ‘catch’ trials to ensure children were paying attention to the screen. The order of trials was randomized. As before, the task took approximately 10 minutes to complete and children were allowed to pause the experiment and take a short break at any time.

Literacy related measures

Reading. Children in the dyslexic group completed the Word Reading subtest from the Wechsler Individual Achievement Test II (WIAT II; Wechsler, 2005) where they were asked to read aloud a list of words that became increasingly difficult. As part of this assessment children are tested on their phonological awareness (e.g. rhyme generation and phoneme identification) and decoding skills (e.g. naming letters and single word reading). Testing was discontinued after 7 consecutive errors or refusals.

Spelling. Children in the dyslexic group also completed the Spelling subtest from the WIAT II where they were asked to spell a list of words decreasing in frequency and increasing in length. As with the Word Reading subtest, the Spelling subtest began by measuring early spelling ability, requiring the children to spell their name and individual letters. Testing was discontinued after 6 consecutive scores of 0.

At one of the specialist schools, tests from the WIAT II were administered by trained teachers and teaching assistants at the beginning of the school year in order to monitor children’s literacy progress. This study took place less than a month after these tests were administered. Parents gave informed consent that these scores could be shared with researchers as part of the study.

Existing data from the cross-sectional study provided a means of matching typically developing children based on their reading ability. Scores from the Single Word Reading Test were used (SWRT 6-16; Foster, 2007). As described in Chapter 3, children were asked to read aloud a list of words that became increasingly difficult. Testing was discontinued after 5 consecutive scores of 0.

5.3 Results

Means and standard deviations describing the two groups’ performance on literacy measures and the letter-sound priming task are presented in Table 5.1 and Table 5.2.

5.3.1 Effects of priming in the letter-sound integration task

Before analyses were conducted, outliers were removed from the raw RT data. Only correct responses were included in the analysis. Responses that were over 5000ms were first removed as this was considered to reflect a lapse in attention rather than accurate performance on the task. A non-recursive outlier removal procedure was then used, as recommended by Selst and Jolicoeur (1994). The percentage of RT data that was excluded for each group, as both response errors and outliers, is shown in Table 5.3. For each group over 90% of the possible RT data were available for analysis.

Means and standard deviations describing the two groups' performance on the letter-sound priming task are presented in Table 5.2. The mean correct response times for each group in each condition of the letter-sound priming task, together with 95% within-subject confidence intervals (Morey, 2008) are shown in Figure 5.1. In both groups the data show substantial facilitation in the congruent priming condition and a very small degree of interference in the incongruent condition compared to the baseline condition. To assess the reliability of these differences, response times for the baseline, congruent and incongruent condition were compared using a mixed effects linear regression model treating participants and items as crossed random effects (xtmixed in Stata 13.1) in order to account for variability across participants and target items. Whilst there are a small number of levels of target item to be treated as a random effect, comparison of models with target items as fixed and as random effects were found to be almost identical.

The two models predicted participant's target response times as a function of experimental condition, using two dummy coded variables (baseline vs. congruent (0, 1) and baseline vs. incongruent (0, 1)). Results for the dyslexic group showed that the difference in target response time between the baseline and congruent condition was significant (estimated difference = -142.55, z = -4.40, 95% confidence interval = [-206.01, -79.09], p < .001). The effect size of this difference (ignoring participant and item variability) is d =.40. However, the difference between response times in the baseline and incongruent condition was not significant (estimated difference = 26.24, z = 0.81, 95% confidence interval = [-36.95, 89.42], p =. 416). The effect size here (ignoring participant and item variability) is d = -.10.

Table 5.1 Characteristics of the dyslexic and typically developing groups

	Mean (SD)	**Minimum**	**Maximum**
Dyslexic group (N=24)			
Age (months)	115.23 (11.47)	95.84	132.70
WIAT II Reading (raw score /131)	89.08 (13.00)	57	112
WIAT II Reading (standard score)	87.79 (10.21)	68	107
WIAT II Spelling (raw score /53)	19.57 (3.76)	13	26
WIAT II Spelling (standard score)	75.92 (6.06)	57	85
TD matched group (N=78)			
Age (months)	78.90 (6.72)	65.71	91.27
SWRT (raw score /60)	28.86 (8.21)	12	48
SWRT (standard score)	114.10 (9.52)	90	133

Results for the typically developing group followed the same pattern; the difference in target response time between the baseline and congruent condition was significant (estimated difference = -110.29, z = -7.13, 95% confidence interval = [-140.59, -79.99], p < .001). The effect size of this difference (ignoring participant and item variability) is d =.36. The difference between response times in the baseline and incongruent condition was not significant (estimated difference = -10.89, z = -.71, 95% confidence interval = [-41.15, 19.37], p =.481). The effect size here (ignoring participant and item variability) is d =.02.

Table 5.2 Summary statistics of performance for each group on letter-sound priming task

	Dyslexic group (N=24)			**TD Matched group (N=78)**		
	Mean (SD)	**Min.**	**Max.**	**Mean (SD)**	**Min.**	**Max.**
Baseline accuracy (/20)	18.96 (1.16)	16	20	19.04 (1.59)	10	20
Congruent accuracy (/20)	19.21 (.88)	17	20	19.09 (1.01)	16	20
Incongruent accuracy (/20)	19.21 (1.10)	16	20	19.13 (1.41)	12	20
Baseline RT (ms)	1178.30 (321.39)	640.95	1681.22	1217.31 (341.70)	774.12	2198.55
Congruent RT (ms)	1031.02 (298.84)	590.06	1835.50	1106.38 (278.34)	643.78	2144.29
Incongruent RT (ms)	1202.59 (296.10)	623.63	1802.42	1208.99 (327.64)	768.30	2584.29

Analyses were conducted to determine whether response times in the baseline, congruent and incongruent condition differed between typically developing and dyslexic participants. A mixed effects regression model predicting participant's target response times as a function of experimental condition and group (using dummy coded variables 0 = typically developing, 1 = dyslexic) showed that group did not significantly predict participant's baseline response times on the letter-sound priming task (estimated difference = -42.55, z = -0.61, 95% confidence interval = [-180.09, 94.99], p = .544). This was also true for the congruent condition (estimated difference = -74.77, z = -1.07, 95% confidence interval = [-212.33, 62.79], p = .287) and incongruent condition (estimated difference = -5.22, z = -0.07, 95% confidence interval = [-142.67, 132.23], p = .941).

Furthermore the interactions between experimental conditions and group were not significant indicating that the size of the priming effects (identified in prior analyses) does not differ between groups.

The difference in target response time between the baseline and congruent condition did not differ significantly between typically developing and dyslexic groups (estimated difference = -32.22, z = -.97, 95% confidence interval = [-97.23, 32.78], p = .331). Similarly, the difference between response times in the baseline and incongruent condition did not differ significantly between typically developing and dyslexic groups (estimated difference = 37.33, z = 1.13, 95% confidence interval = [-27.45, 102.10], p =. 259).

Table 5.3 Percentage RT data not available for analysis in the letter-sound priming task for each group

	Response error (%)	Outliers (%)
Dyslexic group (N=24)		
Baseline	1.67	1.21
Congruent	1.44	1.67
Incongruent	1.44	1.03
Total	4.55	3.91
TD Matched group (N=78)		
Baseline	1.39	1.24
Congruent	1.26	1.22
Incongruent	1.22	1.13
Total	3.87	3.59

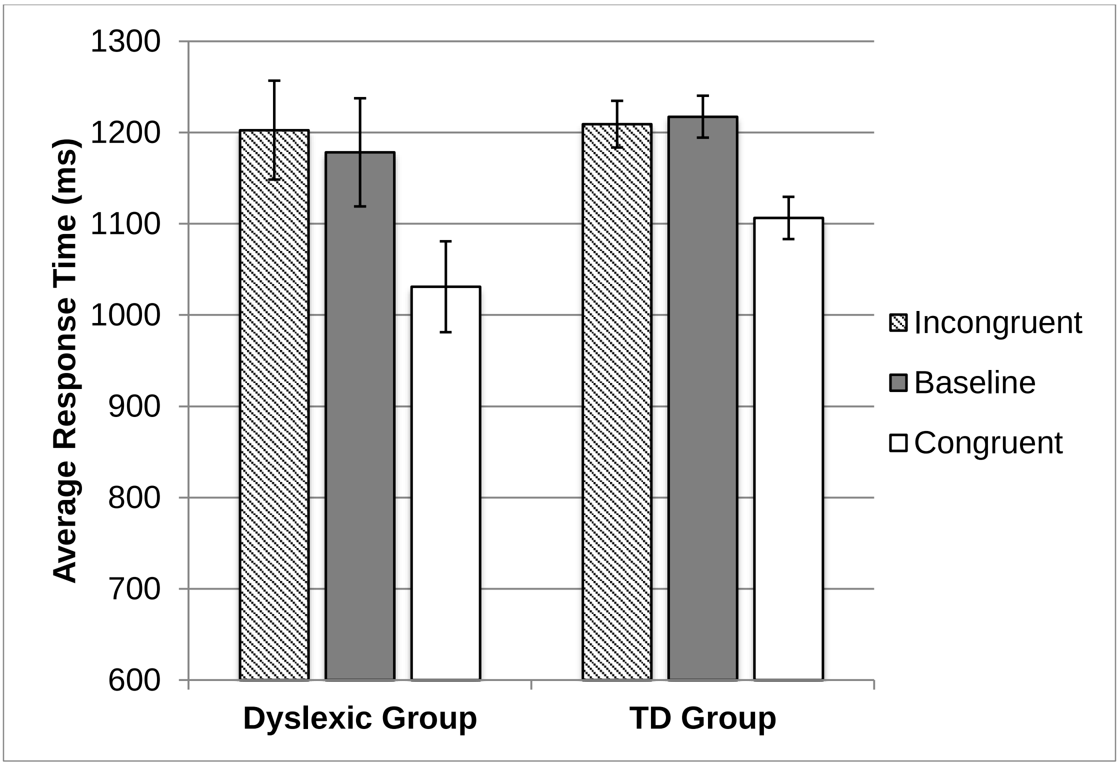


Figure 5.1 Average response times (and 95% CIs) for each condition of the letter-sound priming task for the dyslexic (N= 24) and TD group (N=78)

However, the difference in target response time between the congruent and incongruent condition did differ significantly between typically developing and dyslexic groups (estimated difference = -69.55, z = -.2.10, 95% confidence interval = [-134.36, -4.74], p = .035), indicating that the dyslexic group displayed a significantly larger difference between congruent and incongruent response times.

Differences in accuracy on the letter-sound priming task

An independent samples t-test confirmed there was no significant difference between the dyslexic (mean total accuracy= 57.38, SD= 2.50) and typically developing group (mean total accuracy= 57.26, SD= 2.97) in terms of their overall accuracy on the letter-sound priming task (t= -0.18, df = 100, p < .859).

5.3.2 Relationship between letter-sound integration and measures of reading

Measures of facilitation and interference were used to investigate the relationship between letter-sound integration and reading. Facilitation was calculated for the letter-sound priming task by subtracting each child's average response time in the baseline condition from their average response time in the congruent condition, a negative score indicated facilitation. Interference was calculated by subtracting baseline response times from incongruent response times, a positive score indicated interference.

Table 5.4 shows the simple correlations among reading and letter-sound integration measures. As shown, there were no significant correlations between measures of reading and letter-sound integration for the dyslexic group or the typically developing group. However, average response times for each condition of the letter-sound priming task was significantly correlated with reading performance in the typically developing group.

As age was significantly correlated with both performance on the priming task and reading score in the typically developing group, partial correlations were used to control for effects of age. Table 5.5 shows these partial correlations among reading and letter-sound integration measures controlling for age. As shown, the only correlation to remain significant was between reading score and average response time in the incongruent condition (r=-.22; p= .049).

Table 5.4 Simple correlations between age, performance on the letter-sound priming task and reading

	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**
1. Age		-.42*	-.38	.09	-.22	-.21	.51*
2. Facilitation	.31**		.63**	-.45*	.27	.02	-.15
3. Interference	.27*	.45**		-.48*	-.04	.30	-.23
4. Baseline RT	-.37**	-.59**	-.35**		.74**	.70**	-.16
5. Congruent RT	-.27*	-.11	-.16	.87**		.77**	-.28
6. Incongruent RT	-.23*	-.35**	.22	.84**	.81**		-.35
7. Reading score	.47**	.15	-.01	-.28*	-.26*	-.30**	

*Note: ** = p <.01, * = p <.05. Correlations above the diagonal for dyslexic participants (N=24) and below the diagonal for the typically developing group (N=78).*

Table 5.5 Partial correlations between performance on the letter-sound priming task and reading (controlling for age).

	1.	**2.**	**3.**	**4.**	**5.**	**6.**
1. Facilitation		.55*	-.45*	.20	-.07	.09
2. Interference	.40**		-.48*	-.14	.24	-.04
3. Baseline RT	-.54**	-.28*		.78**	.74**	-.23
4. Congruent RT	-.03	-.09	.86**		.76**	-.20
5. Incongruent RT	-.30*	.30	.83**	.80**		-.29
6. Reading score	.01	-.16	-.13	-.15	-.22*	

*Note: ** = p <.01, * = p <.05. Correlations above the diagonal for dyslexic participants (N=24) and below the diagonal for the typically developing group (N=78).*

5.4 Discussion

This study investigated automatic letter-sound integration in children with dyslexia to assess whether variations in this skill are associated with individual differences in reading skill. Children with dyslexia showed clear evidence of automatic letter-sound integration and, in line with previous results from typically developing children, the extent to which letters and speech-sounds are integrated did not predict variations in reading skill in this group.

5.4.1 Evidence of automatic letter-sound integration in children with dyslexia

The data reported in this study provide strong evidence that children with dyslexia are able to form automatic mappings between printed letters and the speech-sounds they represent. Children with dyslexia showed facilitation in the congruent condition, relative to the incongruent and baseline conditions. However they did not demonstrate inhibition in the incongruent condition relative to the baseline condition. This pattern was also found for the RA control group. The absence of a group difference in speeded performance on a behavioural measure of letter-sound integration is in line with findings from Žarić et al. (2014). This study found no significant difference in reaction time between children with and without dyslexia on a speeded letter-sound identification task. In addition, this finding is in line with results from Nash et al. (submitted) which found that children with dyslexia also demonstrate behavioural evidence of letter-sound integration.

Furthermore, the present results show that the size of this priming effect (relative to the baseline condition) did not differ significantly across the two groups, indicating that children with dyslexia and typically developing children matched for reading age show equal facilitation when primed with a congruent visual letter compared to a novel symbol. However, when comparing congruent and incongruent response times, children with dyslexia displayed a greater effect of facilitation (i.e. they showed a larger difference between response times in the congruent versus incongruent condition).

Further analyses revealed that children with dyslexia were, on average, quicker to make a response on the priming task, however average response times did not differ significantly between groups. This finding is perhaps surprising given that the dyslexic group were, on average, three years older than the reading-age matched group. Results presented in Chapter 3 suggest that typically developing children demonstrate age-related decreases in reaction time on this task. Given these age-related differences, it may be expected that children in the dyslexic group would display significantly faster responses on the priming task when compared with a group of much younger children. While further research is required to compare the performance of a chronological-age matched control group, it is possible that slower response times on the priming task may reflect impaired phonological processing in children with dyslexia (Breznitz, 2003). Accuracy on this task was at ceiling for both groups in the present study, suggesting that children with dyslexia were equally able to discriminate phonemes and their scrambled counterparts. Group differences may therefore reflect variation in the speed with which phonological information can be retrieved from memory.

Taken together, the current findings suggest that children with dyslexia display comparable, or perhaps even slightly enhanced, integration between letters and speech-sounds, compared to a group of typically developing children of similar reading ability. Overall, performance on the priming task may be slower in the dyslexic group, however it is not possible to conclude this without a CA matched control group. One interpretation of these results is that children with dyslexia struggle or are less efficient on the speech-sound identification aspect of this task and are therefore more likely to rely on any available orthographic information (i.e. the visual letter prime) to aid their performance. This interpretation is supported by the findings in the Nash et al. (submitted) study, where the poorest readers demonstrated greater facilitation of the congruent letter on the processing of the auditory speech-sound. However, this interpretation implies that the priming effect is amenable to strategic, rather than automatic processing, an issue that will be discussed further in Chapter 7.

5.4.2 Automatic letter-sound integration is not a concurrent predictor of reading ability in children with dyslexia

Measures of priming and interference were not significantly correlated with reading ability in children with dyslexia, although caution needs to exercised when interpreting this pattern given the small sample size. Nevertheless, the absence of such a correlation suggests that the extent to which letters and speech-sounds are integrated is not associated with individual differences in reading ability in children with dyslexia. Furthermore, average response times on the priming task were not significantly correlated with children's reading scores in the dyslexic group, suggesting that the speed at which children can decide whether a sound is speech or not, is not associated with individual differences in reading ability.

However, while correlations between average response times and reading performance were not significant, they were of similar strength and direction as the correlations reported in the large cross-sectional study in Chapter 3. In line with results from Chapter 3, response times in the incongruent condition were significantly correlated with reading performance in the typically developing group. This suggests that average reaction time on the letter-sound priming task is associated with children's reading ability, a hypothesis that is further explored in Chapter 6.

5.4.3 Limitations of the present study

Whilst findings from this study provide clear evidence that children with dyslexia are able to integrate letters and their corresponding speech-sounds, there are some limitations to address.

The majority of children with dyslexia in this study were recruited from a specialist school located outside of London, where performance on the WIAT-II had recently been assessed. As such, these pre-existing reading scores were used in the current study. These tests were administered by trained teachers and teaching assistants less than a month before this study took place. However, the typically developing children from the larger cross-sectional sample were matched based on their reading performance on a different standardized measure (SWRT 6-16). Whilst this is not an ideal method to select a RA control group, scores on standardized measures of reading are often very highly correlated and it is therefore likely that the two groups are comparable in terms of their reading ability.

It should also be noted that a number of children with dyslexia were also reported to suffer from various comorbid disorders, most commonly developmental dyspraxia and attention deficit hyperactivity disorder (ADHD). It is therefore possible that performance may have been influenced by the presence of such additional difficulties. For example, Gooch, Snowling, and Hulme (2012) report that children with ADHD symptoms display increased variability in reaction time data. Indeed, some have suggested that reaction times are inherently variable in children with developmental disorders, including children with dyslexia (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). In line with this hypothesis, average standard deviations of reaction time data were similar across the two groups in the present study. Given the age-related differences reported in Chapter 3 (i.e. decreasing variability with increasing age), it would expected that the older children with dyslexia would display lower standard deviations when compared with children who were on average three years younger. It is therefore important to interpret group differences in reaction time data with caution. However, on the other hand, given the high level of comorbidity among children with learning disabilities, it could also be argued that this sample reflects a more representative group of children with dyslexia (Peterson & Pennington, 2015).

5.4.4 Concluding remarks

The findings from this study indicate that children with dyslexia demonstrate behavioural evidence of automatic letter-sound integration. This study therefore contradicts the claim that reading difficulties are the result of impaired or weakened associations between letters and speech-sounds (Blomert, 2011). Furthermore, in line with previous results from typically developing children, the extent to which letters and speech-sounds are integrated is not correlated with variations in reading skill in children with dyslexia.

The performance of children with dyslexia on the priming task was comparable to that of a younger group of typically developing children, matched for reading ability. While further research is required, it is possible that comparable performance between these groups reflects impaired phonological processing skills in the children with dyslexia.

Chapter 6 A follow up study investigating the relationship between speech-sound processing and letter sound integration

6.1 Introduction

The present study explores further the relationship between letter-sound priming and children's reading ability. Like most experimental measures, performance on the priming task is likely to involve a number of different cognitive skills. The present study therefore aimed to determine the specific aspect of the priming task that is most closely related to children's reading performance.

There are a number of potential explanations as to why performance on the priming task might predict children's reading ability. To begin with, it is possible to rule out explanations regarding the processing of the visual prime. The regression analyses reported in Chapter 3 demonstrated that response times in both the congruent and the incongruent condition did not predict unique variance in children's reading when controlling for response times in the baseline condition. Given that the visual prime was the only difference between these conditions, these results provide good evidence that the relationship between reading and performance on the priming task is unlikely to be related to the processing of the visual prime.

Further evidence comes from earlier pilot work, where an auditory-only baseline condition was included in the letter-sound priming task. In this condition there was no visual prime, participants were simply presented with a blank screen before the onset of the auditory target. While response times were significantly longer in the auditory-only baseline condition, average response times were highly correlated with performance on other experimental conditions in the task (for example, the correlation with average response times on baseline condition was $r = .79$, $p < .001$). Furthermore, performance on this auditory-only baseline was similarly correlated with reading ability ($r= -.25$, $p = .05$) in this smaller sample (N=49). Together, these results suggest the relationship between performance on the task and reading is unlikely to be driven by the conscious processing of the visual prime.

An alternative theory is that variations in general cognitive ability may account for this relationship. For example, differences in reaction time may relate to general differences in intellectual ability (e.g. Vernon, 1983). As discussed earlier in the thesis, some have suggested that reading difficulties observed in children with dyslexia are caused by a global deficit in skill automatisation, arising from difficulties with cognitive information processing and impaired motor skills. This theory is known as the cerebellar deficit hypothesis (Nicolson, Fawcett, & Dean, 2001). In line with this theory, Catts et al. (2002) found that poor readers were significantly slower on a range of linguistic and non-linguistic reaction time tasks when compared with a group of good readers. Furthermore, in this study reaction time was found to predict unique variance in reading performance after controlling for children’s IQ and phonological awareness. However, results from other studies are mixed and many have found no evidence of a relationship between simple reaction time and reading (Poulsen et al., 2015; Powell et al., 2007; Stringer & Stanovich, 2000).

An additional related theory is that variations in general cognitive ability (IQ) might underlie performance on the priming task and account for the relationship with reading ability. While many have argued that IQ does not play an important role in children’s reading performance (e.g. Fletcher et al., 1994; Stanovich & Siegel, 1994), there is evidence to suggest a relationship between non-verbal measures of general ability and reading achievement (Bowey et al., 2005; Durand, Hulme, Larkin, & Snowling, 2005; Naglieri & Ronning, 2000). It is therefore possible that variations in children’s general cognitive ability could account for performance on the priming task and differences in reading performance.

Alternatively, it is possible that the priming task is measuring a domain-specific skill that is important for reading. Performance on the task ultimately requires children to make a speeded decision about an auditory stimulus. Specifically, children are required to categorise the auditory target as speech or not speech as rapidly as possible. It is therefore possible that the relationship between performance on the task and reading could be driven by variations in children's phonological processing. As previously discussed, there are many studies showing a relationship between phonological processing skills and children's reading development (Vellutino et al., 2004; Wagner & Torgesen, 1987).

However, the results reported in Chapter 3 showed that performance on the priming task predicted reading performance even when controlling for individual differences in phoneme awareness (measured by performance on a phoneme deletion task). This suggests that performance on the priming task and performance on the phoneme deletion task are measuring distinct aspects of phonological processing. Whilst phoneme deletion requires input processing, manipulation of phonological representations and articulation, performance on the priming task may provide a more sensitive measure of the speed with which phonological information can be processed and matched to information in memory. Although these phonological skills may be related, a further distinction can be made between implicit versus explicit phonological processing mechanisms (Morais & Kolinsky, 1997). Whilst performance on the phoneme deletion task requires explicit manipulation of phonological information, performance on the priming task may reflect a more implicit measure of phonological processing.

Further analysis of the results from the cross-sectional study reported in Chapter 3 found that response times on the control condition of the priming task (where children are presented with a novel symbol followed by a scrambled speech-sound) were highly correlated with response times in the baseline condition ($r= .75$, $p < .001$). These results suggest that children who are quick to decide that the auditory target is speech are also quick to determine that the target is not speech, presumably because both decisions involve accessing phonological representations (i.e. higher-level speech processing).

The aim of the present study was to test the hypothesis that the relationship between performance on the priming task and reading ability is driven by the higher-level speech processing demands of the task. To test this hypothesis, children completed a non-speech version of the priming task, designed to be analogous to the letter-sound task. In the non-speech version of the priming task children are required to decide whether an auditory stimulus is an animal sound (e.g. a cat’s meow) or not. It is predicted that performance on the letter-sound, but not the animal-sound, version of the priming task will correlate with children’s reading performance.

In addition, children completed measures of non-verbal reasoning and simple reaction time in order to determine, firstly, whether these measures correlate with performance on the priming task and, secondly, whether domain-general cognitive ability can account for the relationship between performance on the priming task and reading ability. It is predicted that performance on the simple reaction time and non-verbal reasoning measures will correlate with children’s reading scores but that performance on the letter-sound priming task will predict additional unique variance in children’s reading ability.

To summarise, the present study aimed to answer the following questions:

1. Does performance on a non-speech version of the priming task predict children's reading performance?
2. Does performance on the letter-sound priming task predict reading when controlling for individual differences in reaction time and general cognitive ability?

6.2 Method

6.2.1 Participants

Seventy-seven children (40 male, 37 female) with a mean age of 6 years and 8 months (range = 28.51 months) from schools in Greater London participated in this experiment. Children were unselected for reading ability and all children whose native language was not English were fluent in both spoken and written

English. Written consent was gained from parents and the children were given a sticker for their participation. The University College London Ethics Committee granted ethical approval for this study.

6.2.2 Design and materials

Priming Measures

Children completed the letter-sound priming task, as described in Chapter 3. Children also completed an animal sound priming task which was designed to be a non-speech analogy of the original letter-sound priming task.

The animal sound task involved the successive presentation of a prime and a target. The prime was a visually presented cartoon; followed shortly after by the target which was a sound presented over headphones. Children were required to decide on each trial whether the second stimulus (the target) was a “real” animal sound or not. Children were familiarised with the stimuli and task in an initial learning trial.

Stimuli. Stimuli in this task were the recorded sounds of a cat (488ms), dog (429ms), duck (313ms), sheep (435ms) and pig (376ms) and corresponding colour cartoons of each animal (pixel size 80 x 113). Cartoons of fruit (grapes/orange/banana/strawberry/apple) and scrambled animal sounds (scrambled cat (488ms), scrambled dog (429ms), scrambled duck (313ms), scrambled sheep (435ms) and scrambled pig (376ms)) served as control stimuli. Scrambled animal sounds were created using the same Matlab script that was used for creating scrambled phonemes. Each animal sound was divided into 5ms overlapping hanning windows. The order of these windows was then randomised within a 250ms radius. The randomly overlapping windows were then combined to form the scrambled animal sound. The length, overall power and frequency spectrum remained identical to the original animal sound recording.

Apparatus. As in the letter-sound priming experiment, stimuli were presented and responses recorded (speed and accuracy) using E-Prime Software (version 2.0) and a Psychology Software Tools Serial Response Box (SRB; model 200a) with a Dell laptop (Latitude E5520) running Windows 7. Auditory stimuli were presented through Beyer Dynamic headphones (DT 770).

Design. In the priming task a cartoon prime was presented prior to an animal sound target. A centrally located fixation point was presented for 1000ms followed by the presentation of the animal or fruit visual stimulus, which appeared on the white screen for 500ms. The auditory target was then presented over headphones on termination of the visual stimulus. Each trial was followed by the visual prompt “Real animal sound?” Children were instructed to attend to both the visual cartoon and the auditory stimulus and decide whether the sound was a ‘real’ animal sound using “YES” and “NO” response keys. The experimenter monitored the child’s performance, controlling the presentation of trials. Figure 6.1 displays the structure of a trial.

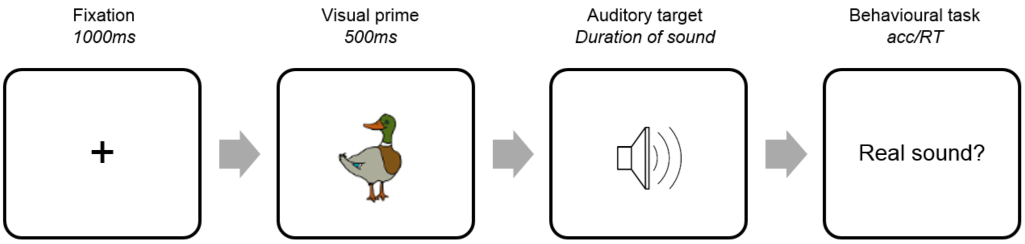


Figure 6.1 The structure of an animal sound priming task trial

As in the letter-sound priming task, there were 6 conditions. In the congruent condition, the prime and target were the same animal (i.e. the visual cartoon was the same animal as the animal sound). In the unrelated (or incongruent) condition the prime and target were not the same animal. In the baseline condition, the prime and target were not the same; the prime was a cartoon of a piece of fruit and the target was an animal sound. There were 3 control conditions to prevent children detecting the relationship between primes and targets and generating expectancies about the up-coming target. These conditions are shown in Table 6.2 along with examples. In the control conditions visual stimuli were always paired as shown in Table 6.1.

Table 6.1 Animal and control prime pairings

Animal prime	Baseline prime	Target
		**cat**
		**dog**
		**duck**
		**sheep**
		**pig**

There were 20 trials for each condition and each condition included 4 trials of each pairing, apart from the incongruent condition where each animal prime was presented once and paired with all of the other animal sounds. There were 135 trials in total, including 15 ‘catch’ trials to ensure children were paying attention to the screen. On catch trials children were shown the same animal cartoons pictured in a cage, children were instructed to press the “GO” response button to release the animals as quickly as they could.

The order of trials was randomized. The letter-sound and animal sound priming tasks each took approximately 10 minutes to complete. Children were allowed to pause the experiment and take a short break at any time. The two priming tasks were completed in separate sessions to prevent

Table 6.2 Experimental conditions for the animal-sound priming task.

Prime (Visual stimulus)	Target (Auditory stimulus)	Response required	Condition
	Duck animal sound	Is it an animal sound (YES)	Congruent
	Duck animal sound	Is it an animal sound (YES)	Baseline
	Duck animal sound	Is it an animal sound (YES)	Incongruent
	Scrambled duck sound	Is it an animal sound (NO)	Control
	Scrambled duck sound	Is it an animal sound (NO)	Control
	Scrambled duck sound	Is it an animal sound (NO)	Control

possible interference and the order of these tasks was counterbalanced

Simple Reaction Time Measure

Children completed a computer task to provide a measure of simple reaction time. On each trial of this task a fixation cross was presented for either 300, 600 or 900ms, followed by a cartoon bug which children were instructed to ‘splat’ as quickly as they could. Children made their response by pressing the middle “GO” button on a Serial Response Box. The bug stimulus was presented for 800ms, during which time children were able to make their response. If children were able to make their response in less than 800ms, “Splat!” appeared on the screen for 500ms. If the button was not pressed in this time “Too slow!” appeared for 500ms. Children completed 3 practice trials followed by 30 reaction time trials.

Stimuli were presented and responses recorded (reaction time) using E-Prime Software (version 2.0) and a Psychology Software Tools Serial Response Box (SRB; model 200a) with a Dell laptop (Latitude E5520) running Windows 7.

Standardised Measures

Reading. Children completed the word and non-word reading subtests from the Test of Word Reading Efficiency (TOWRE 2; Torgesen et al., 1999). These subtests required children to read as many words/non-words as possible in 45 seconds. Practice items were administered prior to test items. The number of items read correctly was recorded. The word-reading subtest provided a measure of single word reading fluency whereas the non-word subtest provided an additional measure of decoding skill and fluency. Children also completed the Single Word Reading Test (SWRT 6-16; Foster, 2007) where they were asked to read aloud a list of words, which became increasingly difficult. This test provided a measure of word reading skill.

Non-verbal reasoning. Children completed the Matrix Reasoning subtest from the Weschler Abbreviated Scale of Intelligence (WASI; Weschler, 1999). This subtest required children to study a picture and to select the correct missing piece from a selection of five possible answers. This test measures the participant's ability to manipulate abstract symbols and detect the relationship among them. Performance on this subtest provided a measure of general intellectual ability.

6.3 Results

Means and standard deviations for performance on standardized tests, the simple reaction time task and the two priming tasks are presented in Table 6.3 and Table 6.4. A reading composite score was calculated by summing z-scores for timed and untimed measures of word and non-word reading as these scores were highly correlated.

Measures of non-verbal reasoning and average response times on the priming tasks were not normally distributed and so were transformed by examining the results of transformations from Tukey's ladder of powers (using the "ladder" command in Stata v 13.0). Matrix reasoning scores were transformed using an inverse root transformation. Baseline RTs on the letter-sound priming task were transformed using a log transformation, congruent RTs using an inverse root transformation and incongruent RTs with a square transformation. Congruent and incongruent RTs in the animal-sound priming task were transformed using inverse root and log transformation (respectively). However, correlational analyses of untransformed data yielded essentially identical patterns of results (correlations using transformed data are included in appendix 4, 5 and 6).

Table 6.3 Descriptive statistics for performance on standardised measures of ability

Measure	N	Mean (SD)	Min.	Max.
Age (months)	77	80.16 (7.89)	65.39	93.9
SWRT raw score /60	77	28.29 (11.93)	2	52
SWRT standard score		111.56 (14.18)	75	136
TOWRE SWE raw score /104	76	47.46 (17.53)	8	73
TOWRE SWE standard score		116.71 (12.21)	84	139
TOWRE PDE raw score /63	75	24.48 (11.92)	1	53
TOWRE PDE standard score		116.53 (10.88)	92	141
WASI Matrix Reasoning raw score	77	11.47 (5.19)	4	23
WASI Matrix Reasoning scaled score		10.92 (2.69)	6	18
Simple Reaction Time task (ms)	77	398.65 (65.07)	267.00	559.70
Reading composite score	75	.09 (2.81)	-5.41	5.61

6.3.1 Effect of priming

Before analyses were conducted, outliers were removed from the raw RT data. Only correct responses were included in the analysis. Responses that were over 5000ms were first removed as this was considered to reflect a lapse in attention rather than accurate performance on the task. A non-recursive outlier removal procedure was then used, as recommended by Selst and Jolicoeur (1994). Reaction time data from two participants were excluded from the analysis due to below chance accuracy on the animal sound priming task.

The percentage of RT data that was excluded, as both response errors and outliers, is shown in Table 6.5. As shown in the table, for the letter-sound priming task, over 90% of the possible RT data were available for analysis. In the animal sound task, over 85% of the data were available for analysis.

Table 6.4 Performance on the letter-sound and animal sound priming tasks

	Mean (SD)	Minimum	Maximum
Letter Sound (N=77)			
Baseline accuracy (/20)	18.94 (1.49)	12.00	20.00
Congruent accuracy (/20)	19.13 (1.20)	13.00	20.00
Incongruent accuracy (/20)	19.14 (1.08)	16.00	20.00
Baseline RT (ms)	1175.60 (308.16)	739.00	2147.95
Congruent RT (ms)	1048.18 (267.41)	656.26	1951.16
Incongruent RT (ms)	1121.19 (235.09)	700.59	1672.25
Animal Sound (N=74)			
Baseline accuracy (/20)	18.19 (2.26)	11.00	20.00
Congruent accuracy (/20)	18.69 (1.81)	11.00	20.00
Incongruent accuracy (/20)	18.30 (1.94)	13.00	20.00
Baseline RT (ms)	1212.25 (289.62)	717.79	1980.44
Congruent RT (ms)	1095.26 (275.23)	634.53	2141.68
Incongruent RT (ms)	1227.65 (317.25)	767.25	2312.53

The mean correct response times in each condition of the letter-sound priming experiment, together with 95% within-subject confidence intervals (Morey, 2008) are shown in Figure 6.2. Compared to the baseline condition the data show facilitation in the congruent priming condition and also facilitation in the incongruent condition. To assess the reliability of these differences, response times for the baseline, congruent and incongruent condition were compared using a mixed effects linear regression model treating participants and items as crossed random effects (xtmixed in Stata 13.1) in order to account for variability across participants and target items. Whilst there are a small number of levels of target item to be treated as a random effect, comparison of models with target items as fixed and as random effects were found to be almost identical.

Table 6.5 Percentage RT data excluded for each experimental condition of the letter sound and animal sound priming task

	Response error (%)	Outliers (%)
Letter Sound Priming		
Baseline	1.69	1.39
Congruent	1.30	1.21
Incongruent	1.21	1.39
Total	4.20	3.99
Animal Sound Priming		
Baseline	3.71	1.67
Congruent	2.06	1.29
Incongruent	3.65	1.31
Total	9.42	4.27

This model predicted participant's target response times as a function of experimental condition, using two dummy coded variables (baseline vs. congruent (0, 1) and baseline vs. incongruent (0, 1)). Results for the letter-sound priming task showed that the difference in target response time between the baseline and congruent condition was significant (estimated difference = -127.35, z = -7.39, 95% confidence interval = [-161.11, -93.59], p < .001). The effect size of this difference (ignoring participant and item variability) is d =.44. The difference between response times in the baseline and incongruent condition was also significant (estimated difference = -53.78, z = -3.12, 95% confidence interval = [-87.55, -20.01], p =. 002). The effect size here (ignoring participant and item variability) is d = .20.

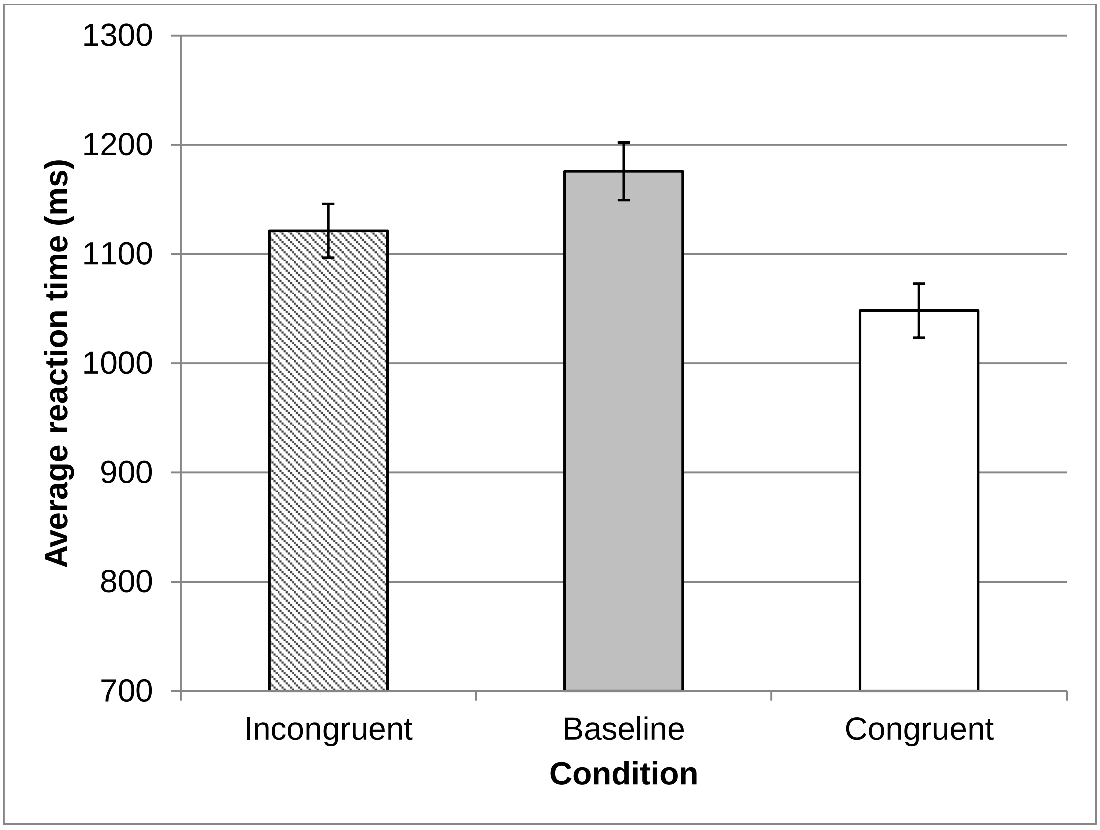


Figure 6.2 Average response times (and 95% CIs) for each condition of the letter-sound priming task (N=77)

The mean correct response times in each condition of the animal sound priming experiment, together with 95% within-subject confidence intervals (Morey, 2008) are shown in Figure 6.3. Compared to the baseline condition the data show facilitation in the congruent priming condition and very slight interference in the incongruent condition. As with the letter-sound priming data, response times for the baseline, congruent and incongruent condition were compared using a mixed effects linear regression model treating participants and items as crossed random effects. (Once again comparison of models with target items as fixed and as random effects were found to be almost identical).

This model predicted participant's target response times as a function of experimental condition, using two dummy coded variables (baseline vs. congruent (0, 1) and baseline vs. incongruent (0, 1)). Results for the animal-sound task followed a similar pattern as those for the letter-sound task: the difference in target response time between the baseline and congruent condition was significant (estimated difference = -116.93, z = -6.91, 95%

confidence interval = [-150.11, -83.74], p < .001). The effect size of this difference (ignoring participant and item variability) is d =.41. However, the difference between response times in the baseline and incongruent condition was not significant (estimated difference = 9.76, z = .57, 95% confidence interval = [-23.51, 43.02], p =. 565). The effect size here (ignoring participant and item variability) is d = -.05.

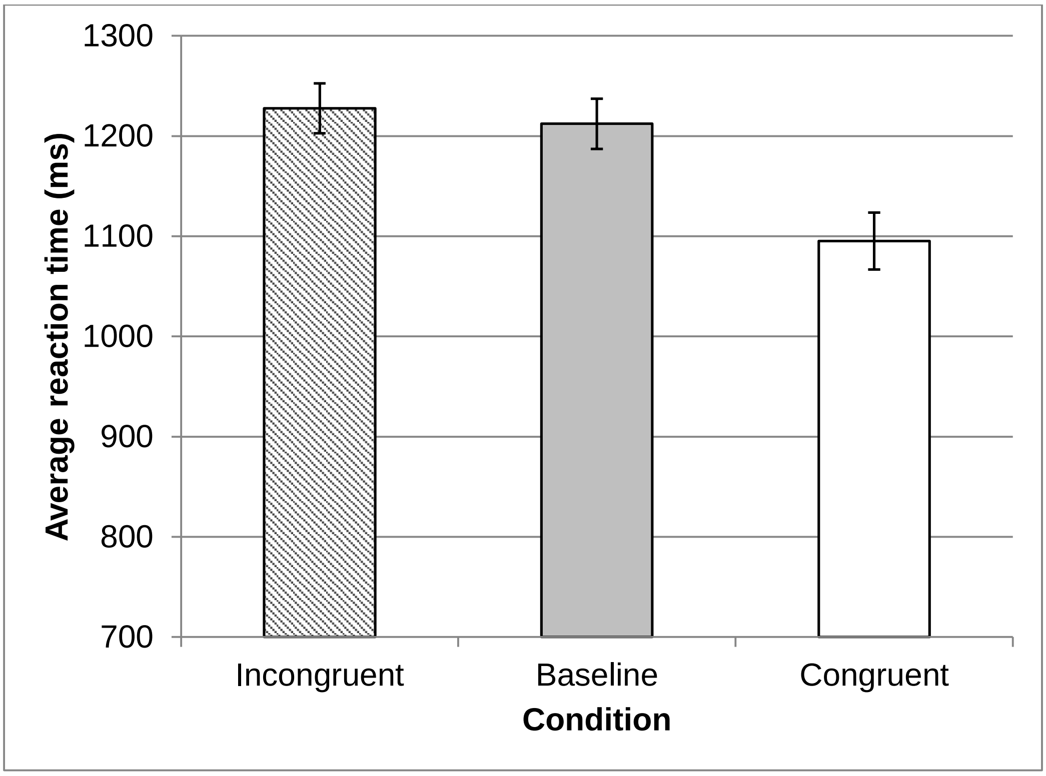


Figure 6.3 Average response times (and 95% CIs) for each condition of the animal-sound priming task (N=74)

6.3.2 Relationship between performance on the priming task and children’s reading, non-verbal reasoning and simple reaction time

Average response times for each condition of the two priming tasks were used to investigate the relationship between performance on the priming tasks and children’s reading, non-verbal reasoning and simple reaction time.

Table 6.7 shows the simple correlations among the various reading measures and average response times on the two priming tasks, partial correlations controlling for age are shown below the diagonal. The subsequent analysis will focus on these partial correlations as the majority of reaction time and standardized measures were significantly correlated with age (as shown in Table 6.6).

Performance on the letter-sound priming task was significantly correlated with children's reading composite score (r's between -.23 and -.35, p between .0487 and .0024). Interestingly, performance on the incongruent condition of the letter-sound priming task correlated most strongly with children's reading ability (r's between -.30 and -.36, p between .0024 and .0001). In contrast, there were no significant correlations (r's between -.07 and -.00, p between .9747 and .5880) between average response times on the animal-sound priming task and children's reading scores. Notably, the strength of correlation between baseline RT for the letter-sound priming task and reading (r = -.25) was stronger than the corresponding correlation between baseline RT for the animal sound task and reading (r = -.03; z = -1.66; p = 0.0484).

These results demonstrate that reading ability is negatively correlated with children's speed of response on the speech version of the priming task, rather than on the non-speech version. The two priming tasks involve the same demands; the crucial difference lies in the use of speech stimuli in the letter-sound version of the task. This result indicates that children with higher reading scores are quicker to decide whether a presented sound is speech.

In addition, there were no significant correlations between children's non-verbal reasoning ability and simple reaction time and average response times on either of the two priming tasks (correlations are presented in Table 6.8).

The absence of a relationship between these measures suggests that the priming task is most likely measuring children's ability to make a speeded decision about an auditory stimulus, rather than simply providing a measure of general cognitive ability or reaction time.

Hierarchical regression analyses were used to further explore the relationship between general cognitive ability, baseline performance on the letter-sound priming task and reading. Together, children’s age, performance on matrix reasoning and simple RT accounted for 40% of the variance in reading performance ((F 3, 71) = 15.78, p < .0001). Adding baseline response time significantly improved the model, accounting for an additional 3.53% of the variance in reading performance ((F 1, 70) = 4.38, p = .0400). Adding baseline response time on the animal sound priming task to the same regression model (predicting children’s reading performance from age, performance on matrix reasoning and simple RT) did not account for additional variance ((F 1, 67) = 0.01, p = .9232).

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Table 6.6 Simple correlations between age and performance on reading, non-verbal reasoning and reaction time measures.

	2.	3.	4.	5.	6.	7.	8.	9.
1. Age	.19 77	.50*** 77	.49*** 76	.45*** 75	.48*** 45	-.27* 77	-.18 74	-.28* 77
2. WASI Matrix Reasoning		.45*** 77	.46*** 76	.41*** 75	.44*** 75	-.14 77	-.08 74	-.25* 77
3. SWRT			.92*** 76	.89*** 75	.97*** 75	-.29* 77	-.09 74	-.33** 77
4. TOWRE-SDE				.88*** 75	.96*** 75	-.32** 76	-.14 73	-.34** 76
5. TOWRE-PDE					.96*** 75	-.35** 75	-.08 72	-.22 75
6. Reading composite						-.34** 75	-.11 72	-.28* 75
7. LS baseline RT							.37** 74	.17 77
8. AS baseline RT								.21 74
9. Simple RT								

*Note: *** = p <.001, ** = p <.01, * = p <.05. AS = Animal sound LS = Letter sound. N for each correlation reported beneath coefficient.*

Table 6.7 Simple and partial correlations between reading and average response times on the two priming task measures

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. SWRT		.92*** 76	.89*** 75	.97*** 75	-.29* 77	-.24* 77	-.42*** 77	-.09 74	-.12 74	-.02 74
2. TOWRE-SDE	.89*** 76		.88*** 75	.96*** 75	-.32** 76	-.33** 76	-.46*** 76	.14 73	-.15 73	-.05 73
3. TOWRE-PDE	.87*** 75	.85*** 75		.96*** 75	-.35** 75	-.28* 75	-.43*** 75	-.08 72	-.11 72	-.00 72
4. Reading Composite	.96*** 75	.95*** 75	.95*** 75		-.34** 75	-.30** 75	-.45*** 75	-.08 72	-.11 72	-.00 72
5. LS Baseline RT	-.18 77	-.22 76	-.26* 75	-.25* 75		.77*** 77	.77*** 77	.37** 74	.38*** 74	.36** 74
6. LS Congruent RT	-.15 77	-.26* 76	-.21 75	-.23* 75	.76*** 77		.74*** 77	.53*** 74	.59*** 74	.57*** 74
7. LS Incongruent RT	-.30** 77	-.36** 76	-.33** 75	-.35** 75	.75*** 77	.72*** 77		.42*** 74	.42*** 74	.39*** 74
8. AS Baseline RT	-.00 74	-.07 73	-.00 72	-.03 72	.34** 74	.51*** 74	.39** 74		.74*** 74	.83*** 74
9. AS Congruent RT	.00 74	-.04 73	-.01 72	.01 72	.33** 74	.56*** 74	.37** 74	.73*** 74		.77*** 74
10. AS Incongruent RT	.01 74	-.02 73	.03 72	.01 72	.36** 74	.57*** 74	.39** 74	.83*** 74	.78*** 74	

*Note: *** = p <.001, ** = p <.01, * = p <.05. AS = Animal sound LS = Letter sound. Simple correlations above the diagonal and partial correlations controlling for age below the diagonal. N for each correlation reported beneath coefficient.*

Table 6.8 Simple and partial correlations between non-verbal reasoning, simple reaction time and average response times on the two priming tasks

	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
1. WASI Matrix Reasoning		-.25* 77	-.14 77	-.13 77	-.19 77	-.07 74	-.03 74	-.04 74
2. Simple RT	-.29* 77		.17 77	.19 77	.22 77	.21 74	.06 74	.07 74
3. LS Baseline RT	-.10 77	.18 77		.77*** 77	.77*** 77	.37** 74	.38*** 74	.36** 74
4. LS Congruent RT	-.10 77	.15 77	.76*** 77		.74*** 77	.53*** 74	.59*** 74	.57*** 74
5. LS Incongruent RT	-.14 77	.13 77	.75*** 77	.72*** 77		.42*** 74	.42*** 74	.39*** 74
6. AS Baseline RT	-.04 74	-.14 74	.34** 74	.51*** 74	.39** 74		.74*** 74	.83*** 74
7. AS Congruent RT	.02 74	.02 74	.33** 74	.56*** 74	.37** 74	.73*** 74		.77*** 74
8. AS Incongruent RT	-.03 74	-.01 74	.36** 74	.57*** 74	.39** 74	.83*** 74	.78*** 74	

*Note: *** = p <.001, ** = p <.01, * = p <.05. AS = Animal sound LS = Letter sound. Simple correlations above the diagonal and partial correlations controlling for age below the diagonal. N for each correlation reported beneath coefficient.*

6.4 Discussion

This study explored the relationship between performance on the letter-sound priming task and children's reading ability. Taken together, the results from this study suggest that the relationship between performance on the priming task and children's reading ability is likely to be driven by the higher-level speech processing demands of the task.

6.4.1 The relationship between performance on the two priming tasks and children's reading ability

The results indicate that performance on the letter-sound version of the priming task was significantly correlated with reading, whereas performance on the animal sound version of the priming task was not. Children who were quicker to decide if the presented sound was speech or not, also performed better on measures of reading. Conversely, the speed with which children were able to decide if a sound was an animal sound, was unrelated to children's reading performance. As the only difference between these two tasks was the use of speech stimuli, this result provides good evidence that the relationship between performance on the priming task and children's reading ability is likely to reflect the phonological (speech) processing component of the letter-sound priming task. This finding is in line with a wide literature supporting the important role of phonological skills in children's reading acquisition (Hulme & Snowling, 2013).

Performance on the priming task requires the efficient access to phonological representations in memory, thus performance may be influenced by a number of different factors. For example, performance may be influenced by the quality of phonological representations in memory, the speed at which these representations can be accessed or perhaps differences in low level auditory processing of speech-sounds. It therefore remains to be seen which specific aspect of phonological processing is being measured by the letter-sound priming task, an issue that will be further discussed in Chapter 7.

An additional finding from the present study was that performance on the baseline condition of the letter-sound priming task significantly predicted reading, even when controlling for children’s simple reaction time and general cognitive ability (measured using a non-verbal reasoning task), while the animal sound task RTs did not. This finding provides further evidence that the relationship between performance on the letter-sound priming task and reading is likely to be driven by the phonological demands of the task.

Average response times on the letter-sound and animal-sound priming task followed a very similar pattern across conditions. In both tasks, children were significantly faster to identify the auditory target when it was primed by a related visual stimulus. In the letter-sound priming task, children were significantly quicker to identify an auditory phoneme when it was primed by the same visual letter, compared to when primed by a novel symbol. In the animal-sound task, children were significantly quicker to identify the animal-sound when it was primed by a cartoon of the same animal, compared to when primed by an unrelated cartoon (in this case a piece of fruit).

It is encouraging that the two tasks follow a similar pattern of results as this suggests that the animal sound task serves as an effective analogy. However, it also raises an alternative interpretation of children’s performance in the letter-sound priming task. If it is assumed that facilitation in the animal sound version of the task is driven by explicit semantic knowledge (of animals and the sounds they make) rather than automatic activation of auditory information, it is difficult to rule out the possibility that similar explicit processes are involved in the letter-sound priming task. This issue of strategy use and automaticity will be discussed further in Chapter 7.

The amount of interference (the difference between baseline and incongruent response times) was different across the two priming tasks. In the letter-sound priming task, children were significantly quicker to identify an auditory phoneme when it was primed by a different (incongruent) visual letter, compared to when primed by a novel symbol. In the animal sound task children were slightly slower to identify the animal-sound when it was primed by a cartoon of a different animal, compared to when primed by an unrelated cartoon (in this case a piece of fruit). However this difference was not significant.

The significant facilitation in the incongruent condition of the letter-sound priming task contrasts with results reported in Chapter 3. Although this difference was not significant in the larger study, the data followed a similar pattern, showing quicker response times in the incongruent relative to the baseline condition. Although it was not the focus of this study, it would be of interest to further examine this facilitating effect in the incongruent condition. As previously discussed in Chapter 3, it is possible that longer response times in the baseline condition could account for this unexpected finding.

6.4.2 The relationship between performance on the letter-sound priming task, reading and general cognitive ability

Children in this follow up study completed additional measures of general cognitive ability: a simple reaction time task and a measure of non-verbal reasoning. Partial correlations revealed that there was no significant relationship between performance on the priming task and general cognitive ability; as correlations with both simple reaction time and non-verbal reasoning were non-significant. The absence of a relationship between these measures provides clear evidence that the priming task is measuring a skill that is independent from children’s simple reaction time and general cognitive ability.

The present results show that simple reaction time was not a significant predictor of variance in children’s reading performance. This finding is in line with a number of studies that have found no evidence of a relationship between simple reaction time and reading (Poulsen et al., 2015; Powell et al., 2007; Stringer & Stanovich, 2000). In contrast, performance on measures of non-verbal reasoning was significantly correlated with children’s reading performance (r = .40 controlling for age). This contrasts with previous research, where studies have generally reported a much more modest influence of non-verbal IQ (Durand et al., 2005).

6.4.3 Concluding remarks

Overall, the results comparing the two versions of the priming task and their relationship with reading were in line with predictions. Average response times on the letter-sound version, but not the animal sound version of the task, were significantly correlated with reading performance. In addition, this study found that performance on the baseline condition of the priming task significantly predicted reading when controlling for individual differences in simple reaction time and non-verbal reasoning (IQ). Together, these results provide clear evidence to suggest that that the relationship between performance on the letter-sound priming task and reading is driven by the phonological processing demands of the letter-sound priming task. The wider implications of this finding will be discussed in the following chapter.

Chapter 7 Discussion and conclusions

This thesis has investigated automatic integration of letters and speech-sounds in typically developing and dyslexic readers. These studies assess whether a specific deficit establishing automatic associations between letters and speech-sounds is a plausible explanation for problems in learning to read.

Recent research has suggested that letters and speech-sounds become automatically integrated with increasing reading experience (Froyen et al., 2009). In addition, a number of studies from the same research group have claimed that children with dyslexia fail to integrate letter-sound pairs into fully automated audio-visual objects (Blau et al., 2010; Froyen et al., 2011; Žarić et al., 2014). These studies propose a novel theory of dyslexia, whereby difficulties learning to read are caused by impaired or weakened associations between letters and speech-sounds.

This appears to be a reasonable hypothesis and is consistent with evidence that letter knowledge, phoneme awareness and RAN speed reliably predict children’s early reading achievement. However, as previously discussed, there is limited empirical evidence for this theory. The majority of work in this field comes from studies using neuroimaging techniques. These studies typically have small sample sizes and the reliability of these neural measures is not known. In addition, it is not clear from these studies whether neural differences in automatic letter-sound integration are characteristic of children with dyslexia or simply reflect a consequence of limited reading experience.

In order to investigate this novel hypothesis, a series of behavioural experiments were conducted. The first experiment with adults tested whether a priming paradigm would provide evidence of automatic letter-sound integration. This priming task was then adapted for use with children in a large cross-sectional study. This experiment examined whether typically developing children with approximately two years of reading experience show evidence of automatic letter-sound integration and, also, whether this skill is associated with early reading ability or with variation in other known predictors of reading (letter knowledge, phoneme awareness and RAN). The performance of children with dyslexia on this priming task was also measured in an additional study and compared with a reading-age matched control group. Based on these findings, a further experiment was conducted to investigate the relationship between performance on the priming task and reading.

There were three main findings from these experiments:

1) Adults, typically developing children (aged 5-7 years) and 9-year-old children with dyslexia were significantly quicker to identify a speech-sound when primed by a congruent visual letter.
2) The extent to which children automatically activated letter-sounds following a congruent visual letter prime was not predictive of reading performance (in addition, children with dyslexia showed comparable priming to reading-age matched controls).
3) The speed with which children were able to determine whether an auditory target is speech or not was predictive of reading performance. This was true even when controlling for children's age, RAN speed and phoneme awareness. This relationship also appears to be independent of other task demands such as simple reaction time.

The following sections discuss each of these findings in turn, outlining the limitations of the present research, potential directions for future research and also the implications for theories of reading and dyslexia.

7.1 Priming effects: Evidence of automatic letter-sound integration?

The data presented in this thesis show that adults, typically developing children and children with dyslexia were significantly quicker to identify a speech-sound when primed by a congruent visual letter (the congruent condition) compared to when primed by a novel letter-like symbol (the baseline condition). This significant effect of facilitation suggests that the presentation of congruent visual information leads to rapid activation of the corresponding speech-sound, resulting in decreased reaction time to decide whether the auditory target was speech or not. This facilitation is interpreted as evidence of automatic letter-sound integration, as the only difference between the congruent and baseline condition is the relationship between the visual prime and the speech-sound. This finding suggests after repeated exposure to visual letters and their corresponding speech-sounds during early literacy instruction, auditory and visual representations have become strongly associated in memory.

One interpretation of this facilitating effect is that presentation of the visual letter prime automatically activates the corresponding pathway in long-term memory, which then accelerates subsequent processing of related signals (Posner & Snyder, 2004). An alternative interpretation could be that participants were consciously reflecting on the relationship between the prime and the target, which could call into question the extent to which the priming task measures automatic associations between letters and speech-sounds.

Whether a cognitive process can be described as “automatic” is a common source of debate in studies of priming (Moors & De Houwer, 2006). A number of different criteria have been cited to determine whether a process is fully automatic. For example, Posner and Snyder (2004) propose a fairly simple view that a process must meet the following criteria to be considered automatic:

1) The process is involuntary and occurs without intention
2) The participant is unaware of the process taking place
3) The process does not interfere with other on-going cognitive processes

These criteria are difficult to apply to the existing data. Nonetheless, with respect to the first criterion, it could be argued that letter-sound integration occurs without intention, as the task does not require the participant to reflect upon the relationship between the prime and the target. The current priming paradigm could be adapted in order to meet the two additional criteria for automaticity. For example, one possible way to ensure the participant is unaware of automatic letter-sound activation would be to mask the visual prime by degrading the quality of the stimulus and reducing the presentation duration. A dual-task paradigm could be employed in order to satisfy the third criterion, for example children could be asked to perform an additional auditory detection task during the experiment (e.g. indicate using a different button-press when they hear a particular auditory tone).

In evaluating automaticity, an alternative approach is to consider ‘cost benefit analysis’ of the data (Posner & Snyder, 2004). This theory proposes that if a process is automatic, activated pathways will facilitate the processing of related information, however 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 letter and speech-sound) processing will be slowed down in response to any unrelated or incongruent information.

This effect was demonstrated in a series of early experiments by Posner and Snyder (1975). In one of these experiments participants were presented with a visual prime followed by an array. The prime was either a plus sign or an item that would appear in the array. The array consisted of a pair of letters and participants were required to decide whether the letters matched or not. Three groups of participants completed the experiment; for one group the probability that the prime matched the letter pair was 80% (80 congruent trials: 20 incongruent trials), for another group it was 50% (50:50) and for another it was 20% (20:80). The amount of facilitation and inhibition was calculated for matching trials by calculating the difference between participants’ reaction time when the prime was a letter versus a plus sign. As predicted, “yes” responses showed clear facilitation and inhibition when the prime was highly predictive of the array (80:20). However, when the prime was not particularly informative (20:80), there was significant facilitation but no inhibition. Reaction times for the 50:50 condition were in between the two, however only the effect of facilitation was significant. Figure 7.1 shows the pattern of results for the different conditions in the three probability conditions of the task. Posner and Snyder (1975) argue that this pattern of facilitation in the absence of inhibition is evidence of an automatic process.

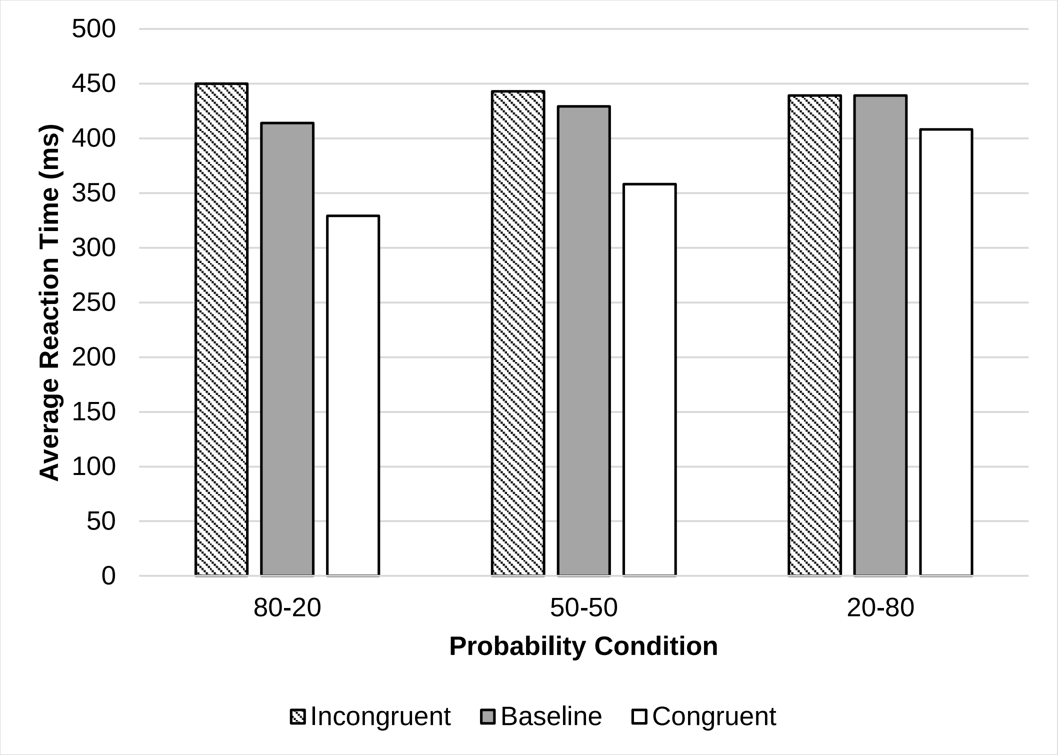

Figure 7.1 Average correct reaction times for the different conditions in three probability conditions of the letter-matching task as reported in Posner and Snyder (1975)

The present research therefore suggests that typically developing children (aged 5 -7 years) and children with dyslexia (aged 9 years) show evidence of automatic letter-sound integration. While children were significantly quicker to identify the speech-sound in the congruent compared to the baseline condition, the difference between response times in the baseline and incongruent condition was not significant for these groups. The absence of an inhibitory effect in typically developing children and children with dyslexia may therefore provide evidence that the facilitating effect of the visual letter prime was automatic, rather than conscious.

Results from the study with adults showed that participants were significantly quicker to identify the speech-sound in the congruent compared to the baseline condition and were also significantly slower in the incongruent compared to the baseline condition. Therefore, according to Posner and Snyder (1975), the facilitation effect in the adult sample may have resulted from participants actively attending to the relationship between the prime and target. This difference between adults and children may reflect the timings of the experiment (e.g. the duration of the stimulus and the inter-stimulus interval). It is possible that the timing of the present experimental paradigm was suitable to elicit automatic processing in children, but for adults provided enough time for participants to consciously attend to the relationship between the prime and target. This interpretation is supported by results from a second letter-sound matching experiment by Posner and Snyder (1975) which found significant facilitation but no inhibition (i.e. evidence of automatic processing) across short inter-stimulus intervals (e.g. 150ms). In contrast, when participants are provided with a longer interval between the prime and array (e.g. 300ms) there was both significant facilitation and inhibition, suggesting that participants may be consciously attending to the relationship between the prime and array.

An additional issue to be addressed concerns the validity of the baseline condition. As previously noted, results from the youngest group of children in the cross-sectional study (the 5-year-old group) indicated that children were significantly quicker to identify the speech-sound when it was primed by an incongruent letter, compared to when primed by a novel symbol. This finding is difficult to explain and it was hypothesised that reaction times in the baseline condition may have been exaggerated due to the novelty of the letter-like symbols. Perhaps because these unusual symbols were distracting for younger children. An alternative explanation concerns the proportion of trials with a real versus novel letter prime. As previously described, novel symbols only occurred on a third of all trials (in the baseline condition) whereas letters occurred on the remaining two thirds of trials. Therefore it was more likely that children would be presented with a real letter than a novel symbol. As a result, children may have found the baseline stimuli increasingly distracting.

It is important to address this baseline issue in future research, for example by balancing the proportion of baseline and congruent/incongruent trials (50:50). Whilst, it is clear from comparing congruent and incongruent reaction times that the visual prime influences processing of the auditory target, the presence of a baseline condition provides a crucial insight into whether this effect is driven simply by facilitation (and can therefore be considered automatic) or by both facilitation and inhibition.

In addition to varying the proportion of baseline trials, future research could also vary the probability of congruent versus incongruent trials. As in the Posner and Snyder (1975) study, it might be predicted that children would show a large facilitation effect and small inhibition effect when the visual prime is highly predictive of the auditory target (for example, 80:20 balance of congruent and incongruent trials). However, when the prime is less predictive of the auditory target (e.g. 20:80 balance of congruent and incongruent trials) children should show significant facilitation but not inhibition.

7.2 The relationship between letter-sound priming and reading

The present research indicates that automatic letter-sound integration is not predictive of variations in reading ability. Measures of facilitation (i.e. the extent to which children automatically activate letter-sounds following a congruent prime) did not correlate with children's reading scores or with variation in other known predictors of reading (letter knowledge, phoneme awareness and RAN).

The present findings therefore contradict the hypothesis of Blomert and colleagues that letters and speech-sounds become automatically integrated with increasing reading experience (Froyen et al., 2009). Blomert (2011) proposed that there is an extended period in which children develop automatic letter-sound integration and that this gradual change from basic association to automatic integration develops in parallel with reading experience. Results from the present research appear to suggest that letters and speech-sounds become automatically integrated during the first few years of formal reading experience, however the complete absence of a relationship with reading ability across a large unselected sample indicates that variations in this skill are not associated with individual differences in reading ability.

The present research also found that children with dyslexia show comparable letter-sound integration to a group of younger typically developing children matched for reading ability. This finding indicates that children with dyslexia are able to form automatic mappings between printed letters and the speech-sounds they represent, and contradicts the claim that problems learning to read arise from a specific deficit establishing automatic associations between letters and speech-sounds (Blau et al., 2010; Froyen et al., 2011; Žarić et al., 2014). Furthermore, in line with results from the cross-sectional study, the extent to which letters and speech-sounds were automatically integrated was not associated with individual differences in reading ability in children with dyslexia or in the reading-age matched control group.

So, is it possible to conclude from the present research that individual differences in reading ability are not associated with variations in the degree of automatic integration of letters and speech-sounds? As previously noted, this is one of the first behavioural investigations in this field, as the majority of existing evidence in support of this novel theory of dyslexia comes from neuroimaging studies. Given the strong claims made by these studies, it was predicted that research involving carefully controlled behavioural experiments would mirror these findings and provide additional empirical evidence for a relationship between automatic letter-sound integration and reading ability. While further studies are clearly required, this theory of dyslexia is not supported by evidence from the current studies.

It is of interest to note that research involving behavioural and neuroimaging measures of automatic letter-sound integration have typically revealed dissociations between the two different types of data (e.g. Žarić et al., 2014; Nash et al., submitted). For example, in their recent study Nash and colleagues (submitted) report that children with dyslexia and typically developing children (reading-age and chronological-age matched controls) all demonstrated a significant priming effect, indicating that letters and speech-sounds were automatically integrated. However, analysis of EEG data collected during a passive version of the priming task revealed developmental differences between the two typically developing groups and also differences in children with dyslexia. The authors speculate that the observed neural differences may reflect automatic versus attention-driven processing of letters and speech-sounds, however they also acknowledge that auditory ERPs are influenced by age.

While some may argue that neural techniques provide an increasingly sensitive measure, if differences in automatic letter-sound integration were driving individual differences in reading performance one would expect to see evidence of a relationship at a cognitive level. Given the poor reliability and inherent noise in imaging data (e.g. the variability in selecting electrodes, time windows, statistical thresholds and typically small sample sizes) it is important to interpret findings with caution. This, together with the complete absence of behavioural evidence in support of this theory, suggests it is unlikely that variations in the degree of automatic letter-sound integration are associated with reading ability.

The finding that English speakers show evidence of automatic letter-sound integration challenges the conclusion of Holloway et al. (2015) that English speakers do not show automatic letter-sound integration due to the inconsistency of the orthography. It may be argued that the absence of a relationship between letter-sound integration and reading in the present English-speaking sample reflects the relatively inconsistent orthography. However, as previously discussed, recent research suggests that predictors of reading are consistent across languages varying in orthographic consistency (Caravolas et al., 2013).

An additional and important finding concerns the relationship between average response times on the priming task and children’s reading performance. The finding that baseline performance on the priming task (i.e. the speed at which children are able to identify an auditory target as speech or not) is predictive of reading performance illustrates that rather than simply revealing a null result, the priming task used in the present research measures a meaningful skill that appears to be relevant to children’s reading performance.

7.3 Baseline response time on the letter-sound priming task: The relationship between phonological processing and reading

The finding that average response time on the letter-sound priming task was significantly correlated with children's reading performance was unexpected. Children who were quicker to determine whether the auditory target was speech or not, regardless of the visual prime, were also better readers. Results reported in Chapter 3 showed that performance in the baseline condition of priming task predicted reading performance even when controlling for other known predictors of reading: children's age and individual differences in phoneme deletion and RAN speed.

Further evidence indicated that the relationship between performance on the priming task and children's reading ability is likely to be driven by the speech processing demands of the task. Results from Chapter 6 show that performance on a letter-sound, but not an animal-sound, version of the priming task was significantly correlated with reading ability. Furthermore, results from this study suggest that the relationship with reading is independent of children's general cognitive ability and simple reaction time.

Results reported in Chapter 5 are also consistent with the finding that response times on the priming task are associated with reading ability. This study reported that average reaction times on the priming task for children with dyslexia (aged 9 years) were comparable to the reading-age matched control group (aged 6 years). Given the significant age-related differences in average reaction time reported in the cross-sectional study, it was suggested that slower than expected reaction times on the priming task may reflect impaired phonological processing in children with dyslexia. This interpretation is in line with a wide literature proposing a phonological deficit as the cognitive basis of dyslexia (Peterson & Pennington, 2015). Nevertheless, further research with a chronological age-matched control group is required in order to confirm this hypothesis.

As previously discussed, it remains to be seen which specific aspect of phonological processing is being measured by the letter-sound priming task.

This task requires the speeded access to phonological representations in memory, thus performance may be influenced by the quality of stored phonological representations, the speed at which representations can be accessed or perhaps differences in low level auditory processing of speech-sounds. As such, one interpretation could be that the relationship between performance on the priming task and reading reflects the role of speech perception in reading development and dyslexia. In order to perform successfully on this task children must be sensitive to the characteristics of speech.

As previously discussed, some researchers propose that impaired speech perception underlies the phonological deficit observed in children with dyslexia (e.g. Chiappe et al., 2004; Serniclaes et al., 2004). According to Serniclaes et al. (2004), deficits in speech perception in children with dyslexia prevent the formation of adequate phonological representations and as a result lead to difficulties learning grapheme-phoneme correspondences. However, as illustrated in Figure 7.2, the reverse may also be true of children with dyslexia. Individuals with dyslexia may experience difficulty perceiving speech as a consequence of their poorly specified phonological representations.

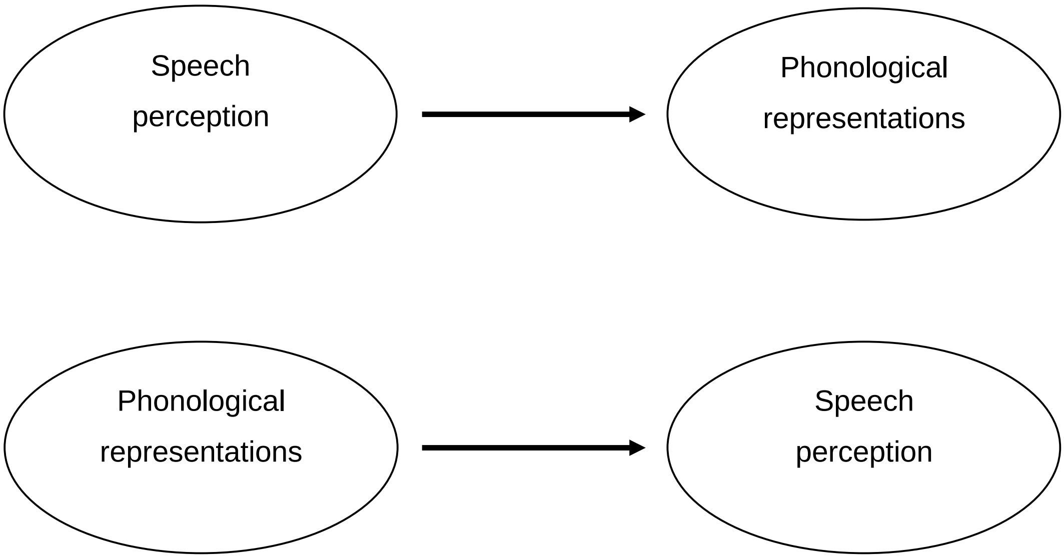

Figure 7.2 Two path diagrams illustrating the hypothesized relationship between speech perception and phonological representations

However, results from the present research suggest that children with dyslexia show differences in reaction time, but are highly accurate, on the letter-sound priming task. Thus, slower responses on the letter-sound priming task may reflect a difficulty accessing phonological representations, rather than the quality of the representations themselves.

This idea is supported by recent research proposing that children with dyslexia have a specific deficit accessing phonological representations (Ramus, 2014). The main evidence for this theory comes from a recent neuroimaging study by Boets et al. (2013). In this study, 23 adults with dyslexia and 22 non-impaired readers listened to phonetically identical syllables, syllables differing in a consonant, syllables differing in a vowel and syllables differing in both a consonant and a vowel. Participants were required to complete a phoneme discrimination task during fMRI scanning.

In line with the results from the present research, Boets et al. (2013) report that while both groups of participants were at ceiling on the phoneme-discrimination task, individuals with dyslexia were significantly slower to make their response. Analysis of neuroimaging data revealed that both dyslexic and control participants showed similar patterns of neural activation during the discrimination task, which the authors interpreted as evidence of intact phonological representations in individuals with dyslexia. However, participants with dyslexia displayed evidence of weaker connectivity between frontal and temporal language areas, which the authors interpreted as evidence of impaired access to phonological representations.

However, as acknowledged by Ramus (2014), it is most widely held that the phonological deficit observed in children with dyslexia primarily arises from inaccurate or “fuzzy” phonological representations (Fowler, 1991; Snowling & Hulme, 1994). This dominant view is also consistent with the present results, in that poorly specified representations would presumably take longer to access, therefore, children with dyslexia and impaired phonological representations would take longer to decide whether a sound is speech or not.

While it is beyond the scope of the present research to settle the debate regarding the nature of the phonological deficit in dyslexia, the unexpected finding that baseline response time on the letter-sound priming task is a significant predictor of reading highlights the importance of phonological skills and the need for further investigation. A challenge facing future research is to tease apart phonological representations and access to these representations, in order to measure their independent contribution in learning to read.

7.4 Concluding thoughts

The aim of this thesis was to assert whether problems learning to read are related to a specific deficit in establishing automatic associations between letters and speech-sounds.

It is clear from this research that typically developing children with approximately two years of reading experience have formed strong associations between visual and auditory representations of letters. According to the logic of Posner and Snyder (1975), the results from this study indicate that letters and speech-sounds have become automatically integrated as children show clear evidence of facilitation, but not inhibition. Future research is needed to further investigate the automaticity of processes underlying performance on the letter-sound priming task.

Overall, the findings from this research do not support the theory that reading difficulties are the result of impaired or weakened associations between letters and speech-sounds (Blomert, 2011). The present research represents one of the first attempts to systematically test this claim using behavioural methods. As such, it is particularly noteworthy that individual differences in the extent to which letters and speech-sounds are integrated were not found to predict variance in reading skill. Furthermore, in contrast to previous work, the present findings indicate that children with dyslexia show the same amount of letter-sound integration as younger typically developing children matched for reading age. Thus, the findings reported here suggest that letter-sound integration is most likely to emerge as a consequence of children’s reading experience, rather than drive differences in the development of reading.

In addition, results from this research revealed that baseline response times on the priming task were predictive of children’s reading performance, above and beyond established predictors of reading. This finding is intriguing and may provide additional support for the role of phonological processing skills in learning to read. Thus, while research has come a long way in understanding why children with dyslexia struggle to learn to read, it is clear that there is still much to be done in order to fully understand the complex nature of the phonological deficit in dyslexia.

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Appendices

Appendix 1 Simple and partial correlations between measures of RAN (transformed data) and letter-sound integration

	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
1. RAN Digits		.74*** 136	.67*** 160	.08 162	-.04 162	-.34*** 162	-.34*** 162	-.38*** 162
2. RAN Letters	.69*** 136		.54*** 132	-.05 133	-.05 133	-.27** 133	-.33*** 133	-.29*** 133
3. RAN Objects	.61*** 160	.46*** 132		.15 159	.08 159	-.29*** 159	-.24** 159	-.25** 159
4. Facilitation	-.01 162	-.17 133	.07 159		.44*** 212	-.46*** 212	.12 212	-.22** 212
5. Interference	-.11 162	-.12 133	.02 159	.42*** 212		-.38*** 212	-.15* 212	.19** 212
6. Baseline Ave RT	-.18* 162	-.09 133	-.13 159	-.41*** 212	-.35*** 212		.83*** 212	.83*** 212
7. Congruent Ave RT	-.22** 162	-.21* 133	-.11 159	.23*** 212	-.09 212	.79*** 212		.788*** 212
8. Incongruent Ave RT	-.25** 162	-.15 133	-.11 159	-.14* 212	.30*** 212	.79*** 212	.75*** 212	

*Note: *** = p <.001, ** = p <.01, * = p <.05. Simple correlations above the diagonal and partial correlations controlling for age below the diagonal. N for each correlation reported beneath coefficient. See Table 3.9 for comparison with non-transformed data.*

Appendix 2 Simple and partial correlations between measures of RAN (transformed data) and performance on the letter-sound matching task

	1.	2.	3.	4.	5.	6.	7.
1. RAN Digits		.70*** 34	.58*** 46	-.29* 47	-.35* 47	-38** 47	-.33* 47
2. RAN Letters	.69*** 34		.40* 33	-.51** 34	-.56** 34	-.52** 34	-.55*** 34
3. RAN Objects	.57*** 46	.39* 33		-.11 46	-.09* 46	.10 46	.10 46
4. 0MS Congruent Ave RT	.29 47	.50** 34	-.09 46		.06 48	.71*** 48	.73*** 48
5. 0MS Incongruent Ave RT	-.35* 47	.55** 34	-.07 46	.80*** 48		.08 48	-.07 48
6. 500MS Congruent Ave RT	-.37** 47	-.50** 34	-.07 46	.69*** 48	.60*** 48		.80*** 48
7. 500MS Incongruent Ave RT	-.33* 47	-.55** 34	-.10 46	.74*** 48	.63*** 48	.82*** 48	

*Note: *** = p <.001, ** = p <.01, * = p <.05. Simple correlations above the diagonal and partial correlations controlling for age below the diagonal. N for each correlation reported beneath coefficient. See Table 4.5 for comparison with non-transformed data.*

Appendix 3 Simple correlations between different measures of letter-sound integration (using transformed Priming: Congruent Ave RT data)

	2.	3.	4.	5.	6.	7.	8.	9.
1. Priming: Facilitation	.34*	-.12	.40**	.07	-.07	.06	-.08	-.13
2. Priming: Interference		-.34*	.09	.21	-.20	-.03	-.18	-.20
3. Priming: Baseline Ave RT			-.83***	.84***	.66***	.57***	.71***	.62***
4. Priming: Congruent Ave RT				-.81***	-.60***	-.55**	-.66**	-.55***
5. Priming: Incongruent Ave RT					.57***	.57***	.64***	.54***
6. Matching: Congruent 0ms SOA Ave RT						.80***	.71***	.73***
7. Matching: Incongruent 0ms SOA Ave RT							.61***	.63***
8. Matching: Congruent 500ms SOA Ave RT								.80***
9. Matching: Incongruent 500ms SOA Ave RT								

*Note: *** = p <.001, ** = p <.01, * = p <.05. See Table 4.7 for comparison with non-transformed data. N=46.*

Appendix 4 Simple correlations between age and performance on reading, non-verbal reasoning and reaction time measures (using transformed WASI Matrix Reasoning and LS Baseline RT data)

	2.	3.	4.	5.	6.	7.	8.	9.
1. Age	-.25* 77	.50*** 77	.49*** 76	.45*** 75	.48*** 45	-.29* 77	-.18 74	-.28* 77
2. WASI Matrix Reasoning		-.52*** 77	-.51*** 76	-.45*** 75	-.48*** 75	.13 77	.04 74	.25* 77
3. SWRT			.92*** 76	.89*** 75	.97*** 75	-.31** 77	-.09 74	-.33** 77
4. TOWRE-SDE				.88*** 75	.96*** 75	-.34** 76	-.14 73	-.34** 76
5. TOWRE-PDE					.96*** 75	-.37** 75	-.08 72	-.22 75
6. Reading composite						-.36** 75	-.11 72	-.28* 75
7. LS Baseline RT							.37** 74	.17 77
8. AS Baseline RT								.21 74
9. Simple RT								

*Note: * = p < .05 ** = p <. 01, AS = Animal sound LS = Letter sound. See Table 6.6 for comparison with non-transformed data.*

Appendix 5 Simple and partial correlations between reading and average response times on the two priming task measures (using transformed LS Baseline / Congruent / Incongruent RT and AS Congruent / Incongruent RT data)

	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**	**10.**
1. SWRT		.92***	.89***	.97***	-.31**	.25*	-.40***	-.09	.12	-.05
		76	75	75	77	77	77	74	74	74
2. TOWRE-SDE	.89***		.88***	.96***	-.34**	.34**	-.44***	.14	.16	-.07
	76		75	75	76	76	76	73	73	73
3. TOWRE-PDE	.87***	.85***		.96***	-.37**	.28*	-.41***	-.08	.14	-.02
	75	75		75	75	75	75	72	72	72
4. Reading Composite	.96***	.95***	.95***		-.36**	-31**	-.43***	-.12	.12	-.04
	75	75	75		75	75	75	72	72	72
5. LS Baseline RT	-.20	-.24*	-.28*	-.27*		-.78***	.80***	.38**	-.35**	.38***
	77	76	75	75		77	77	74	74	74
6. LS Congruent RT	.17	.27*	-.21	.24*	-.76***		-.74***	-.53***	.54***	-.57***
	77	76	75	75	77		77	74	74	74
7. LS Incongruent RT	-.28**	-.34**	-.30*	-.32**	.77***	-.73***		.42***	-.37**	.38***
	77	76	75	75	77	77		74	74	74
8. AS Baseline RT	-.00	-.06	-.00	-.03	.35***	-.51***	.39**		-.75***	.83***
	74	73	72	72	74	74	74		74	74
9. AS Congruent RT	.00	.05	.03	.01	-.30**	.51***	-.32**	-.74***		-.79***
	74	73	72	72	74	74	74	74		74
10. AS Incongruent RT	.00	-.02	.03	.01	.37**	.56***	.37***	.83***	-.80***	
	74	73	72	72	74	74	74	74	74	

*Note: * = p < .05 ** = p <. 01. See Table 6.7 for comparison with non-transformed data.*

Appendix 6 Simple and partial correlations between non-verbal reasoning, simple reaction time and average response times on the two priming tasks (using transformed WASI Matrix Reasoning, LS Baseline / Congruent / Incongruent RT and AS Congruent / Incongruent RT data)

	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
1. WASI Matrix Reasoning		-.25*	-.16	.11	-.18	-.08	.03	-.03
		77	77	77	77	74	74	74
2. Simple RT	-.28*		.20	-.23*	.21	.21	-.08	.10
	77		77	77	77	74	74	74
3. LS Baseline RT	-.11	.17		-.78***	.80***	.38**	-.35**	.38***
	77	77		77	77	74	74	74
4. LS Congruent RT	.08	-.11	-.76***		-.74***	-.53***	.54***	-.57***
	77	77	77		77	74	74	74
5. LS Incongruent RT	-.13	.13	.77***	-.73***		.42***	-.37**	.38***
	77	77	77	77		74	74	74
6. AS Baseline RT	-.04	-.14	.35***	-.51***	.39**		-.75***	.83***
	74	74	74	74	74		74	74
7. AS Congruent RT	-.02	-.04	-.30**	.51***	-.32**	-.74***		-.79***
	74	74	74	74	74	74		74
8. AS Incongruent RT	-.01	.01	.37**	.56***	.37***	.83***	-.80***	
	74	74	74	74	74	74	74	

*Note: * = p < .05 ** = p <. 01. See Table 6.8 for comparison with non-transformed data.*