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Episodic traces and statistical regularities: Paired associate learning in typical and dyslexic readers

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ABSTRACT

Learning visual-phonological associations is a key skill underlying successful reading acquisition. However, we are yet to understand the cognitive mechanisms that enable efficient learning in good readers, and those which are aberrant in individuals with developmental dyslexia. Here, we use a repeated cued-recall task to examine how typical and reading-impaired adults acquire novel associations between visual and phonological stimuli, incorporating a looking-at-nothing paradigm to probe implicit memory for target locations. Cued recall accuracy revealed that typical readers' recall of novel phonological associates was better than dyslexic readers' recall, and it also improved more with repetition. Eye fixation-contingent error analyses suggest that typical readers' greater improvement from repetition reflects their more robust encoding and/or retrieval of each instance in which a given pair was presented: whereas dyslexic readers tended to recall a phonological target better when fixating its most recent location, typical readers showed this pattern more strongly when the target location was consistent across multiple trials. Thus, typical readers' greater success in reading acquisition may derive from their better use of statistical contingencies to identify consistent stimulus features across multiple exposures. We discuss these findings in relation to the role of implicit memory in forming new visual-phonological associations as a foundational skill in reading, and areas of weakness in developmental dyslexia.

1. Introduction

Converting letters into sounds is a fundamental skill in reading acquisition, explaining both clinical and sub-clinical individual differences in reading abilities. Poor visual-phonological mapping is a defining feature of developmental dyslexia (Lervåg & Hulme, 2010; Warmington & Hulme, 2012; Wimmer, 1993), and an emerging body of research suggests that competence in forming novel visual-phonological associations provides a strong, unique predictor of reading ability among typical readers as well (Ehri, 2005; Ehri & Saltmarsh, 1995; Wang, Allen, Lee, & Hsieh, 2015). Yet, despite repeated demonstrations of visual-phonological mapping skills as an important explanatory variable in reading, the cognitive mechanisms underlying them remain largely unknown. In this paper, we consider the contributions of episodic memory and statistical learning to typical and dyslexic adult readers' acquisition of new visual-phonological associations over multiple exposures.

1.1. Learning new visual-phonological associations

In the domain of reading, learning visual-phonological associations can be considered the cornerstone of letter-sound acquisition, and is duly instantiated in connectionist models of orthographically driven phonological retrieval (Harm & Seidenberg, 1999; Manis, Seidenberg, & Doi, 1999; Seidenberg & McClelland, 1989). Seidenberg and McClelland's (1989) model, for instance, characterises skilled reading as a mapping from letters to phonological forms, gradually acquired via a backpropogation algorithm that is best understood as implementing implicit or statistical learning. Implicit learning can also leverage explicit memory (e.g. McClelland, McNaughton, & O'reilly, 1995), a relationship often emphasised by phonological-awareness-based approaches to reading instruction (e.g. Seidenberg, 2017).

One method that researchers have used to examine the relationship between novel visual-phonological mapping and reading acquisition is *paired associate learning* (cf. Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Vellutino, Steger, Harding, & Phillips, 1975; Wang, Wass, & Castles, 2016). This method uses explicit cued recall (e.g. "Which word goes with this picture/shape?") to probe participants' gradual

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acquisition of associations between arbitrarily paired stimuli, typically over the course of four or five repetitions. Recall of unimodal associations (e.g., a visual object paired with another visual object or a sound paired with another sound) is typically used to establish a baseline, whereas recall of cross-modal associations (e.g., a visual object paired with an auditory stimulus), is assumed to more directly reflect the cross-modal skills necessary for learning to read. It has recently been claimed that only cross-modal association recall contributes unique variance to reading abilities, as evidenced in measures such as exception word reading, nonword decoding, and reading speed (Hulme et al., 2007; Warmington & Hulme, 2012), perhaps because readers specifically use their visual-phonological paired-associate learning abilities in forming orthographic knowledge (Wang et al., 2016). For more general reading measures, particularly those relying more on a verbal component, the cross-modal aspect of paired-associate learning is less important than the verbal component *per se* (Litt, de Jong, van Bergen, & Nation, 2013; Litt & Nation, 2014).

As well as predicting variation in reading skill among typical readers, paired-associate learning performance discriminates dyslexic from typically developing children and adults: individuals with dyslexia typically recall associated representations much less accurately (Jones, Ashby, & Branigan, 2013; Litt & Nation, 2014; Messbauer & de Jong, 2003; Vellutino, Scanlon, & Spearing, 1995; Wimmer, Mayringer, & Landerl, 1998). If visual-phonological association learning is impaired in dyslexia, what then are the cognitive mechanisms that allow skilled readers to form stable associations where those with dyslexia cannot? Because paired-associate learning in reading research is typically considered an index of a reading-related subskill—without explicit reference to specific underlying cognitive processes—we suggest that resituating it within a working memory framework may help delineate mechanisms under lying success and failure in this skill.

1.2. Learning mechanisms

Beyond paired-associate learning—reflecting early acquisition processes—visual-phonological associations remain impaired in dyslexia, even for highly-overlearned pairings, such as letter-to-letter sound associations (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Jones, Kuipers, & Thierry, 2016; Žarić et al., 2015). Failure to learn efficiently during the first exposures must therefore have long-term consequences for memory consolidation, despite potentially ameliorating factors such as practice and maturation (Snowling, 2000). What then are the cognitive mechanisms that allow skilled readers to form stable associations where readers with dyslexia cannot?

In the working memory literature, forming visual-phonological associations can be considered a subtype of *binding*, that is, integrating individual features to create a compound representation that can be retrieved as a single unit (Brockmole & Franconeri, 2009). Although associations can eventually be encoded into long term memory, establishing a novel binding—such as a new visual/phonological pairing—requires maintenance in a capacity-limited episodic buffer (Baddeley, Allen, & Hitch, 2011), placing significant demands on attentional resources (Hommel & Colzato, 2009; Vanrullen, 2009). Novel bindings also crucially depend on spatial-temporal proximity for detecting and recalling associations (Logie, Brockmole, & Jaswal, 2011; Treisman, 2006; Treisman & Gelade, 1980; Treisman & Zhang, 2006).

Episodic encoding and retrieval of such spatial-temporal proximities has been cited as a basis for a "looking-at-nothing" (LAN) phenomenon, in which verbally recalling auditory information is associated with looks to previously relevant screen locations (Ferreira, Apel, & Henderson, 2008; Hoover & Richardson, 2008; Jahn & Braatz, 2014; Laeng, Bloem, D'Ascenzo, & Tommasi, 2014; Richardson & Spivey, 2000; Scholz, Mehlhorn, & Krems, 2016; but see Staudte & Altmann, 2017). Due to the overlap in processes engaged in the encoding and retrieval of an event stored in episodic memory, activating spatial information may spread to the oculomotor programme conducted during encoding, which then triggers associated visual and/or auditory components learned during encoding (Johansson, Holsanova, Dewhurst, & Holmqvist, 2012; Johansson & Johansson, 2014; Laeng et al., 2014). Perhaps the strongest functional interpretation of looking-at-nothing claims a relationship between eye movements and verbal recall, in which stronger tendencies to look-at-nothing are associated with increased accuracy (Scholz et al., 2016; Wantz, Martarelli, & Mast, 2016).

Recalling features of episodic memories, such as the spatial configuration of an item display during encoding, may therefore involve rebinding multimodal (e.g., visual-phonological) representations. This rebinding may be an important ability underlying reading acquisition, as evidenced by its impairment in readers with dyslexia: we have previously found that, following a single exposure, adult typical readers recall visual-phonological pairs more accurately than dyslexic readers, but this difference only emerges in the presence of spatial cues (Jones, Branigan, Parra, & Logie, 2013).

Fluent reading involves automatizing access to visual-phonological associations (Froyen, Bonte, van Atteveldt, & Blomert, 2009; Froyen, Willems, & Blomert, 2011; Jones et al., 2016). Thus, episodic contributions to visual-phonological mappings must gradually decrease as repeated presentations of letter-sound correspondences strengthen implicit pathways for reading (Denckla & Rudel, 1976; Jones, Obregón, Kelly, & Branigan, 2008; Jones et al., 2013; LaBerge and Samuels, 1974). We might therefore expect such episodic memory-based effects to decrease with practice. Here, it may be useful to consider letter learning as an example of the more general process of category learning: skilled reading would be impossible without identifying each printed letter (e.g. b, *b*, or B) as an instance of its more general letter category ('b'), inheriting learned knowledge about that category (that it maps to the sound /b/). Exemplar-based theories of category learning (e.g. Hintzman, 1986; Medin & Schaffer, 1978; Nosofsky, 1986), describe a process whereby each instance of a stimulus is stored in memory and contributes to category development: as learning progresses, category use becomes less dependent on the details of any particular instance (e.g., Kruschke, 1992; Logan, 2002; Love, Medin, & Gureckis, 2004). Implicit or statistical learning can be thought of as the process of developing these more 'abstracted' representations (see also Altmann, 2017).

Indeed, the ability to track simple statistics, such as sensitivity to repeated stimuli and stimulus sequences is a strong predictor of reading ability (cf. Ahissar, 2007). For instance, implicit memory for previous exposures to perceptual stimuli has been shown to decay more quickly in dyslexic readers compared with typical readers (Jaffe-Dax, Frenkel, & Ahissar, 2017; Jaffe-Dax, Lieder, Biron, & Ahissar, 2016; Jaffe-Dax, Raviv, Jacoby, Loewenstein, & Ahissar, 2015). Such decay may reflect dyslexic readers' failure to adequately encode previous instances of a given stimulus, leading to 'noisy' or ineffective processing of the current instance (Jaffe-Dax et al., 2017, 2016, 2015). Although this explanation has primarily been applied to extracting central tendencies from perceptual instances, it seems plausible that poor encoding of individual instances could similarly affect processes such as the gradual automatization of access to bound visual-phonological representations.

1.3. The current study

In the above, we have described a view of reading acquisition wherein skilled reading development involves a transition from an initial stage, in which reading depends on recalling visual-phonological bindings as presented in individual episodes, to later stages, in which it depends more on integrated mappings developed through repetition, that is, shifting from recalling a specific instance to recalling statistical tendencies. Extant literature suggests that dyslexic readers experience difficulty with both.

The current study therefore directly compares typical and dyslexic readers' acquisition of new shape-nonword pairs, via a paired-associate learning paradigm in which we track cued recall accuracy as a function