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The slow development of real-time processing:

Spoken Word Recognition as a crucible for new thinking about language acquisition and disorders.

Running Head: Development of real-time processing

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Abstract

Words are fundamental to language, linking sound, articulation and spelling to meaning and syntax; and lexical deficits are core to communicative disorders. Work in language acquisition commonly asks how lexical knowledge – the sound pattern and meaning of words – is acquired. This is insufficient to account for skilled behavior. Sophisticated real-time processes must decode the sound pattern of words and interpret them appropriately. This paper reviews work that bridges this gap by using sensitive real-time measures of language processing (eye-tracking in the Visual World Paradigm) along with highly familiar words with school-age children. This work reveals that the development of word recognition skills can be characterized by differences in the rate by which decisions unfold in the lexical system (the activation rate) and that this develops extremely slowly – through adolescence. In contrast language disorders can be linked to differences in the ultimate degree to which competing interpretations are suppressed (competition resolution), and this can be mechanistically linked to deficits in inhibition. This has implications for real-world problems such as reading and second language acquisition. It suggests that developing accurate, flexible, and efficient processing is just as important a developmental goal as is acquiring language knowledge.

Key words: Word recognition, speech perception, real-time processing, development, language acquisition, language disorders, developmental language disorder, inhibition

**The slow development of real-time processing:
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Words are fundamental to language, linking sound, articulation and spelling to meaning and syntax. Because of this centrality, lexical processing deficits may underlie higher-level language disorders (Nation, 2014; Stothard et al., 1998). Consequently, vocabulary acquisition is a central topic in language development (Samuelson & McMurray, 2017). The majority of this work emphasizes knowledge: how do children learn the meanings of words given the ambiguity in word learning situations?

But learning is only half the challenge. Even with a robust vocabulary, active processes must be engaged to use that knowledge in the moment. Words have multiple meanings and must be interpreted relative to context (Elman, 2009). Even at the level of sound, words are briefly ambiguous. The onset of a word like *wizard* (*wi-*) is consistent with many words (*wizard*, *whistle*, *window*, etc). Listeners must cope with this *temporary ambiguity* to efficiently process language. Children must solve these problems to effectively use the rich knowledge that words bind. Thus, becoming a skilled language user requires learners to acquire both word knowledge (sound-patterns and meanings) and also real-time skills to use that knowledge in the moment.

Our own work has addressed these questions by examining processing in highly familiar words in school-age children. Studies of older children enable adult psycholinguistic methods that go beyond speed-of-processing to measure dynamically unfolding lexical representations more directly. Even in this context, it is difficult to dissociate differences in processing from knowledge. A child may present with less efficient or flexible real-time skills because those skills are not fully developed (even as linguistic knowledge is) or because representations are incomplete in some way. Our argument is that changing the emphasis to processing raises

Figure 1: Lexical competition. A) Activation from the TRACE model (McClelland & Elman, 1986) after the model hears the target word *wizard*. TRACE activates a wide range of candidate words over time, starting from a resting level of 0 and many are inhibited (with activity below 0 by the end of processing). Competitors can include *cohorts* (which overlap with the target word at onset), *rhymes* (which overlap at offset) and other types of words. B) In a typical VWP study of word recognition (Allopenna et al., 1998), participants hear a target word like *wizard* in the context of pictures representing the target, cohort and/or rhyme competitors (*whistle* and *lizard*), and an unrelated baseline (*beaver*). C) Fixations over time in this paradigm (data from the TD group of McMurray et al., 2010; Stothard et al., 1998). Early in the trial, listeners fixate both the target (e.g., *wizard*) and cohort competitors (e.g., *whistle*). Later they begin to suppress the cohort, but may also fixate a rhyme competitor (*lizard*). By around 1 second, they are fully committed to the target.

critical questions about how children become skilled language users that are not addressed by standard approaches that focus on acquiring word knowledge.

Spoken Word Recognition

The process of mapping sound to meaning is served by *competition* (Dahan & Magnuson, 2006). When listeners hear the onset of a word (the *wi-* in *wizard*), they activate a range of candidates (*whisper*, *window*) which compete (Figure 1A). This process does not passively reflect the unfolding input. Competition dynamics are biased by word frequency and inhibition from neighbors, and words without a strict temporal match are activated—listeners might activate *lizard* after hearing *wizard*, or *pack* after hearing *cap*. Thus, competition weighs and combines evidence for words to flexibly cope with ambiguity.

This view is supported by measures that trace the timecourse of competition in real-time. In the Visual World Paradigm [VWP] (Figure 1B; Allopenna et al., 1998), listeners hear a word and select its referent from an array of pictures including the target and competitors (for *wizard*,

94 *whistle* and *lizard*). To locate the correct picture, participants make several fixations to the
95 various pictures while lexical processing unfolds. Critically, fixations reflect processing at the
96 point when they are launched. Thus, at the onset of *wizard* (*wi-*), listeners may fixate the target
97 and onset (cohort) competitor (*whistle*); however, later in the word, fixations to *whistle* decrease,
98 even as *lizard* is considered (Figure 1C).

100 **The Development of Real-Time Word Recognition**

101 The first developmental studies of real-time lexical processing used a simplified VWP
102 with toddlers (e.g., Fernald & Marchman, 2012). They found development in speed of word
103 recognition that predicts later language. Our work built on this in older children (9- and 16-year-
104 olds) using more sophisticated VWP tasks that more fully characterize the dynamics of word
105 recognition (Rigler et al., 2015). We found clear evidence of development: 16-year-olds
106 converged on the target and resolved competition more rapidly than 9-year-olds (Figure 2A, D)
107 (see also Sekerina & Brooks, 2007). Speech and word recognition were thought to develop
108 during the infant and toddler years (Werker & Curtin, 2005). By this standard, this was
109 shockingly late.

110 This was highlighted by a study examining even lower-level speech perception skills.
111 McMurray et al. (2018) used the VWP to test children's sensitivity to the structure of speech
112 categories using continua spanning similar words (*bear/pear*, *sip/ship*) in small uniform steps.
113 Categorization functions (the mouse-click response; Figure 3A) were steep even at 7 years, with
114 a small (though significant) steepening over development (Hazan & Barrett, 2000). More
115 dramatic changes were seen earlier in processing by using the fixation record to construct
116 categorization functions showing commitment to B or P as processing unfolds (Figure 3B,C;

Figure 2: In typically developing children (Rigler et al., 2015) (Panels A, B) fixations to the target (A) show steeper slopes over development while cohort competitors (B) show reduced competition early in processing. In contrast, when we examine variation in language ability within 16-17 year old adolescents (McMurray et al., 2010) (Panels C, D), Developmental Language Disorder (DLD) is associated with changes in the late asymptotes, with lower asymptotic target fixations (C), and higher cohort fixations (D). Finally, prelingually deaf school-age children who wear a Cochlear Implant (CI) (Panels E, F) (McMurray et al., 2017) show a “wait and see” profile. Here, target fixations are substantially delayed (by upwards of 200 msec) (E), and this results in reduced peak cohort fixations (F).

<http://osf.io/w5bqq> for animations). Early in processing, there was marked development even between 12- and 18-years. Moreover, older children showed more gradient sensitivity to the continuum step than younger children (Figure 3B), suggesting increased attunement to acoustic/phonetic detail between 7 and 18. This contrasts with standard perceptual narrowing accounts (Maurer & Werker, 2014) which posit that children lose access to within-category differences.

Again, this is surprisingly late. Obviously, 7-9-year-olds have the relevant knowledge. A typical 9-year-old knows thousands of words (and these experiments used simple words like *bees* and *ship*), and categories like B and P are in place by 4 months (Galle & McMurray, 2014). Yet we see development in the ability to use this knowledge.

Why do these real-time processes develop? Word recognition (and much of language) requires learners to simultaneously be accurate, efficient and flexible. Listeners could wait until

Figure 3: A) Identification of speech continuum (ranging from B to P) in small steps. Note that VOT is expressed relative to each participant's own boundary such that 0 is the participant's boundary, -1 is one step to the left and so forth. Examining the categorization function over development shows a small but significant steepening of the function. B) VWP fixations can be converted to a similar measure to show how this categorization unfolds over time. Here a fixation bias of -1 indicates that the listener is fully committed to B, while a bias of +1 indicates a complete commitment to P. At 300 msec post-stimulus (adjusted for the oculomotor delay), 7-8 year old children show little departure from 0 at any step along the continuum, suggesting they have not yet begun to categorize the sounds. However, older children show some departure, with differences between 12-13 and 17-18 y.o. children. At later times (C-E), the categorization function expands, but developmental differences can be seen throughout. F) Proportion of looks to the competitor (area under the curve) as a function of distance from the category boundary, for trials in which the child chose the "correct" phoneme. Older children (blue lines), like adults, show a gradient response with competition falling off as the continuum step departs in either direction from the boundary at 0. This suggests robust sensitivity to fine grained detail. In contrast, younger children show heightened competition overall, and reduced sensitivity. G) Adolescents with DLD (McMurray et al., 2014) show a strong gradient effect, but differ from typically developing children in the overall amount of competition (consistent with difficulties in resolution).

129 the end of a word to begin lexical access, bypassing temporary ambiguity and maximizing
 130 accuracy. However, this would be slow as downstream processes would have to wait for the
 131 end of the word. Conversely, if listeners are too rapid to commit to a target and suppress
 132 competitors, this would be inflexible—an early misperception would be hard to overcome when
 133 later information arrives. A goal of development may be to tune processing along such
 134 dimensions.

135

Individual Variation in Language Ability (Language Disorders)

The standard view is that language disorders derive from incomplete “knowledge” (e.g., number of words known, the depth of lexical knowledge), driven by differences in learning (Ullman et al., 2020). In contrast, we hypothesized that if real-time lexical competition plays a functional role in language ability, then language difficulties may derive from difficulties achieving efficiency and flexibility. Our first study examined Developmental Language Disorder (DLD, previously termed Specific Language Impairment). DLD affects 12-15% of children (Tomblin et al., 1997) and is characterized by poor language without obvious cause. DLD may not be a distinct disorder, and may simply be the low end of the ability range (Reilly et al., 2014). Indeed, it is diagnosed with *continuous* measures of language, scored against a normative sample *relative to age*. Thus, DLD is a convenient proxy for variation in language ability.

McMurray et al. (2010) used the same VWP task as Rigler et al. (2015) with older adolescents with and without DLD. Children with lower language ability were as quick as typical children to initially activate candidates (Figure 2C, D). However, later in the trial (at asymptote) target fixations were lower, and competitors were never fully suppressed, even as children chose the correct object. This profile is consistent with studies using other paradigms (Dollaghan, 1998; Helenius et al., 2009), and was not related to non-verbal cognitive ability.

Such a deficit could relate to overall language via multiple routes. If a child keeps multiple candidates active for each word, this could affect downstream sentence processing. Alternatively, since competition is thought to underlie every level of language, the deficits seen here could be a biomarker of poor competition resolution throughout the system.

Dimensions of Individual Differences in Processing

These studies suggest variation in ability over development has a distinct profile from variation in ability within an age (DLD). Over development (Figure 2A,B), lexical competition initiates and resolves more quickly, whereas DLD is associated with lingering unresolved

competition (Figure 2C,D). Children with DLD are not just behind; they cope with temporary ambiguity differently and less effectively. These profiles may reflect something like two latent traits: **activation rate** and **competition resolution**. Though we focus our discussion on lexical processing, the fact that language processing at every level may use activation/competition mechanisms means that this framing could be extended to many levels of language.

Activation Rate. Activation rate is the rate at which information in the inputs impacts lexical activation. This could be determined in part by fidelity of perceptual encoding—greater perceptual fidelity provides more information to discriminate words. This is supported by our finding that older children are increasingly sensitive to fine-grained acoustic detail (Figure 3F). It is also seen in children with hearing impairment (McMurray et al., 2017) and adults in challenging listening conditions (Hendrickson et al., 2020; McMurray et al., 2017). In these situations, word recognition can be delayed by as much as 250 msec (Figure 2C) as each “slice” of the input contains less information. This results in less consideration of cohorts (Figure 2E), a pattern colloquially termed **wait and see**. Thus, activation rate is not simply processing speed; variation in activation rate has complex consequences.

Over development, differences in activation rate likely derive from changes internal to the lexical system. Computational modeling suggests activation rate is affected by the strength of connections between phonemes and words (McMurray et al., 2010) or by the degree to which irrelevant connections between phonemes and words are pruned (McMurray et al., 2012). In such models, phonological representations of words are stored in these connections. Thus, improvements in activation rate could reflect refinement in the stored sound patterns of words. However, there may be across-the-board changes reflecting a latent trait – children could have higher or lower activation rates (more robust connections) across all words. Either way, improving this pathway would speed up both the initial commitment to candidates (activating *wizard* and *window* after “wi...”) and the elimination of competitors (since disconfirming input has a larger impact).

Competition Resolution. Competition resolution reflects the degree to which competitors are ultimately suppressed when the system stabilizes. Incomplete resolution is typically maladaptive (see Gernsbacher, 1997, for related ideas in higher level language). However, in cases of phonetic ambiguity or hearing difficulty, it may be useful to keep competitors available in case listeners must revise.

Several mechanisms may contribute to resolution. Simulations in McMurray et al. (2010) link resolution to *decay of activation* (Helenius et al., 2009). When the target word cannot maintain its activity, it inhibits competitors less, giving rise to the effects in Figure 2C,D. *Lateral inhibition* among words within the lexicon (Dahan et al., 2001) may also contribute: As one word becomes more active than its neighbors, it suppresses them. This form of inhibition is distinct from domain-general cognitive control (and not correlated with it: Kapnoula & McMurray, in press), as well as conceptions of inhibition from classic learning theory (e.g. pruning connections). Lateral inhibition cannot have effects until words become somewhat active, thus its effects arise late, as a sort of clean up operation.

This framing makes two predictions for DLD. First, researchers have proposed a perceptual locus to DLD (Goswami et al., 2016). Perceptual deficits should appear in *activation rate* as they impact the ability to extract information from the signal. We tested a perceptual deficit in adolescents with DLD using a similar paradigm to (McMurray et al., 2018; Figure 3G). If DLD listeners struggle with perceptual skills, they should have shown different levels of sensitivity to within-category differences (like 7-year-olds). They did not, despite increased competition across all continuum steps (Figure 3E). Second, we tested lexical inhibition using a paradigm in which the target word's acoustics were manipulated to boost a competitor (which then inhibits the target). In this paradigm, those with DLD showed no evidence for inhibition (McMurray et al., 2019). Together, this supports a distinctly lexical deficit in DLD, isolated to resolution.

A non-linguistic locus?

A critical question is whether these results reflect development or differences in task-specific factors (e.g., eye-movement control) or domain-general skills (e.g., working memory, cognitive control). Converging evidence suggests this is not the whole story. With respect to the former, effects of DLD are not due differences in eye-movement control (McMurray et al., 2010) and mirror effects found in other paradigms (Dollaghan, 1998; Helenius et al., 2009). Moreover, effects on competitor fixations are significant even after unrelated fixations are subtracted or partialled out (McMurray et al., 2018; McMurray et al., 2014; Rigler et al., 2015). With respect to the latter, our DLD studies find no effects of non-verbal cognitive skills (McMurray et al., 2010), and the CI users in Figure 2E,F, show no differences in a completely non-speech analogue to the VWP (McMurray et al., 2017). It is unclear whether developmental effects derive in part from general cognitive development (e.g., cognitive control), and ongoing longitudinal work may achieve a more definitive answer.

Implications and Future Directions

This work suggests language development research must move beyond questions of how a child “knows” words to ask what they can do with them in the moment. We focused on one process: accumulating auditory input to recognize a wordform. However, ambiguity can arise at multiple levels. Even if a child knows the word *chicken*, they have to deal with phonetically reduced forms (“chi’n”), temporary ambiguity, and ambiguity in the intended meaning (the food? the animal?). The real-time mechanisms that sort this out are as important to language competency as is knowledge.

Real-time development changes the developmental story. The canonical story is that speech and word recognition develop during infancy (Werker & Curtin, 2005): infants first master the sounds of language and then master higher-level skills. However, an examination of real-time processing suggests these skills develop slowly—perhaps concurrently with higher-

level skills. This offers new solutions to the classic problem of how children learn the sounds of language. Infants know few words, cannot produce speech, and don't get feedback on their perception. If speech sounds are acquired early unsupervised learning may be the only available mechanism (Werker & Curtin, 2005). In contrast, if speech development is slow, learning could use semi-supervised mechanisms, bootstrapping off the later-developing lexicon, speech production skills, richer social interactions, and reading instruction.

In addition to questions of learning, are these real-time processes plastic? Recent work suggests lexical inhibition is amenable to training (Kapnoula & McMurray, 2016): brief training on tasks that encourage competing words to be co-active (e.g., discriminating similar words) can strengthen inhibitory pathways and help participants recover from interference. It is unclear if other aspects of real-time processing are amenable to training. However, such plasticity may be how resolution is tuned to maximize flexibility and efficiency, and it could pave the way to remediation approaches for DLD.

Finally, how do children learn to balance efficiency, flexibility and accuracy? School may be a catalyst for this, as children are exposed to more words, to reading, and to a more diverse set of talkers. To the extent that such development hinges on minimizing the cost of an error, balancing these factors may require experience with mistakes, which are likely infrequent, further slowing development.

Other domains. Our broader hypothesis is that activation rate reflects development or skill acquisition, whereas resolution reflects processes that stabilize representations later in processing. These constructs may be useful in other domains. For example, written word recognition relies on similar competition mechanisms as spoken words (Rastle, 2007). Thus, these constructs may prove similarly diagnostic for understanding variation in reading development or disorders (c.f., Roembke et al., in press). Second-language acquisition may present similar challenges as learners must recognize words with poorer representations, and manage competition from two lexica. Diagnostics of activation rate and resolution can reveal

whether poorer performance is due to a lack of practice or difficulties managing competition (Sarrett et al., in press).

Knowledge vs. Processing

At a neural level, learning/representation may seem dissociable from processing. Neural mechanisms that contribute to learning (long-term potentiation and synaptogenesis) differ from those involved in processing (activation flow, lateral inhibition). Yet each may be shaped by the other: long-term potentiation reflects the amount of activity, and processing takes place over learned connections. This makes it difficult to dissociate representation from processing, and we are not advocating for a strong distinction. However, a focus on processing poses new questions that address problems (that children solve) that are entirely different from those that motivate typical learning-based accounts. Moreover, conceptualizing language acquisition along both dimensions has practical value. We can teach new words or ask if a child “knows” a word, even as we can assess efficient processing. Nonetheless, future work requires mechanistic theories that can relate learning and processing.

Some would argue these constructs are isomorphic. In connectionist accounts, knowledge is stored in the connections *over which processing occurs* (Elman, 2009)—the sound pattern of *BUG* is stored in its connections to B, U and G. Consequently, tuning these connections (over development) improves knowledge and processing. Even in traditional information processing accounts (Perfetti, 2007; Yap et al., 2009), lexical knowledge is a continuum of quality or integrity along multiple dimensions (semantic, orthographic, phonological)¹. Under both views, differences in real-time processes derive from learning that is incomplete (at earlier development stages) or impaired (Ullman et al., 2020). However, it is unclear in this kind of account why we observe different profiles of processing for two

¹ Though we note that much of the evidence for this relates overall vocabulary to real-time processing measures.

equivalently poor states of knowledge (younger children vs. DLD). Thus, these accounts may need to be developed such that even within the phonological level, lexical integrity is not a single dimension: different aspects of lexical representation must vary to drive differences in activation rate or resolution.

Competition models offer some leverage for disentangling mechanisms of representation/learning and processing (McClelland & Elman, 1986; McMurray et al., 2012). In such systems, some connections (e.g., between phonemes and words) reflect stored representations, while other connections (inhibition and feedback) enable flexible or efficient processing. Thus, the type and function of the pathways being formed or tuned may help distinguish processing from knowledge. In practice, this may be challenging. For example, stronger bottom up pathways (“knowledge” of the wordform) could boost competitor activation creating more interference, even if inhibitory connections are stable. Future work may disentangle such effects with more sophisticated designs or by leveraging the match between the VWP and competition models (Allopenna et al., 1998) by varying specific parameters controlling the strength of bottom-up activation, inhibition and decay in the model and relating this to variation in VWP performance (Kapnoula & McMurray, 2016; McMurray et al., 2010).

The functional differences we’ve established (activation rate and resolution) are meaningful regardless of their precise instantiation. Our focus on processing raises new questions. In a knowledge-centered view, good processing derives solely from robustly learned representations. However, in our framework, processing skills could develop on their own to balance demands on word recognition (Kapnoula & McMurray, 2016). Real-time processing could also influence what is learned—better resolution of competition may help learners achieve more precise word/referent mappings (Apfelbaum & McMurray, 2017).

It is easy to dismiss these effects as mere speed: Who cares if the child is a bit slower to identify words? This belies the rapid pace of language. If the child is to understand sentences in real time, sentence processing cannot wait for word recognition to asymptote at 1500 msec – it

is likely based on the state of lexical competition much earlier. Thus, poorer sentence processing may derive from still developing lexical representations. Consequently, the development of real-time processing may be a primary determinant of how well children can translate language knowledge into *real-world* language behavior.

Acknowledgements

The authors would like to thank Jamie Klein-Packard and the Growing Words Team for helpful conversations during the development of this work. This project was supported by DC008089 awarded to BM.

Recommended Readings

- Kapnoula, E. C., & McMurray, B. (2016). Inhibitory processes are plastic: Training alters competition between words. *Journal of Experimental Psychology: General*, 145(1), 8-30.
- McMurray, B., Danelz, A., Rigler, H., & Seedorff, M. (2018). Speech categorization develops slowly through adolescence. *Developmental Psychology*, 54(8), 1472-1491.
- McMurray, B., Samelson, V. S., Lee, S. H., & Tomblin, J. B. (2010). Individual differences in online spoken word recognition: Implications for SLI. *Cognitive Psychology*, 60(1), 1-39.
- Nation, K. (2014). Lexical learning and lexical processing in children with developmental language impairments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369(1634), 20120387.
- Rigler, H., Farris-Trimble, A., Greiner, L., Walker, J., Tomblin, J. B., & McMurray, B. (2015). The slow developmental timecourse of real-time spoken word recognition. *Developmental Psychology*, 51(12), 1690-1703.

References

- Alloppenna, P., Magnuson, J. S., & Tanenhaus, M. K. (1998). Tracking the time course of spoken word recognition using eye-movements: evidence for continuous mapping models. *Journal of Memory and Language*, 38(4), 419-439.
- Apfelbaum, K. S., & McMurray, B. (2017). Learning During Processing: Word Learning Doesn't Wait for Word Recognition to Finish. *Cognitive Science*, 41(S4), 706-747.
- Dahan, D., & Magnuson, J. S. (2006). Spoken-word recognition. In M. J. Traxler & M. A. Gernsbacher (Eds.), *Handbook of Psycholinguistics* (pp. 249-283). Academic Press.
- Dahan, D., Magnuson, J. S., Tanenhaus, M. K., & Hogan, E. (2001). Subcategorical mismatches and the time course of lexical access: Evidence for lexical competition. *Language and Cognitive Processes*, 16(5/6), 507-534.
- Dollaghan, C. (1998). Spoken word recognition in children with and without specific language impairment. *Applied Psycholinguistics*, 19, 193-207.
- Elman, J. L. (2009). On the meaning of words and dinosaur bones: Lexical knowledge without a lexicon. *Cognitive Science*, 33, 547-582.
- Fernald, A., & Marchman, V. A. (2012). Individual differences in lexical processing at 18 months predict vocabulary growth in typically developing and late-talking toddlers. *Child Development*, 83(1), 203-222.

- Galle, M. E., & McMurray, B. (2014). The development of voicing categories: A meta-analysis of 40 years of infant research. *Psychonomic Bulletin and Review*, 21(4), 884-906.
- Gernsbacher, M. A. (1997). Group differences in suppression skill. *Aging, Neuropsychology, and Cognition*, 4(3), 175-184. <https://doi.org/10.1080/13825589708256646>
- Goswami, U., Cumming, R., Chait, M., Huss, M., Mead, N., Wilson, A. M., Barnes, L., & Fosker, T. (2016). Perception of Filtered Speech by Children with Developmental Dyslexia and Children with Specific Language Impairments [Original Research]. *Frontiers in Psychology*, 7(791). <https://doi.org/10.3389/fpsyg.2016.00791>
- Hazan, V., & Barrett, S. (2000). The development of phonemic categorization in children aged 6–12. *Journal of Phonetics*, 28(4), 377-396. <https://doi.org/http://dx.doi.org/10.1006/jpho.2000.0121>
- Helenius, P., Parviainen, T., Paetau, R., & Salmelin, R. (2009). Neural processing of spoken words in specific language impairment and dyslexia. *Brain*, 132(7), 1918-1927. <https://doi.org/10.1093/brain/awp134>
- Hendrickson, K., Spinelli, J., & Walker, E. (2020). Cognitive processes underlying spoken word recognition during soft speech. *Cognition*, 198, 104196. <https://doi.org/10.1016/j.cognition.2020.104196>
- Kapnoula, E. C., & McMurray, B. (2016). Inhibitory processes are plastic: Training alters competition between words. *Journal of Experimental Psychology: General*, 145(1), 8-30.
- Kapnoula, E. C., & McMurray, B. (in press). On the locus of individual differences in perceptual flexibility: ERP evidence for perceptual warping of speech sounds. <https://doi.org/10.31234/osf.io/q9stn>.
- Maurer, D., & Werker, J. F. (2014). Perceptual Narrowing During Infancy: A Comparison of Language and Faces. *Developmental psychobiology*, 56(2), 154-178.
- McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology*, 18(1), 1-86.
- McMurray, B., Danelz, A., Rigler, H., & Seedorff, M. (2018). Speech categorization develops slowly through adolescence. *Developmental Psychology*, 54(8), 1472-1491.
- McMurray, B., Farris-Trimble, A., & Rigler, H. (2017). Waiting for lexical access: Cochlear implants or severely degraded input lead listeners to process speech less incrementally. *Cognition*, 169, 147-164.
- McMurray, B., Horst, J. S., & Samuelson, L. (2012). Word learning emerges from the interaction of online referent selection and slow associative learning. *Psychological Review*, 119(4), 831-877.
- McMurray, B., Klein-Packard, J., & Tomblin, J. B. (2019). A real-time mechanism underlying lexical deficits in developmental language disorder: Between-word inhibition. *Cognition*, 191, 104000.
- McMurray, B., Munson, C., & Tomblin, J. B. (2014). Individual differences in language ability are related to variation in word recognition, not speech perception: Evidence from eye-movements. *Journal of Speech Language and Hearing Research*, 57, 1344-1362.
- McMurray, B., Samuelson, V. S., Lee, S. H., & Tomblin, J. B. (2010). Individual differences in online spoken word recognition: Implications for SLI. *Cognitive Psychology*, 60(1), 1-39.
- Nation, K. (2014). Lexical learning and lexical processing in children with developmental language impairments. *Philosophical Transactions of the Royal Society B*, 369(1634), 20120387.
- Perfetti, C. A. (2007). Reading Ability: Lexical Quality to Comprehension. *Scientific Studies of Reading*, 11(4), 357-383. <https://doi.org/10.1080/10888430701530730>
- Rastle, K. (2007). Visual Word In M. G. Gaskell (Ed.), *The Oxford Handbook of Psycholinguistics*. Oxford University Press.
- Reilly, S., Tomblin, B., Law, J., McKean, C., Mensah, F. K., Morgan, A., Goldfeld, S., Nicholson, J. M., & Wake, M. (2014). Specific language impairment: a convenient label for whom?

- 412 *International Journal of Language & Communication Disorders*, 49(4), 416-451.
413 <https://doi.org/10.1111/1460-6984.12102>
- 414 Rigler, H., Farris-Trimble, A., Greiner, L., Walker, J., Tomblin, J. B., & McMurray, B. (2015). The
415 slow developmental timecourse of real-time spoken word recognition. *Developmental*
416 *Psychology*, 51(12), 1690-1703.
- 417 Roembke, T., Hazeltine, E., Reed, D. K., & McMurray, B. (in press). Automaticity as an
418 Independent Trait in Predicting Reading Outcomes in Middle-School. *Developmental*
419 *Psychology*.
- 420 Samuelson, L. K., & McMurray, B. (2017). What does it take to learn a word? *WIREs Cognitive*
421 *Science*, 8(1-2).
- 422 Sarrett, M., Shea, C., & McMurray, B. (in press). Within- and between-language competition in
423 adult second language learners: implications for language proficiency.
424 <https://psyarxiv.com/bwv7c/>.
- 425 Sekerina, I. A., & Brooks, P. J. (2007). Eye movements during spoken word recognition in
426 russian children. *Journal of Experimental Child Psychology*, 98, 20-45.
- 427 Stothard, S. E., Snowling, M. J., Bishop, D. V. M., Chipchase, B. B., & Kaplan, C. A. (1998).
428 Language-Impaired Preschoolers A Follow-Up Into Adolescence. *Journal of Speech,*
429 *Language, and Hearing Research*, 41(2), 407-418. <https://doi.org/10.1044/jslhr.4102.407>
- 430 Tomblin, J. B., Records, N. L., Buckwalter, P., Zhang, X., Smith, E., & O'Brien, M. (1997).
431 Prevalence of specific language impairment in kindergarten children. *Journal of Speech*
432 *and Hearing Research*, 40, 1245-1260.
- 433 Ullman, M. T., Earle, F. S., Walenski, M., & Janacsek, K. (2020). The neurocognition of
434 developmental disorders of language. *Annual Review of Psychology*, 71, 389-417.
- 435 Werker, J. F., & Curtin, S. (2005). PRIMIR: A Developmental Framework of Infant Speech
436 Processing. *Language Learning and Development*, 1(2), 197-234.
437 <https://doi.org/10.1080/15475441.2005.9684216>
- 438 Yap, M. J., Tse, C.-S., & Balota, D. A. (2009). Individual differences in the joint effects of
439 semantic priming and word frequency revealed by RT distributional analyses: The role of
440 lexical integrity. *Journal of Memory and Language*, 61(3), 303-325.
441 <https://doi.org/https://doi.org/10.1016/j.jml.2009.07.001>

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