What drives increased lexical reliance in language impairment?

Nikole Giovannone and Rachel M. Theodore

Department of Speech, Language, and Hearing Sciences
University of Connecticut
2 Alethia Drive, Unit 1085
Storrs, CT
06269-1085, USA

Connecticut Institute for the Brain and Cognitive Sciences
University of Connecticut
337 Mansfield Road, Unit 1272
Storrs, CT 06269-1272, USA

Declarations of interest: None

Corresponding author: Nikole Giovannone (nikole.giovannone@uconn.edu)

Abstract

Purpose: Some communication disorders associated with language impairment, including developmental language disorder, are marked by deficits in lexical processes. However, emerging evidence suggests that individuals with these disorders may (somewhat counterintuitively) demonstrate increased reliance on lexical information during speech perception. This review paper seeks to answer the question: What might drive increased lexical reliance in individuals with language impairment?

Conclusions: A comprehensive review of the extant literature combined with computational simulations in the TRACE architecture suggests that increased lexical reliance in this population may reflect relatively heightened lexical-semantic activation in response to decreased stability in processing the speech stream. Heightened lexical-semantic activation may reflect (1) increased lexical competition during spoken word recognition, (2) a perceptual deficit, and/or (3) a lexical bias during language processing. Critically, these three potential mechanisms may not be mutually exclusive; it is possible that all three may to some extent contribute to increased lexical reliance. These conclusions provide both a framework and critical considerations for future research that aims to apply the multifaceted contributions of different processing levels towards an understanding of individual differences in language processing, including an understanding of heterogeneity within clinical populations such as developmental language disorder.

Introduction

Communication disorders, including developmental language disorder (DLD) and specific language impairment (SLI), often reflect complex patterns of expressive and receptive language deficits. Of the many deficits that can be observed in disorders characterized by language impairment[1], deficits in lexical processing are often robust. For example, children with language impairment often have a reduced vocabulary relative to their peers (Gray et al., 1999; McGregor et al., 2002; McGregor, Oleson et al., 2013), perhaps related to deficits in word learning (Alt & Plante, 2006; McGregor, Licandro et al., 2013; McGregor, Arbisi-Kelm et al., 2017). A reduced vocabulary can have considerable implications for language comprehension, as a lack of comprehension at the lexical level can feed forward to discourse-level comprehension difficulties. In addition to reduced vocabulary size, there is evidence to suggest that individuals with language impairment have weaker semantic representations; that is, they demonstrate shallower depth of knowledge about a given word. When asked to verbally define developmentally appropriate vocabulary words, children with DLD not only give more incorrect definitions (McGregor et al., 2002; McGregor, Oleson et al., 2017), but also provide fewer details in their correct definitions than their peers (McGregor, Oleson et al., 2017). Observed difficulties related to naming and defining may be further exacerbated by deficits in lexical retrieval processes (e.g., Lahey & Edwards, 1996; McGregor et al, 2002; Messer & Dockrell, 2006); even when a word is part of the lexicon, deficits in lexical access can make the word itself and related information in the lexical-semantic network more difficult to retrieve during processing. A growing body of research suggests that despite diminished vocabulary size,

[1] We will use the term *language impairment* throughout this paper as a general term to describe a population including diagnostic categories such as developmental language disorder, specific language impairment, and language disorders (in the absence of secondary diagnoses such as intellectual disability or autism spectrum disorder). Although the label *developmental language disorder* is now widely accepted by clinicians and researchers alike to refer to this population, we acknowledge that many of the studies cited in this paper rely on differing terminology and diagnostic criteria. When discussing specific studies, we will use the labels used in that paper to describe the study's results.

semantic depth, and deficits in lexical access, individuals with language impairment may rely more highly on lexical-semantic information during speech perception than their typically-developing peers (Derawi et al., 2021; Dollaghan, 1998; Giovannone & Theodore, 2021a, 2021b; Reed, 1989; Schwartz et al., 1998). While increased lexical reliance may sound like a strength at first blush, this may not be the case. Rather, increased lexical reliance may be the consequence of speech processing weaknesses in individuals with language impairment.

In this paper, we seek to answer the question: What might drive increased lexical reliance in individuals with language impairment? We posit that increased lexical reliance in this population may reflect relatively heightened lexical-semantic activation in response to decreased stability in processing the speech stream. Heightened lexical-semantic activation may reflect (1) increased lexical competition during spoken word recognition, (2) a perceptual deficit, and/or (3) a lexical bias during language processing. Critically, these three potential mechanisms may not be mutually exclusive; it is possible that all three may to some extent contribute to increased lexical reliance. Here we will review evidence related to these three potential mechanisms for increased lexical reliance in this population through the lens of theoretical and computational frameworks of language processing and language impairment.

Lexical reliance

Before we expand upon potential mechanisms for increased lexical reliance, we will begin by reviewing findings related to lexical reliance in populations with language impairment. The Ganong task (Ganong, 1980) is a common task that is used to measure lexical reliance for interpreting phonetic cues. In this task, listeners are asked to make phonetic decisions for variable acoustic-phonetic cues (for example, a voice-onset-time [VOT] continuum ranging from /g/ to /k/) appended to different lexical contexts (e.g., *-ift* as in *gift* and *-iss* as in *kiss)*. In this example, the Ganong effect would emerge as a higher proportion of /g/ responses in the *-ift* - context compared to the *-iss* context, in line with lexical status (Ganong, 1980). A larger Ganong effect is indicative of heightened lexical reliance. Extant research suggests that both children

(Schwartz et al., 2013) and adults (Giovannone & Theodore, 2021a, 2021b) with language impairment demonstrate larger Ganong effects (Ganong, 1980) compared to their peers. Moreover, similar findings have been observed in children (Reed, 1989) and adults (Derawi et al., 2021) with developmental dyslexia, which is often associated with language impairment (Bishop & Snowling, 2004).

Evidence for increased lexical reliance is not limited to Ganong tasks, though. For example, Dollaghan (1998) found that children with SLI show increased reliance on lexical information during a perceptual gating task, in which familiar and unfamiliar words were segmented into gated portions of the full acoustic-phonetic signal. Participants were asked to identify the word after hearing progressively more of the signal on each trial. Dollaghan found that children with SLI and their peers could recognize *familiar* words after a comparable number of segments. However, children with SLI needed to hear significantly more of the acoustic-phonetic signal than their peers to recognize *unfamiliar* words, suggesting that the availability of lexical information impacted performance for children with SLI.

In the following sections, we will discuss three potential mechanisms for increased lexical reliance in individuals with language impairment. We first discuss increased lexical competition during spoken word recognition as a potential mechanism, followed by perceptual deficits. Then, we consider the possibility of an overall lexical bias.

Increased lexical competition

Both the Ganong and perceptual gating tasks described above illustrate the interactive nature of acoustic-phonetic and lexical information during spoken word recognition. As the speech signal begins to unfold, multiple words may initially become activated in a listener's lexical-semantic network. For example, hearing the word *kiss* initially activates our representations of its first speech sounds, /k/ and /ɪ/. Phoneme activation feeds forward to activate not only the target item *kiss,* but also other lexical items that share this onset, including words like *kick* and *kit* (e.g., Marslen-Wilson, 1987; McClelland & Elman, 1986). As the acoustic-phonetic signal unfolds over time, the final phoneme /s/ becomes activated, facilitating increased activation of the target lexical item (in this case, *kiss*), and subsequent inhibition of competitor items (such as *kick and kit*). Further, the Ganong task offers a clear-cut example of how competition can also occur on the phoneme level. In the Ganong task, the initial phoneme can be ambiguous between two competitors (e.g., /g/ and /k/). However, as more of the speech signal unfolds and additional phonemes become activated (e.g., /ɪ/ and /s/), this phonetic competition can be resolved; the lexical item *kiss* becomes activated, but *giss* does not given that it is not a real word. In some models of spoken word recognition (like the TRACE model; McClelland & Elman, 1986), lexical activation of the word *kiss* feeds back to the phoneme level, strengthening activation of the phoneme /k/, which in turn inhibits activation of the competitor /g/. Thus, reliance on lexical information during speech perception can assist with resolving ambiguity in the acoustic-phonetic signal.

Because the speech signal is often initially ambiguous (i.e., /kɪ/ may be the onset of *kiss, kick, kit,* or any number of onset competitors), successful and efficient spoken word recognition is reliant on competition (Dahan & Magnuson, 2006). Without parallel activation of numerous potential lexical candidates during processing, a listener may activate and select the word *kick* before receiving enough of the signal to recognize that the word was indeed *kiss*. This misinterpretation may lead to unnecessary additional processing costs associated with revising the first interpretation (as well as potential repercussions if one happens to respond to a request for a *kiss* with a swift *kick*). Likewise, activation of only a single phoneme candidate when acoustic-phonetic input is ambiguous could cause similar problems if the incorrect phoneme (in the above example, /g/) is initially activated. Parallel target and competitor activation in the lexicon therefore allows listeners to be flexible during online processing. However, too much activation of competitors can also pose a problem, interfering with a listener's ability to select the correct word from the lexicon. The same statements can be made with respect to phonetic competition. Parallel activation of multiple candidate phonemes can facilitate efficient processing, particularly when the acoustic-phonetic signal is ambiguous; however, too much competitor activation can have a domino effect on the lexical level, causing more diffuse activation of lexical candidates, and therefore increased competition on the lexical level.

A growing body of evidence suggests that disorders characterized by language impairment may be associated with heightened activation of competitor items in the lexical-semantic network (Mainela-Arnold et al., 2008; McMurray, et al. 2010, 2014, 2019). A series of studies by McMurray and colleagues (2010, 2014, 2019) investigated lexical-semantic activation in DLD using a visual world paradigm (Allopenna et al., 1998). In the visual world paradigm, a listener's eye movements are tracked as they interact with visual scenes and hear spoken language. Most commonly, fixations to four images displayed on a screen are tracked: an image of the correct target object (e.g., a beach), an onset competitor (e.g., a beak), a rhyme competitor (e.g., a peach), and an unrelated object (e.g., a shoe). Early fixation patterns generally reflect the initial parallel lexical activation of target and competitor items (particularly the onset competitor). At first, the proportion of fixations to the target and competitor items are similar, but over time looks to the target increase and looks to competitors decrease (Allopenna et al., 1998). McMurray and colleagues (2010, 2014, 2019) found that adolescents with DLD show decreased fixations to the target item and increased fixations to onset and rhyme competitors relative to control participants, suggesting that disorders like DLD may be associated with lower activation of the target item and higher activation of competitors during language processing. Like Dollaghan (1998), Mainela-Arnold et al. (2008) used a perceptual gating task to assess lexical access in children with and without SLI. They found that while both groups initially supplied the correct word after a similar amount of the acoustic-phonetic signal, children with SLI tended to vacillate between potential competitor items after initial recognition to a greater extent than the control group, also suggestive of increased lexical competitor activation during spoken word recognition.

Mechanisms for increased lexical competition

Increased competition itself can emerge through several different mechanisms during spoken word processing. Through a series of computational simulations implemented in the TRACE framework (i.e., jTRACE; Strauss et al., 2007), McMurray and colleagues (2010) found that the observed behavioral pattern of increased competitor activation and decreased target activation is best modeled by heightened lexical decay. Lexical decay refers to the rate at which lexical activation fades back to its resting state. When lexical decay is higher, lexical activation decreases at a faster rate, which might prevent the target lexical item from becoming fully activated. Empirical evidence for increased lexical decay has been observed via the MEG (magnetoencephalography) N400m response (Helenius et al., 2009). In both MEG and EEG (electroencephalography), the N400 response is associated with lexical-semantic processing (Kutas & Federmeier, 2011). When typically-developing adolescents listened to words repeated in quick succession, the second repetition of the word elicited an attenuated N400m response compared to the first. However, adolescents with SLI did not show as much N400m attenuation to the second repetition, suggesting that activation from the first instance of the word had already faded somewhat, allowing for a stronger second N400m relative to their peers.

Lower activation of the target item due to heightened lexical decay has a direct impact on lateral inhibition processes within the lexical-semantic network. Following our previous example, hearing the word *kiss* might lead to initial parallel activation of the word *kick.* In typical listeners, activation of the target item *kiss* becomes stronger as more of the signal unfolds, inhibiting (or decreasing) activation of competitor items like *kick.* However, if lexical decay is heightened in language impairment, activation of the target word *kiss* may begin fading before it is ever fully activated; thus, activation of the competitor item *kick* might not be inhibited to the same degree in disorders associated with language impairment as it is in typical listeners. This cascade of processes would allow competitor lexical items to achieve higher and more sustained activation than they might have otherwise.

While impairments to lexical decay can lead to decreased lateral inhibition, deficits to inhibition processes themselves can also occur. For example, decreased inhibition at high levels of processing (i.e., semantic processing) has been found in other groups associated with weaker language skills, including poor comprehenders (e.g., Gernsbacher & Faust, 1991; Henderson et al., 2013). McMurray and colleagues (2019) explicitly tested inhibition in adolescents with DLD by acoustically manipulating items to increase competitor activation–for example, by splicing the onset of a competitor item *neck* to the target word *net*. Though these two words' onsets contain the same phonemes, they contain slightly different acoustic-phonetic features as the result of coarticulation (Daniloff & Hammarberg, 1973). Thus, acoustic-phonetic features in the onset drawn from the word *neck* should lead to increased activation of the competitor item *neck,* which would inhibit activation of the target item *net* early in processing. While increased competitor activation inhibited target activation in typically-developing listeners, adolescents with DLD did not seem to show inhibition of the target item, suggesting an overall deficit in inhibition between words on the lexical level (McMurray et al., 2019).

Regardless of whether increased competition is brought about by deficits to decay or inhibition processes, the result is similar: relative to a typically-developing listener, there is likely overall more activation in the lexical semantic networks of listeners with language impairment. If competitor items are held active longer and more strongly, an overall higher amount of activation is likely to be observed in the lexical-semantic networks of listeners in this population. Heightened lexical-semantic network activation has been previously hypothesized by Pizzioli and Schelstraete's *overactivation hypothesis* (2011), which posits that during development, children with language impairments are more reliant on semantic context to facilitate language comprehension than their peers are. This increased reliance strengthens connections in the lexical-semantic network, leading to overall higher activation during language processing. Stronger connections between items in the lexical-semantic network might facilitate the activation of competitors, interfere with their inhibition, or both—these possibilities are difficult to separate given the extant literature, and we posit that they are an excellent area for future research. Regardless, stronger connections between lexical items as suggested by the *overactivation hypothesis* is yet another way in which lexical competition, and therefore overall lexical-semantic network activation, might be heightened in groups with language impairment.

Impact of increased lexical competition on lexical reliance

In this paper, we argue that increased lexical reliance in individuals with language impairment is likely the result of relatively heightened lexical-semantic activation in response to deficits in speech processing. In the previous section, we described how increased lexical competition may contribute to heightened lexical-semantic network activation: maintaining longer and stronger activation of competitors can contribute to overall heightened lexical activation in disorders associated with language impairment. But how might increased lexical competition and activation lead to heightened reliance on lexical information? In situations where the acoustic-phonetic input is potentially ambiguous (as in initial stages of spoken word recognition in general, or paradigms like the Ganong effect in which ambiguity is introduced), increased lexical competition can facilitate a *wait and see* approach to resolving that ambiguity. Because word-level activation would remain stronger for longer in this situation, lexical information may have more time to exert an influence on phonetic-level processing (perhaps via a feedback mechanism, as discussed earlier for the TRACE model; McClelland & Elman, 1986). Under this view, an observation such as a larger Ganong effect may be the product of enduring activation on the lexical level during spoken word recognition.

To explore how lexical competition, lexical-semantic network activation, and lexical reliance may be related, a series of jTRACE (Strauss et al., 2007) simulations were conducted. Note that throughout this paper, simulations are not meant to provide any definitive evidence for one mechanism over another. Rather, we aim to use the TRACE architecture to synthesize candidate mechanisms from the extant literature and thus formalize hypotheses that can be assessed with future empirical studies. Thus, these simulations are meant only to serve as illustrations of potential relationships between different facets of language processing when acoustic-phonetic input is ambiguous. Consider first Figure 1, panel B, which shows simulated lexical activations for the midpoint token of a *top*-*dop* continuum (in which *top* is a lexical item, and *dop* is not). The first facet, which uses default jTRACE parameters to simulate a typical listener, shows early lexical competition: competitor items like *dot* and *tar* are initially active alongside the target *top*, but competitor activation is quickly inhibited as the activation of *top* gets stronger. Contrast this pattern with the second facet, in which the lexical decay parameter has been increased. Activation of *top* is overall lower, as increased decay never allowed it to reach peak activation. As a result, some competitors like *pop* and *shop* remain activated for a longer temporal period.[2] Finally, consider the third facet, in which the lexical inhibition parameter has been lowered (in the absence of any changes to the lexical decay parameter). In this simulation, overall competitor activation appears significantly higher than when parameters are set to default. This activation also fades at a slower rate, yielding both stronger and *longer* competitor activation (as in the increased lexical decay simulation). These simulations demonstrate how deficits in different aspects of lexical processing can contribute to heightened competition, and therefore overall higher lexical-semantic network activation.

The impact of lexical competition on lexical reliance can also be examined via jTRACE by modeling two-alternative forced-choice phonetic identification response probabilities. Given that the input for these simulations is the ambiguous midpoint token of a *top*-*dop* continuum, this process essentially simulates responses to the midpoint token of one continuum in a Ganong task. When jTRACE parameters are set to their defaults, we can observe a lexical effect on phoneme identification as shown in the first facet of Figure 1, panel C; after the first few cycles of the simulation, the probability of a /t/ response is higher than the probability of a /d/ response. This pattern holds for the remainder of the simulation, with the probability of a /d/ response over

[2] We note that this simulation does not show quite the same pattern as observed by McMurray et al. (2010). Namely, competitor activation is overall not demonstrably higher when the lexical decay parameter is increased compared to when parameters are set to default. It is possible that this is an artifact of the specific item chosen for these illustrations.

a /t/ response increasing over time. This pattern holds true when lexical decay is increased (in the second facet) and when lexical inhibition is decreased (in the third facet). Notably, the lexical effect on phonetic identification response probabilities is far more pronounced when lexical inhibition is decreased than in the other two simulations. Not only does the probability of a /t/ response increase at a faster rate in the decreased lexical inhibition simulation, but the ultimate probability of a /t/ response is higher in this simulation than the others. This pattern of results may be taken to represent increased lexical influence on phonetic categorization, like has been observed in behavioral Ganong tasks (e.g., Giovannone & Theodore, 2021a, 2021b; Schwartz et al., 2013). In contrast, the increased lexical decay simulation shows a nearly identical pattern of /d/ and /t/ response probabilities as the simulation using default parameters.

This difference in phonetic identification response probabilities when lexical inhibition is decreased versus when lexical decay is increased might reflect different relative patterns of lexical competitor activation across these two simulations; future empirical work might seek to disentangle the relative contributions of decay versus inhibition to lexical competition and reliance. However, as mentioned previously, lexical competition is not the only type of competition during spoken word recognition, particularly when the input is somewhat ambiguous (as in these simulations). In the next section, we discuss how differences in phonetic competition might arise in disorders associated with language impairment, and how phonetic competition may also contribute to increased lexical reliance.

Perceptual deficits

A significant challenge for speech perception is the lack of invariance in the speech signal (Lisker & Abramson, 1964; Hillenbrand et al., 1995; Newman et al., 2001; Theodore et al., 2009). During speech perception, listeners must be able to assign highly variable acoustic productions (for example, productions from different talkers) to the intended speech sound category. Typically-developing listeners make use of multiple strategies to navigate this enormous computational challenge. Listeners maintain fine-grained representations of within-category variation in speech sound productions (McMurray et al., 2002; Miller, 1994), which allows for dynamic adaptation to changes in the speech signal caused by differences in talker (Nygaard et al. 1994; Theodore & Miller, 2008; Theodore et al., 2015), speaking rate (Volaitis & Miller, 1992), and accent (Kleinschmidt & Jaeger, 2015).

However, deficits in the perceptual system in disorders associated with language impairment may lead to difficulty in using phonological information to facilitate speech perception. A perceptual deficit may contribute to the creation of weak or unstable representations of the acoustic-phonetic signal during processing, which can potentially feed forward to disrupt higher-level linguistic processes dependent on these representations (Joanisse & Seidenberg, 2003; McArthur & Bishop, 2004). For example, marked deficits in the identification and discrimination of speech sounds have been observed in this population (e.g., Tallal & Piercy, 1974; Stark & Heinz, 1996; Elliot et al., 1989; Schwartz et al., 2013; Kraus et al., 1996). If listeners are less attuned to the variability in the acoustic-phonetic signal that differentiates speech sounds, then they may also struggle to use this variability to their advantage during processes like talker, speaking rate, and accent adaptation. Indeed, individuals with weaker language ability demonstrate decreased ability to adapt to acoustic-phonetic variability in speech-based distributional learning tasks (Colby et al., 2018; Theodore et al., 2020), suggesting that adaptation processes in this population may be impaired.

In this section, we will detail how unclear representations of the speech signal can occur due to deficits at multiple potential points on the perceptual pathway, including deficits in general auditory processing and phonological processing. Although there are multiple potential ways in which unclear representations of the speech signal might be formed, we argue that they all are potential means to at least one common end – difficulty in using phonological information during language processing. Specifically, we argue that unclear representations of the speech signal can contribute to overall heightened lexical-semantic network activation, which might result in increased lexical reliance during spoken word recognition.

Mechanisms for speech perception deficits

Auditory processing deficits. It is likely that many—but not all—individuals with language impairment experience low-level auditory processing deficits that can contribute to poorer speech perception. For example, deficits in areas including auditory encoding (e.g., Mason & Mellor, 1984; Rocha-Muniz et al., 2012, 2014; Wible et al., 2005) and non-linguistic frequency discrimination (e.g., McArthur & Bishop, 2004; Mengler et al., 2005; Tallal & Piercy, 1974) have been observed. Given that many phonemes are discriminated based on spectral characteristics such as frequency composition, having decreased ability to discriminate frequencies can contribute to the formation of weaker representations of these phonemes. In fact, frequency analysis of auditory brainstem responses (ABRs) has demonstrated that children with language impairment may show weaker auditory encoding specifically of frequencies that are critical to the discrimination of speech sounds (Rocha-Muniz et al., 2012, 2014). In these experiments, children with language impairment encoded frequencies in the F0-F1 range of a /da/ ABR stimulus comparably to a control group. However, frequencies above F1, which contribute more to phoneme identity relative to lower frequencies, were not encoded as precisely (Rocha-Muniz et al., 2012, 2014). Decreased auditory sensitivity to the frequencies that differentiate phonemes might contribute to known deficits in speech sound discrimination in this population (e.g., Tallal & Piercy, 1974; Stark & Heinz, 1996; Elliot et al., 1989; Kraus et al., 1996). Discrimination deficits can feed forward to disrupt later linguistic processes, such as past tense marking (a known deficit in DLD and SLI; e.g., Leonard, 1989). If a listener is less sensitive to acoustic-phonetic detail that differentiates phonemes, then low-salience grammatical morphemes like the word-final /t/ in words like *jumped* may be more difficult to process, learn, and use (Joanisse & Seidenberg, 2003).

However, overall evidence with respect to a general auditory processing deficit is mixed (see McArthur & Bishop, 2001 for discussion), perhaps even more so when measures of online auditory processing are considered. ERP components including the N100 and the mismatch negativity (MMN) have been well-studied in disorders associated with language impairment; however, the results of these studies are often contradictory. The N100, which indexes the encoding of acoustic information, may be abnormal in groups with language impairment. While some studies of this component revealed no group differences in the N100 as a function of language ability (Kornilov et al., 2014; Mason & Mellor, 1984; Ors et al., 2002), other studies have identified that children with DLD might show larger (Lincoln et al., 1995) or otherwise abnormal (Malins et al., 2013; McArthur & Bishop, 2004) N100 components. Results related to the MMN, which reflects auditory discrimination processes, are possibly even more inconsistent. Numerous studies have found no significant difference in MMN amplitude or latency between language impaired and control groups (Earle et al., 2018; Holopainen et al., 1997, 1998; Kornilov et al., 2014; Korpilahti & Lang, 1994), while others have found differences including increased MMN latencies (Marler et al., 2002), attenuated amplitude (Kraus et al., 1996; Uwer et al., 2002), and decreased duration (Kraus et al., 1996).

Phonological processing deficits. Although not all individuals with language impairment demonstrate general auditory processing deficits, more consistent results surrounding phonological processing suggest widespread deficits on this level. Several areas of processing including (but not limited to) phonological working memory, phonological encoding, and the consolidation of phonological information to memory have been implicated in populations with language impairment. Critically, deficits on any of these levels can contribute to unstable representations of speech on the phonological level independent of an auditory deficit.

To begin, consistent phonological working memory deficits have been observed in individuals with language impairment (e.g., Bishop et al., 1996; Gathercole & Baddeley, 1990; Graf Estes et al., 2007). Deficits in phonological working memory can have significant downstream consequences for processing, as phonological working memory underlies the formation of phonological representations during speech perception. Auditory input is held in working memory as representations are built (Baddeley & Hitch, 1974; Gathercole & Baddeley, 1990). If auditory input cannot be maintained with high fidelity in working memory, then the phonological information that ultimately gets encoded may not be accurate to the speech signal, even in the absence of auditory processing deficits. Further, it is possible that phonological encoding itself can also be impacted in disorders like DLD. Individuals with language impairment can show encoding deficits in areas including word learning (Alt & Plante, 2006; McGregor, Licandro et al., 2013; McGregor, Arbisi-Kelm et al., 2017; McGregor, Gordon et al., 2017), which may be rooted in phonological encoding (Alt, 2011; Nash & Donaldson, 2005). For example, children with SLI show deficits in learning phonological aspects of both unfamiliar words (Nash & Donaldson, 2005) and nonwords that follow the phonotactic rules of English (Alt, 2011). Initial evidence using the P300 ERP component, which can index phonological encoding (Toscano et al., 2010), suggests that phonological encoding may be impaired in this population (Evans et al., 2011; Ors et al., 2002). Ors and colleagues (2002) provide evidence critical to the point that phonological processing deficits can occur independent of auditory processing deficits. Ors and colleagues found attenuated P300 amplitudes in children with language impairment in the absence of any group N100 differences, suggesting that their participants had intact auditory encoding, but likely impaired phonological encoding.

In contrast, a recent study by Earle and colleagues (2018) suggests that for some individuals with weaker language ability, phonological encoding may be intact; however, the subsequent consolidation of acoustic-phonetic information to long-term memory may instead be impaired. Deficits in the consolidation of acoustic-phonetic information can potentially impact the formation of rich phonetic category structure. As previously discussed, typical listeners maintain high sensitivity to within-category phonetic variation (McMurray et al., 2002; Miller, 1994); this internal phonetic category structure supports dynamic adaptation processes that are necessary for successful speech perception (e.g., Nygaard et al. 1994; Theodore & Miller, 2009; Theodore et al., 2015; Volaitis & Miller, 1992; Kleinschmidt & Jaeger, 2015). Deficits in consolidation processes can specifically impact phonetic category structure even in the absence of deficits in auditory sensitivity and/or phonological encoding; if fine-grained acoustic-phonetic detail cannot be accurately consolidated to long-term memory, then the phonetic categories of individuals with DLD may contain less detailed representations than those of their peers.

The heterogeneity of disorders associated with language impairment cannot be overstated. Though the exact impairment in the speech processing stream can differ across individuals with the same diagnosis, the above-described potential impairments might all be considered potential means to at least one common end: difficulties using phonological information for processes including spoken word recognition, language learning, and speech adaptation.

Impact of perceptual deficits on lexical reliance

With respect to spoken word recognition, decreased sensitivity to acoustic-phonetic information can result in increased phonetic competition. If listeners with language impairment form unclear representations of the acoustic-phonetic speech signal, then it is likely that more potential phoneme-level candidates will become activated during processing. This phoneme-level competition can then feed forward to contribute to increased competition at the lexical level, as well. For example, an unclear perceptual representation of the word *beach* may lead to similar activation of both the phonemes /b/ and /p/, which differ only in their voicing. Relatively heightened activation of /p/ in listeners with language impairment might then lead to relatively increased activation of the competitor item *peach.* This increased competition might once again serve the purpose of allowing listeners with language impairment to “keep their options open” while resolving acoustic-phonetic ambiguity, as ambiguity might be particularly challenging if listeners are less sensitive to acoustic-phonetic detail in the speech signal. By keeping a larger set of candidate lexical items active longer, spoken word recognition can be more highly influenced by the lexical information that becomes available at later stages of the process. Increased lexical reliance in tandem with phonological processing deficits have been observed in at least one study of SLI; the children in Schwartz and colleagues’ (2013) study showed cooccurring deficits in phonological processing in the form of shallow phonetic identification functions, indicative of less certainty in their phonetic category judgements. The observed larger lexical effect in these children, however, indicates that when lexical information was present, the children were contrastingly *more certain* than their peers in making phonetic category judgements.

This result raises the possibility that for some listeners with language impairment, increased lexical reliance may in fact be a compensatory mechanism for deficits in processing at the acoustic-phonetic level. While discussing heightened lexical competition as a mechanism for increased lexical reliance, we suggested that increased lexical reliance might be a byproduct of competition. In contrast, it is possible that for listeners with a perceptual deficit, heightened competition and subsequent heightened lexical reliance might instead be a compensatory mechanism to support processing on the acoustic-phonetic level. Compensation between levels of processing in disorders associated with language impairment has previously been proposed. For example, Pizzioli and Schelstraete's (2011) *overactivation hypothesis* suggests that increased lexical reliance may be a compensatory mechanism specifically for weaker syntactic processing in language impairment; further, the *procedural deficit hypothesis* (Ullman & Pierpont, 2005) and related *declarative memory compensation hypothesis* (Ullman & Pullman, 2015) also provide theoretical support for increased lexical reliance as a compensatory mechanism for both syntactic and phonological processing deficits. The *procedural deficit hypothesis* suggests that language impairments like those observed in DLD and SLI are related to deficits in the procedural memory system (Ullman & Pierpont, 2005). The procedural memory system is proposed to support the more rule-governed aspects of language, including grammatical rules involving phonology, morphology, and syntax (Ullman, 2001). In contrast, the declarative memory system, which is proposed to support lexical and semantic knowledge and processing, is thought to be spared (or perhaps stronger) in these populations (Ullman & Pierpont, 2005; Ullman & Pullman, 2015). The *declarative memory compensation hypothesis*

(Ullman & Pullman, 2015) suggests that processes supported by the declarative memory system (including lexical processes) can compensate for deficits in areas supported by the procedural memory system (including phonological and syntactic processes).

To further understand the interaction of perceptual deficits and lexical processing, we again conducted a series of illustrative simulations using jTRACE. Just as there are multiple ways to model lexical deficits in the TRACE architecture, there are multiple ways to model a perceptual deficit. Within jTRACE, a general auditory processing impairment can be modeled by adding a small amount of Gaussian-distribution noise to the input. An impairment to working memory processes can be modeled by increasing the decay parameter for auditory features of the input. Finally, a deficit in phonological encoding might be best modeled by decreasing the strength of connections between the auditory feature level and the phoneme level. By adjusting these parameters, we can explore how different loci of perceptual deficits might contribute to phonetic competition, lexical activation, and lexical reliance.

Once again, the input for all simulations presented in this section was the midpoint token of a *top-dop* continuum. Beginning with the earliest stages of processing, first consider the "Added Noise" facets of Figure 2. Because the "Input Noise" parameter in jTRACE supplies a random pattern of Gaussian-distributed noise for each simulation, the "Added Noise" facets in Figure 2 represent the average of 10 simulations. The "Added Noise" facet in panel A, which shows phoneme-level activation, looks very similar to the phoneme activation observed when parameters are set to default. While there does seem to be slightly higher activation of /t/ and slightly lower activation of /d/ with added noise relative to default, the overall pattern might suggest that phoneme competition is slightly *reduced* when noise is added to the input; the relative activation of /d/ (the competitor) compared to /t/ (the target) is lower compared to default parameters. However, recall that this facet represents the average of 10 simulations, each containing a different pattern of randomly distributed noise. It is entirely possible that at times, the random noise might facilitate activation of the correct phoneme (/t/), and at other times, it might facilitate activation of the competitor (/d/). Figure 3 shows three of the simulations used to obtain the average activations shown in Figure 2. Note that in some simulations (i.e., simulation 6), phonetic competition is strong: parallel activation of the competitor /d/ is strong and long-lasting. Contrast this to simulation 4, in which the activation of the target /t/ strengthens quickly, inhibiting the target /d/ to a greater extent. In Figure 2, panel A, stronger phonetic competition can also be observed when feature decay is increased and when the connections between features and phonemes are weakened. In the case of increased feature decay, heightened phonetic competition emerges as overall lower activation of /d/ and /t/ relative to default; thus, activations for these phonemes as well as other competitors (like /p/ and /k/) are closer to one another. The same is true of decreased feature to phoneme connection strength, primarily at the earliest stages of the simulation.

In all cases, increased competition at the phoneme level can feed forward to create increased competition at the lexical level. With regard to added noise, this pattern is best seen in simulation 6 (shown in Figure 3, panel B): lexical competitors are slightly more activated *and* stay active longer (relative to both default and added noise simulation 4, which contains less phonetic competition). In the increased feature decay and decreased feature to phoneme connection strength facets, heightened lexical competition is represented by prolonged competitor activation relative to default. While increased phonetic competition contributing to increased lexical competition is supported by current models of spoken word recognition including TRACE (McClelland & Elman, 1986), at least one empirical study did not find this pattern. McMurray and colleagues (2014) used VOT continua (e.g., a *beach* to *peach* continuum) in the visual world paradigm. Like other studies in this paradigm, individuals with DLD showed overall higher fixations to competitor items (e.g., *peach* instead of *beach*); however, this effect did not interact with the VOT of the tokens. Regardless of language ability, participants showed higher fixations to the competitor the closer the onset was to their phonetic category boundary. This pattern suggests that not only were the listeners with DLD sensitive to fine-grained differences between continuum steps, but also that phonetic competition was not heightened in these listeners. Replication of this study in listeners who show language impairment marked by auditory or phonological processing deficits would be key for exploring how unstable phonological representations might contribute to phonetic and lexical competition during spoken word recognition.

If increased phonetic competition does indeed feed forward to create increased lexical competition, then the effect of phonetic competition on lexical reliance when there is a perceptual deficit should be similar to the effect of lexical competition on lexical reliance. That is, increased competition facilitates longer and stronger competitor activation, which would lead to a higher influence of lexical information on phonological processes (such as phonetic identification). Across the simulations presented thus far, it seems as though the degree of increased lexical competition is stronger when lexical parameters are adjusted (Figure 1) than when perceptual parameters are adjusted (Figures 2 and 3). It therefore may not be surprising that lexical reliance also seems less consistently impacted by changes to feature and phoneme level parameters in the simulations discussed in this section. Out of the five non-default simulations shown across Figures 2 and 3 (increased feature decay and lowered feature-phoneme connections in Figure 2, and the three added noise simulations in Figure 3), only added noise simulation 4 and decreased feature to phoneme connection weights seem to show a larger lexical effect on phonetic identification response probabilities relative to default. An interesting test case for specifically assessing the influence of phoneme competition on lexical reliance can be drawn from Figure 3. When phoneme competition is relatively lower (i.e., panel A, simulation 4), the lexical effect on phoneme identification appears to be the strongest (as seen in panel C, simulation 4). As phoneme competition increases through simulations 5 to 6, the lexical effect on phoneme identification shrinks. A similar behavioral effect has been observed by our team (Giovannone & Theodore, 2021b). In a typical Ganong task, competition between acoustic-phonetic and lexical cues is high (i.e., listeners hear the same proportion of clear /k/ tokens in an appropriate *-iss* context and an inappropriate *-ift* context). When the level of competition between acoustic-phonetic and lexical cues was reduced, the magnitude of the Ganong effect was larger, regardless of listeners' overall language ability (Giovannone & Theodore, 2021b). This pattern can also be observed in the reduced feature-phoneme connections simulation (Figure 2, panel A) suggesting that while increased lexical competition might be associated with a larger lexical effect, perhaps *lower* phoneme competition is related to larger lexical effects; however, we must emphasize that that conclusion cannot be drawn from these simulations alone, and that further empirical work is necessary to fully understand the impact of phoneme competition on lexical reliance.

While we have modulated each of these parameters independently of each other, we must note that we do not hypothesize that deficits in the processes they represent (auditory processing, phonological working memory, and phonological encoding) must occur in isolation of one another; nor do we make any claims that they might occur independently of the lexical parameters adjusted previously. It is likely that these parameters are deeply intertwined with one another in a way that might differ from listener to listener. Future modeling work might consider assessing potential additive effects of different combinations of parameters relevant to language impairment.

Lexical bias

So far, we have presented two potential avenues (increased lexical competition and perceptual deficits) by which increased lexical reliance might occur in language impairment. However, we have yet to consider possibly the simplest explanation – perhaps listeners with language impairment have an overall lexical bias during processing, or a lexical bias that is not specifically related to deficits on acoustic-phonetic or lexical levels. Although an overall lexical bias might be the simplest potential mechanism for increased lexical reliance in language impairment, it might also be the least supported by the current literature. In this section, we will discuss the current evidence for lexical biases in the absence of acoustic-phonetic or lexical processing differences.

Mechanisms for lexical bias

Evidence for an overall lexical bias in language impairment is extremely limited. Some evidence suggests that individual differences in lexical reliance fall on a spectrum; even in the typically-developing population, some listeners rely more on lexical information during speech perception than others (Ishida et al., 2016; Giovannone & Theodore, under review). It is possible that individuals with language impairment tend to fall on the upper end of this spectrum. However, recent evidence suggests that even in typical listeners, the degree of lexical cue use for speech perception tasks (such as a Ganong task) is linked to acoustic-phonetic cue use (Giovannone & Theodore, under review), suggesting a relationship between lexical bias and acoustic-phonetic processing. Whether the same pattern is true of individuals with language impairment is still an open question.

While not much evidence for an overall lexical bias seems to exist, it is possible that increased lexical reliance might be related to later processing steps. As previously mentioned, increased lexical reliance has been hypothesized to be related to syntactic deficits. The *overactivation hypothesis* (Pizzioli & Schelstraete, 2011) posits that during development, children with language impairment tend to rely more on lexical-semantic information to compensate for weaker syntactic processing. Over time, this increased reliance strengthens connections between items in the lexical-semantic network, leading to overall higher activation (as previously discussed). The *procedural deficit hypothesis* (Ullman & Pierpont, 2005) and *declarative memory compensation hypothesis* (Ullman & Pullman, 2015) also support this possibility, given that procedural memory is thought to underlie syntactic processing and declarative memory is thought to underlie lexical-semantic processing (Ullman, 2001).

Although ample theoretical support for a compensatory relationship between lexical and syntactic processing exists, current empirical evidence for this relationship is weak (Conti-Ramsden et al., 2015; Fonteneau & van der Lely, 2008; Kuppuraj et al., 2016). At least two studies have probed this question via tasks meant to assess procedural and declarative memory processes (Conti-Ramsden et al., 2015; Kuppuraj et al., 2016), but found no correlation between their measures, contrary to the *declarative memory compensation hypothesis.* Some stronger evidence comes from a study by Fonteneau and van der Lely (2008), in which children with and without SLI were exposed to questions containing syntactic violations. Children with SLI did not show the expected early left-anterior negativity (ELAN) ERP response, which is associated with the detection of syntactic violations (Friederici, 2002) Instead, their electrophysiological responses following the syntactic violation resembled an N400, which is associated with lexical-semantic processing (Kutas & Federmeier, 2011). The presence of an N400 rather than the ELAN may be suggestive of lexical-semantic compensation for weaknesses in initial syntactic processing in children with SLI. Further research directly probing the nature of the relationship between lexical and syntactic processes may shed light on the nature of lexical reliance in individuals with language impairment.

Impact of a lexical bias on lexical reliance

Within the TRACE architecture, contributions from the lexicon to phoneme-level processing can be modeled in terms of feedback. Recall that in the TRACE model (McClelland & Elman, 1986), activation from the lexical level can feed back down to the phoneme level, allowing lexical information to influence earlier speech perception processes. Returning to our jTRACE simulations, the ambiguous midpoint token between *top* and *dop* initially activates both the target phoneme /t/ and the competitor /d/. As more of the signal unfolds and additional phonemes become activated (e.g., /ɑ/ and /p/), *top* becomes activated and *dop* does not, given that it is not a real word. Lexical activation from the word *top* feeds back to the phoneme level, strengthening activation of the phoneme /t/, which in turn inhibits activation of the competitor /d/. Feedback can be observed in the default parameters simulation (shown again in Figure 4). In panel A, initial activation of /t/ and /d/ are equivalent until approximately cycle 20, at which point the activation of /t/ begins to exceed the activation of /d/. This roughly corresponds to the point at which lexical activation of the word *top* begins to exceed the activation of its competitors.

In contrast, consider the second facet of each panel in Figure 4, in which the lexical feedback parameter has been set to zero. Both /t/ and /d/ maintain equal activation over the entire timecourse of the simulation, even though word-level activation of *top* is still high. However, turning off the feedback parameter renders it so that the lexical activation of *top* cannot feedback to strengthen the activation of the phoneme /t/. Since the activation of /t/ never increases, it does not inhibit the activation of /d/. This difference between default parameters and no feedback can also be observed when looking at phonetic identification response probabilities in Figure 4, panel C. The typical lexical effect on phonetic identification is again observed when parameters are set to default. However, when feedback is set to zero, lexical information cannot influence phonetic identification, and so the probability of a /t/ versus /d/ response remains at chance.

An overall lexical bias may be best modeled by increasing the lexical feedback parameter, which would in theory create a stronger influence of lexical information on both phoneme activation and phonetic identification response probabilities. As can be seen in the third facet of each panel of Figure 4, this pattern is indeed borne out in the simulations. In panel A, initial activation of /t/ and /d/ are again equivalent until approximately cycle 20. Like when the feedback parameter is set to default, the activation of /t/ begins to exceed the activation of /d/ at about cycle 20. However, the activation of /t/ takes off more quickly, and ultimately reaches a higher level, than default. As such, the activation of /d/ becomes inhibited both more quickly and more strongly. Competition between these two phonemes is therefore reduced; further, lexical competition does not seem to be increased relative to default parameters. The effect of heightened lexical feedback can also be seen on phonetic identification response probabilities in panel C; as one might expect, stronger feedback from the lexicon yields a larger lexical effect on phoneme identification. Thus, stronger feedback is a potential mechanism by which the lexical effect can be larger in the absence of major differences in phonetic and lexical competition.

Interestingly, it is possible that stronger feedback limits overall lexical-semantic network activation (in contrast to the heightened overall activation observed in simulations for the lexical competition and perceptual deficit mechanisms described in the above two sections). Overall lexical activation over time appears similar across the default and increased feedback facets of Figure 4, panel B. In addition, this simulation presents another case in which lower phoneme competition might be associated with heightened lexical reliance.

While an overall lexical bias might result in increased lexical reliance (as demonstrated in these simulations), evidence in favor of this mechanism is limited. Further, it is possible that this mechanism cannot be fully incorporated into a theory that suggests overall increased lexical activation in language impairment (as suggested throughout this paper and by the *overactivation hypothesis*). A fully specified account for increased lexical reliance in populations associated with language impairment would benefit greatly from systematic exploration of individual differences in perceptual, lexical-semantic, and syntactic processes, as well as their interactions.

Conclusions and future directions

In this paper, we suggested that increased lexical reliance in listeners with language impairment may be the result of relatively heightened lexical-semantic as a result of deficits in speech processing. We reviewed literature related to lexical and acoustic-phonetic processing differences in disorders associated with language impairment as we discussed evidence for three potential ways in which increased lexical reliance (e.g., Dollaghan, 1998; Giovannone & Theodore, 2021a, 2021b; Schwartz et al., 2013) can emerge during processing in these disorders. First, we specified how increased lexical reliance in listeners with language impairment can be the result of increased competition at the lexical level, particularly when input from the speech stream is temporarily ambiguous (as it often is at the beginning stages of speech perception and spoken word recognition). Second, we provided evidence for the possibility that increased lexical reliance is related to deficits in perceptual processing that make listeners' representations of the speech signal more unstable. Further, we suggested that increased lexical reliance may serve to compensate for these deficits on the perceptual level. Finally, we considered that increased lexical reliance might reflect an overall lexical bias, or a lexical bias that is not specifically related to processing on the acoustic-phonetic or lexical levels.

In truth, we cannot currently say which of these mechanisms is "right." In much of the current research assessing lexical effects, researchers have measured behavior that is presumably reflecting processing on the phoneme level – for example, Ganong tasks elicit phonetic identification decisions from participants. However, we cannot fully understand the mechanisms for increased lexical reliance without looking beyond phonetic identification responses. The jTRACE simulations presented in this paper have demonstrated that increased lexical reliance for phonetic identification can emerge due to a variety of different processes at different levels, including (but perhaps not limited to) general auditory processing deficits (i.e., added noise), deficits in phonological encoding (i.e., decreased feature-phoneme connections), decreased lexical inhibition, and increased lexical feedback. Although these four processes all result in a similar larger lexical effect on phoneme identification response probabilities, they are very different processes that result in very different effects in the lexical-semantic network. For example, lexical competition seems heightened in some of these simulations that result in a larger lexical effect – however, specific patterns of competitor activation are not consistent. Some of these simulations seem to be associated with low but steady lexical competitor activation (i.e., reduced feature-phoneme connections), while others seem to be associated with both heightened and prolonged competitor activation (i.e., decreased lexical inhibition), and yet others seem to be associated with lexical competition that is very similar to that observed with default parameters (i.e., added noise simulation 4, increased feedback). In addition, the levels of overall lexical-level activations differ greatly across these simulations, ranging from near-default-like (i.e., increased feedback) to rather high (i.e., decreased lexical inhibition). Yet, altering all four of these parameters gives rise to the same general pattern in terms of phonetic identification response probabilities: a heightened lexical effect.

We must emphasize again that language impairment is associated with a broad spectrum of individual differences. No two individuals are the same, even if they have the same diagnostic label. It is very possible that any combination of the above-described mechanisms for increased lexical reliance may simultaneously be true. Further, mechanisms that drive increased lexical reliance can very likely differ across individuals; some might have a perceptual deficit, while others might experience deficits in inhibition processes, and yet others may demonstrate evidence of both. As the field continues its progress towards treating different facets of language ability as predictors for individual differences and more sensitive measures that can index multiple levels of processing are used, our understanding of the driving factors behind increased lexical reliance in populations associated with language impairment will certainly expand.

Acknowledgements

This work was supported by NIH NIDCD grant R21DC016141 to RMT, NSF grants DGE-1747486 and DGE-1144399 to the University of Connecticut, and by the Jorgensen Fellowship (University of Connecticut) to NG. The views expressed here reflect those of the authors and not the NIH, the NIDCD, or the NSF. Gratitude is extended to James Magnuson, Emily Myers, Tammie Spaulding, and Adrián García-Sierra for feedback on earlier iterations of this manuscript. Gratitude is also extended to Lee Drown, Kaidi Chen, Shawn Cummings, and Anne Marie Crinnion for lively and fruitful discussion on the themes presented here.

Data Availability Statement

All simulation data and a script for generating figures is available on the OSF at https://osf.io/uptse/.

References

Allopenna, P. D., 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. https://doi.org/10.1006/jmla.1997.2558

Alt, M. (2011). Phonological working memory impairments in children with specific language impairment: Where does the problem lie? *Journal of Communication Disorders*, *44*(2), 173–185. https://doi.org/10.1016/j.jcomdis.2010.09.003

Alt, M., & Plante, E. (2006). Factors that influence lexical and semantic fast mapping of young children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *49*(5), 941–954. https://doi.org/10.1044/1092-4388(2006/068)

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 8, pp. 47–89). Academic Press. https://doi.org/10.1016/S0079-7421(08)60452-1

Bishop, D. V. M., North, T., & Donlan, C. (1996). Nonword repetition as a behavioural marker for inherited language impairment: Evidence from a twin study. *Journal of Child Psychology and Psychiatry*, *37*(4), 391–403. https://doi.org/10.1111/j.1469-7610.1996.tb01420.x

Bishop, D., & Snowling, M. (2004). Developmental dyslexia and specific language impairment: Same or different? *Psychological Bulletin*, *130*, 858–886. https://doi.org/10.1037/0033-2909.130.6.858

Colby, S., Clayards, M., & Baum, S. (2018). The role of lexical status and individual differences for perceptual learning in younger and older adults. *Journal of Speech, Language, and Hearing Research*, *61*(8), 1855–1874. https://doi.org/10.1044/2018_JSLHR-S-17-0392

Conti-Ramsden, G., Ullman, M. T., & Lum, J. A. G. (2015). The relation between receptive grammar and procedural, declarative, and working memory in specific language impairment. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.01090

Daniloff, R. G., & Hammarberg, R. E. (1973). On defining coarticulation. *Journal of Phonetics*, *1*(3), 239–248. https://doi.org/10.1016/S0095-4470(19)31388-9

Dahan, D., & Magnuson, J. (2006). Spoken Word Recognition. In M. J. Traxler & M. A. Gernsbacher (Eds.), Handbook of psycholinguistics (Vol. 2, pp. 249–284). Amsterdam: Academic Press. https://doi.org/10.1016/B978-012369374-7/50009-2

Derawi, H., Reinisch, E., & Gabay, Y. (2021). Increased reliance on top-down information to compensate for reduced bottom-up use of acoustic cues in dyslexia. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-021-01996-9

Dollaghan, C. (1998). Spoken word recognition in children with and without specific language impairment. *Applied Psycholinguistics*, *19*(2), 193–207. https://doi.org/10.1017/S0142716400010031

Earle, F. S., Landi, N., & Myers, E. B. (2018). Adults with specific language impairment fail to consolidate speech sounds during sleep. *Neuroscience Letters*, *666*, 58–63. https://doi.org/10.1016/j.neulet.2017.12.030

Elliott, L. L., Hammer, M. A., & Scholl, M. (1989). Fine-grained auditory discrimination in normal children and children with language-learning problems. *Journal of Speech, Language, and Hearing Research, 32*(1), 112-119. https://doi.org/10.1044/jshr.3201.112

Evans, J. L., Selinger, C., & Pollak, S. D. (2011). P300 as a measure of processing capacity in auditory and visual domains in specific language impairment. *Brain Research*, *1389*, 93–102. https://doi.org/10.1016/j.brainres.2011.02.010

Fonteneau, E., & van der Lely, H. K. J. (2008). Electrical brain responses in language-impaired children reveal grammar-specific deficits. *PloS One*, *3*(3), e1832. https://doi.org/10.1371/journal.pone.0001832

Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences*, *6*(2), 78–84. https://doi.org/10.1016/S1364-6613(00)01839-8

Ganong, W. F. (1980). Phonetic categorization in auditory word perception. *Journal of Experimental Psychology: Human Perception and Performance*, *6*(1), 110–125.

https://doi.org/10.1037/0096-1523.6.1.110

Gathercole, S. E., & Baddeley, A. D. (1990). Phonological memory deficits in language disordered children: Is there a causal connection? *Journal of Memory and Language*, *29*(3), 336–360. https://doi.org/10.1016/0749-596X(90)90004-J

Gernsbacher, M. A., & Faust, M. E. (1991). The mechanism of suppression: A component of general comprehension skill. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *17*(2), 245–262.

Giovannone, N., & Theodore, R. M. (2021a). Individual differences in lexical contributions to speech perception. *Journal of Speech, Language, and Hearing Research*, *64*(3), 707–724. https://doi.org/10.1044/2020_JSLHR-20-00283

Giovannone, N., & Theodore, R. M. (2021b). Individual differences in the use of acoustic-phonetic versus lexical cues for speech perception. *Frontiers in Communication*, *6*, 120. https://doi.org/10.3389/fcomm.2021.691225

Giovannone, N. & Theodore, R.M. (Under review). Do individual differences in lexical reliance reflect states or traits?

Graf Estes, K., Evans, J. L., & Else-Quest, N. M. (2007). Differences in the nonword repetition performance of children with and without specific language impairment: A meta-analysis. *Journal of Speech, Language, and Hearing Research*, *50*(1), 177–195. https://doi.org/10.1044/1092-4388(2007/015)

Gray, S., Plante, E., Vance, R., & Henrichsen, M. (1999). The diagnostic accuracy of four vocabulary tests administered to preschool-age children. *Language, Speech, and Hearing Services in Schools*, *30*(2), 196–206. https://doi.org/10.1044/0161-1461.3002.196

Henderson, L., Snowling, M., & Clarke, P. (2013). Accessing, integrating, and inhibiting word meaning in poor comprehenders. *Scientific Studies of Reading*, *17*(3), 177–198. https://doi.org/10.1080/10888438.2011.652721

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

Hillenbrand, J., Getty, L. A., Clark, M. J., & Wheeler, K. (1995). Acoustic characteristics of American English vowels. *The Journal of the Acoustical Society of America*, *97*(5), 3099–3111. https://doi.org/10.1121/1.411872

Holopainen, I. E., Korpilahti, P., Juottonen, K., Lang, H., & Sillanpää, M. (1997). Attenuated auditory event-related potential (mismatch negativity) in children with developmental dysphasia. *Neuropediatrics*, *28*(5), 253–256. https://doi.org/10.1055/s-2007-973709

Holopainen, I. E., Korpilahti, P., Juottonen, K., Lang, H., & Sillanpää, M. (1998). Abnormal frequency mismatch negativity in mentally retarded children and in children with developmental dysphasia. *Journal of Child Neurology*, *13*(4), 178–183. https://doi.org/10.1177/088307389801300406

Ishida, M., Samuel, A. G., & Arai, T. (2016). Some people are “more lexical” than others. *Cognition*, *151*, 68–75. https://doi.org/10.1016/j.cognition.2016.03.008

Joanisse, M. F., & Seidenberg, M. S. (2003). Phonology and syntax in specific language impairment: Evidence from a connectionist model. *Brain and Language*, *86*, 40–56. https://doi.org/10.1016/S0093-934X(02)00533-3

Kleinschmidt, D. F., & Jaeger, T. F. (2015). Robust speech perception: Recognize the familiar, generalize to the similar, and adapt to the novel. *Psychological Review, 122*(2), 148-203. https://doi.org/10,1037/a0038695

Korpilahti, P., & Lang, H. A. (1994). Auditory ERP components and mismatch negativity in dysphasic children. *Electroencephalography and Clinical Neurophysiology*, *91*(4), 256–264. https://doi.org/10.1016/0013-4694(94)90189-9

Kornilov, S. A., Landi, N., Rakhlin, N., Fang, S.-Y., Grigorenko, E. L., & Magnuson, J. S. (2014). Attentional but not pre-attentive neural measures of auditory discrimination are atypical in children with developmental language disorder. *Developmental Neuropsychology*, *39*(7), 543–567. https://doi.org/10.1080/87565641.2014.960964

Kraus, N., McGee, T. J., Carrell, T. D., Zecker, S. G., Nicol, T. G., & Koch, D. B. (1996). Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science*, *273*(5277), 971–973.

Kuppuraj, S., Rao, P., & Bishop, D. V. (2016). Declarative capacity does not trade-off with procedural capacity in children with specific language impairment. *Autism & Developmental Language Impairments*, *1*, 1-17. https://doi.org/10.1177/2396941516674416

Kutas, M., & Federmeier, K. D. (2011). Thirty Years and Counting: Finding Meaning in the N400 Component of the Event-Related Brain Potential (ERP). *Annual Review of Psychology*, *62*(1), 621–647. https://doi.org/10.1146/annurev.psych.093008.131123

Lahey, M., & Edwards, J. (1996). Why do children with specific language impairment name pictures more slowly than their peers? *Journal of Speech, Language, and Hearing Research*, *39*(5), 1081–1098. https://doi.org/10.1044/jshr.3905.1081

Leonard, L. B. (1989). Language learnability and specific language impairment in children. *Applied Psycholinguistics*, *10*(2), 179–202. https://doi.org/10.1017/S0142716400008511

Lincoln, A. J., Courchesne, E., Harms, L., & Allen, M. (1995). Sensory modulation of auditory stimuli in children with autism and receptive developmental language disorder: Event-related brain potential evidence. *Journal of Autism and Developmental Disorders*, *25*(5), 521–539. https://doi.org/10.1007/BF02178298

Lisker, L., & Abramson, A. S. (1964). A cross-language study of voicing in initial stops: Acoustical measurements. *WORD*, *20*(3), 384–422. https://doi.org/10.1080/00437956.1964.11659830

Mainela-Arnold, E., Evans, J. L., & Coady, C. A. (2008). Lexical representations in children with SLI: Evidence from a frequency-manipulated gating task. *Journal of Speech, Language, and Hearing Research*, *51*(2), 381–393. https://doi.org/10.1044/1092-4388(2008/028)

Malins, J. G., Desroches, A. S., Robertson, E. K., Newman, R. L., Archibald, L. M. D., &

Joanisse, M. F. (2013). ERPs reveal the temporal dynamics of auditory word recognition in specific language impairment. *Developmental Cognitive Neuroscience*, *5*, 134–148. https://doi.org/10.1016/j.dcn.2013.02.005

Marler, J. A., Champlin, C. A., & Gillam, R. B. (2002). Auditory memory for backward masking signals in children with language impairment. *Psychophysiology*, *39*(6), 767–780. https://doi.org/10.1111/1469-8986.3960767

Marslen-Wilson, W. D. (1987). Functional parallelism in spoken word-recognition. *Cognition*, *25*(1), 71–102. https://doi.org/10.1016/0010-0277(87)90005-9

Mason, S. M., & Mellor, D. H. (1984). Brain-stem, middle latency and late cortical evoked potentials in children with speech and language disorders. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *59*(4), 297–309. https://doi.org/10.1016/0168-5597(84)90047-9

McArthur, G. M., & Bishop, D. V. M. (2001). Auditory perceptual processing in people with reading and oral language impairments: Current issues and recommendations. *Dyslexia*, *7*(3), 150–170. https://doi.org/10.1002/dys.200

McArthur, G. M., & Bishop, D. V. M. (2004). Which people with specific language impairment have auditory processing deficits? *Cognitive Neuropsychology*, *21*(1), 79–94. https://doi.org/10.1080/02643290342000087

McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology*, *18*(1), 1–86. https://doi.org/10.1016/0010-0285(86)90015-0

McGregor, K., Arbisi-Kelm, T., & Eden, N. (2017). The encoding of word forms into memory may be challenging for college students with developmental language impairment. *International Journal of Speech-Language Pathology*, *19*(1), 43–57. https://doi.org/10.3109/17549507.2016.1159337

McGregor, K. K., Gordon, K., Eden, N., Arbisi-Kelm, T., & Oleson, J. (2017). Encoding deficits impede word learning and memory in adults with developmental language disorders.

Journal of Speech, Language, and Hearing Research, *60*(10), 2891–2905. https://doi.org/10.1044/2017_JSLHR-L-17-0031

McGregor, K. K., Newman, R. M., Reilly, R. M., & Capone, N. C. (2002). Semantic representation and naming in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *45*(5), 998–1014. https://doi.org/10.1044/1092-4388(2002/081)

McGregor, K. K., Oleson, J., Bahnsen, A., & Duff, D. (2013). Children with developmental language impairment have vocabulary deficits characterized by limited breadth and depth. *International Journal of Language & Communication Disorders*, *48*(3), 307–319. https://doi.org/10.1111/1460-6984.12008

McGregor, K. K., Licandro, U., Arenas, R., Eden, N., Stiles, D., Bean, A., & Walker, E. (2013). Why words are hard for adults with developmental language impairments. *Journal of Speech, Language, and Hearing Research*, *56*(6), 1845–1856. https://doi.org/10.1044/1092-4388(2013/12-0233)

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. https://doi.org/10.1016/j.cognition.2019.06.012

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*(4), 1344–1362. https://doi.org/10.1044/2014_JSLHR-L-13-0196

McMurray, B., Samelson, V. M., Lee, S. H., & Bruce Tomblin, J. (2010). Individual differences in online spoken word recognition: Implications for SLI. *Cognitive Psychology*, *60*(1), 1–39. https://doi.org/10.1016/j.cogpsych.2009.06.003

McMurray, B., Tanenhaus, M. K., & Aslin, R. N. (2002). Gradient effects of within-category phonetic variation on lexical access. *Cognition*, *86*(2), B33–B42.

https://doi.org/10.1016/S0010-0277(02)00157-9

Miller, J. L. (1994). On the internal structure of phonetic categories: A progress report. *Cognition*, *50*(1), 271–285. https://doi.org/10.1016/0010-0277(94)90031-0

Mengler, E. D., Hogben, J. H., Michie, P., & Bishop, D. V. M. (2005). Poor frequency discrimination is related to oral language disorder in children: A psychoacoustic study. *Dyslexia, 11*(3), 155-173. https://doi.org/10.1002/dys.302

Messer, D., & Dockrell, J. E. (2006). Children's naming and word-finding difficulties: Descriptions and explanations. *Journal of Speech, Language, and Hearing Research*, *49*(2), 309–324. https://doi.org/10.1044/1092-4388(2006/025)

Nash, M., & Donaldson, M. L. (2005). Word learning in children with vocabulary deficits. *Journal of Speech, Language, and Hearing Research*, *48*(2), 439–458. https://doi.org/10.1044/1092-4388(2005/030)

Newman, R. S., Clouse, S. A., & Burnham, J. L. (2001). The perceptual consequences of within-talker variability in fricative production. *The Journal of the Acoustical Society of America*, *109*(3), 1181–1196. https://doi.org/10.1121/1.1348009

Nygaard, L. C., Sommers, M. S., & Pisoni, D. B. (1994). Speech perception as a talker-contingent process. *Psychological Science*, *5*(1), 42–46. https://doi.org/10.1111/j.1467-9280.1994.tb00612.x

Ors, M., Lindgren, M., Blennow, G., Nettelbladt, U., Sahlén, B., & Rosén, I. (2002). Auditory event-related brain potentials in children with specific language impairment. *European Journal of Paediatric Neurology*, *6*(1), 47–62. https://doi.org/10.1053/ejpn.2001.0541

Pizzioli, F., & Schelstraete, M. A. (2011). Lexico-semantic processing in children with specific language impairment: The overactivation hypothesis. *Journal of Communication Disorders*, *44*(1), 75–90. https://doi.org/10.1016/j.jcomdis.2010.07.004

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. *Journal of Experimental Child Psychology*, *48*(2), 270–292.

https://doi.org/10.1016/0022-0965(89)90006-4

Rocha-Muniz, C. N., Befi-Lopes, D. M., & Schochat, E. (2012). Investigation of auditory processing disorder and language impairment using the speech-evoked auditory brainstem response. *Hearing Research*, *294*(1), 143–152. https://doi.org/10.1016/j.heares.2012.08.008

Rocha-Muniz, C. N., Befi-Lopes, D. M., & Schochat, E. (2014). Sensitivity, specificity and efficiency of speech-evoked ABR. *Hearing Research*, *317*, 15–22. https://doi.org/10.1016/j.heares.2014.09.004

Schwartz, R. G., Scheffler, F. L. V., & Lopez, K. (2013). Speech perception and lexical effects in specific language impairment. *Clinical Linguistics & Phonetics*, *27*(5), 339–354. https://doi.org/10.3109/02699206.2013.763386

Stark, R. E., & Heinz, J. M. (1996). Vowel perception in children with and without language impairment. *Journal of Speech and Hearing Research*, *39*(4), 860–869. https://doi.org/10.1044/jshr.3904.860

Strauss, T. J., Harris, H. D., & Magnuson, J. S. (2007). jTRACE: A reimplementation and extension of the TRACE model of speech perception and spoken word recognition. *Behavior Research Methods*, *39*(1), 19–30. https://doi.org/10.3758/BF03192840

Tallal, P., & Piercy, M. (1974). Developmental aphasia: Rate of auditory processing and selective impairment of consonant perception. *Neuropsychologia*, *12*(1), 83–93. https://doi.org/10.1016/0028-3932(74)90030-X

Theodore, R. M., & Miller, J. L. (2010). Characteristics of listener sensitivity to talker-specific phonetic detail. *The Journal of the Acoustical Society of America*, *128*(4), 2090-2099.

Theodore, R. M., Miller, J. L., & DeSteno, D. (2009). Individual talker differences in voice-onset-time: Contextual influences. *The Journal of the Acoustical Society of America*, *125*(6), 3974–3982. https://doi.org/10.1121/1.3106131

Theodore, R. M., Monto, N. R., & Graham, S. (2020). Individual differences in distributional learning for speech: What’s ideal for ideal observers? *Journal of Speech, Language, and Hearing Research*, *63*(1), 1–13. https://doi.org/10.1044/2019_JSLHR-S-19-0152

Theodore, R. M., Myers, E. B., & Lomibao, J. A. (2015). Talker-specific influences on phonetic category structure. *The Journal of the Acoustical Society of America*, *138*(2), 1068–1078. https://doi.org/10.1121/1.4927489

Toscano, J. C., McMurray, B., Dennhardt, J., & Luck, S. J. (2010). Continuous perception and graded categorization: Electrophysiological evidence for a linear relationship between the acoustic signal and perceptual encoding of speech. *Psychological Science*, *21*(10), 1532–1540. https://doi.org/10.1177/0956797610384142

Ullman, M. T. (2001). The declarative/procedural model of lexicon and grammar. *Journal of Psycholinguistic Research*, *30*(1), 37–69. https://doi.org/10.1023/A:1005204207369

Ullman, M. T., & Pierpont, E. I. (2005). Specific language impairment is not specific to language: The procedural deficit hHypothesis. *Cortex*, *41*(3), 399–433. https://doi.org/10.1016/S0010-9452(08)70276-4

Ullman, M. T., & Pullman, M. Y. (2015). A compensatory role for declarative memory in neurodevelopmental disorders. *Neuroscience & Biobehavioral Reviews*, *51*, 205–222. https://doi.org/10.1016/j.neubiorev.2015.01.008

Uwer, R., Albrecht, R., & von Suchodoletz, W. (2002). Automatic processing of tones and speech stimuli in children with specific language impairment. *Developmental Medicine & Child Neurology*, *44*(8), 527–532. https://doi.org/10.1111/j.1469-8749.2002.tb00324.x

Volaitis, L. E., & Miller, J. L. (1992). Phonetic prototypes: Influence of place of articulation and speaking rate on the internal structure of voicing categories. *The Journal of the Acoustical Society of America*, *92*(2), 723–735. https://doi.org/10.1121/1.403997

Wible, B., Nicol, T., & Kraus, N. (2005). Correlation between brainstem and cortical auditory processes in normal and language-impaired children. *Brain*, *128*(2), 417–423. https://doi.org/10.1093/brain/awh367

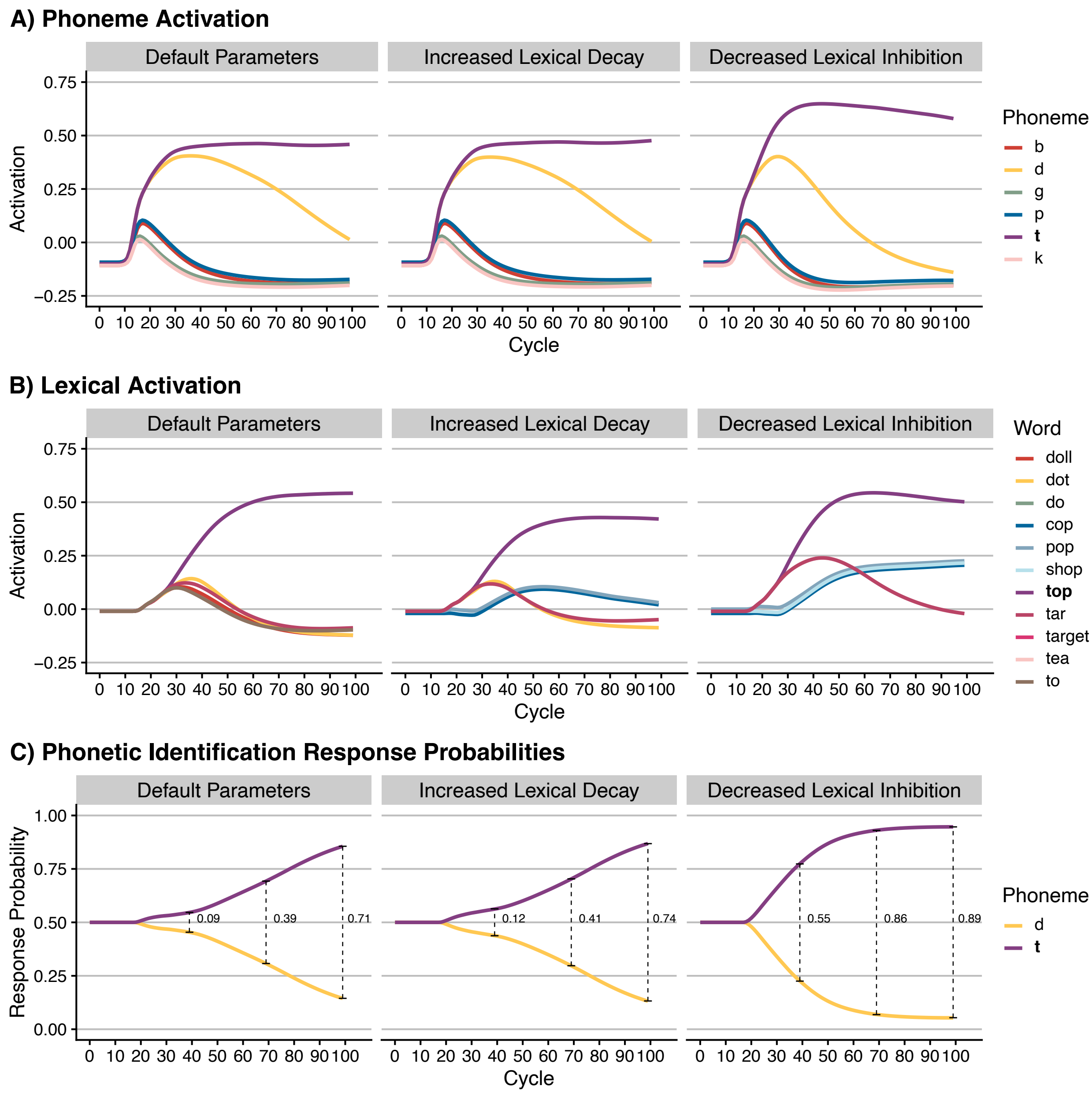

Figure 1. jTRACE simulations modeling disruptions to lexical processes and their potential influence on lexical reliance. Each panel contains three simulations: (1) a simulation using default jTRACE parameters (left), (2) a simulation in which the lexical decay parameter is increased from its default of 0.05 to 0.07 (middle), and (3) a simulation in which the lexical inhibition parameter is decreased from its default of 0.03 to 0.01 (right). In all cases, the input for the simulation is the ambiguous midpoint token of a *top-dop* continuum. For all three simulation types, panel A shows phoneme level activation for all six English stop consonants, panel B shows lexical level activation of the top five most highly activated lexical candidates, and panel C shows phonetic identification response probabilities for /t/ and /d/. In panel C, the numbers to the right of the dashed lines indicate the difference between the probability of a /t/ response and the probability of a /d/ response at each time point. In some cases, activations were shifted slightly on the y-axis (between 0.015 and 0.020) to facilitate the visualization of overlapping activations.

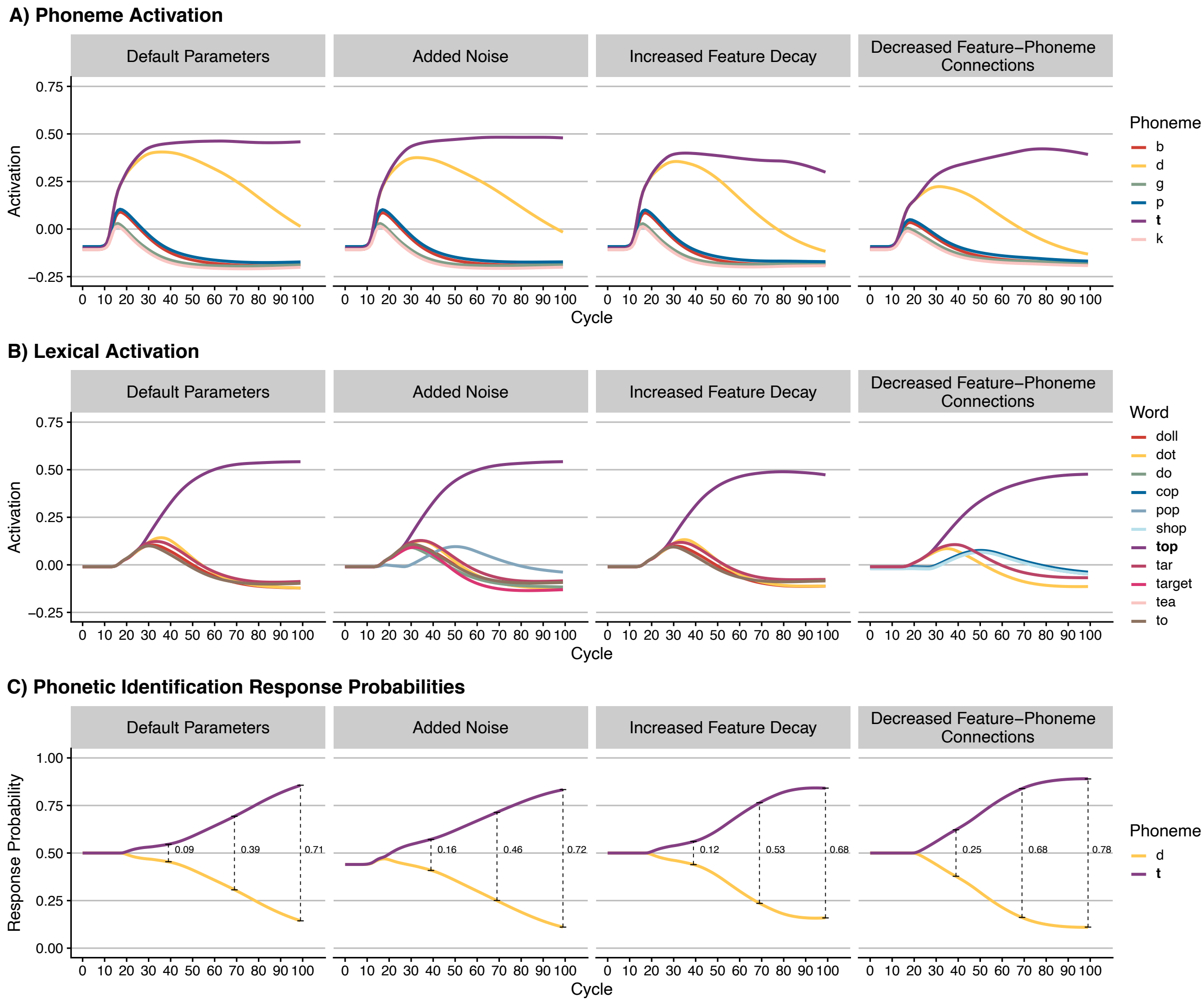

Figure 2. jTRACE simulations modeling disruptions to auditory and/or phonological processes and their potential influence on lexical reliance. Each panel contains four simulations: (1) a simulation using default jTRACE parameters (left), (2) the average of 10 simulations that have 0.1 SD of added Gaussian noise (middle left), (3) a simulation in which the feature decay parameter is increased from its default of 0.01 to 0.03 (middle right), and (4) a simulation in which the strength of feature- to phoneme-level connections is decreased from its default of 0.02 to 0.01 (right). In all cases, the input for the simulation is the ambiguous midpoint token of a *top-dop* continuum. For all three simulation types, panel A shows phoneme level activation for all six English stop consonants, panel B shows lexical level activation of the top five most highly activated lexical candidates, and panel C shows phonetic identification response probabilities for /t/ and /d/. In panel C, the numbers to the right of the dashed lines indicate the difference between the probability of a /t/ response and the probability of a /d/ response at each time point. In some cases, activations were shifted slightly on the y-axis (between 0.015 and 0.020) to facilitate the visualization of overlapping activations.

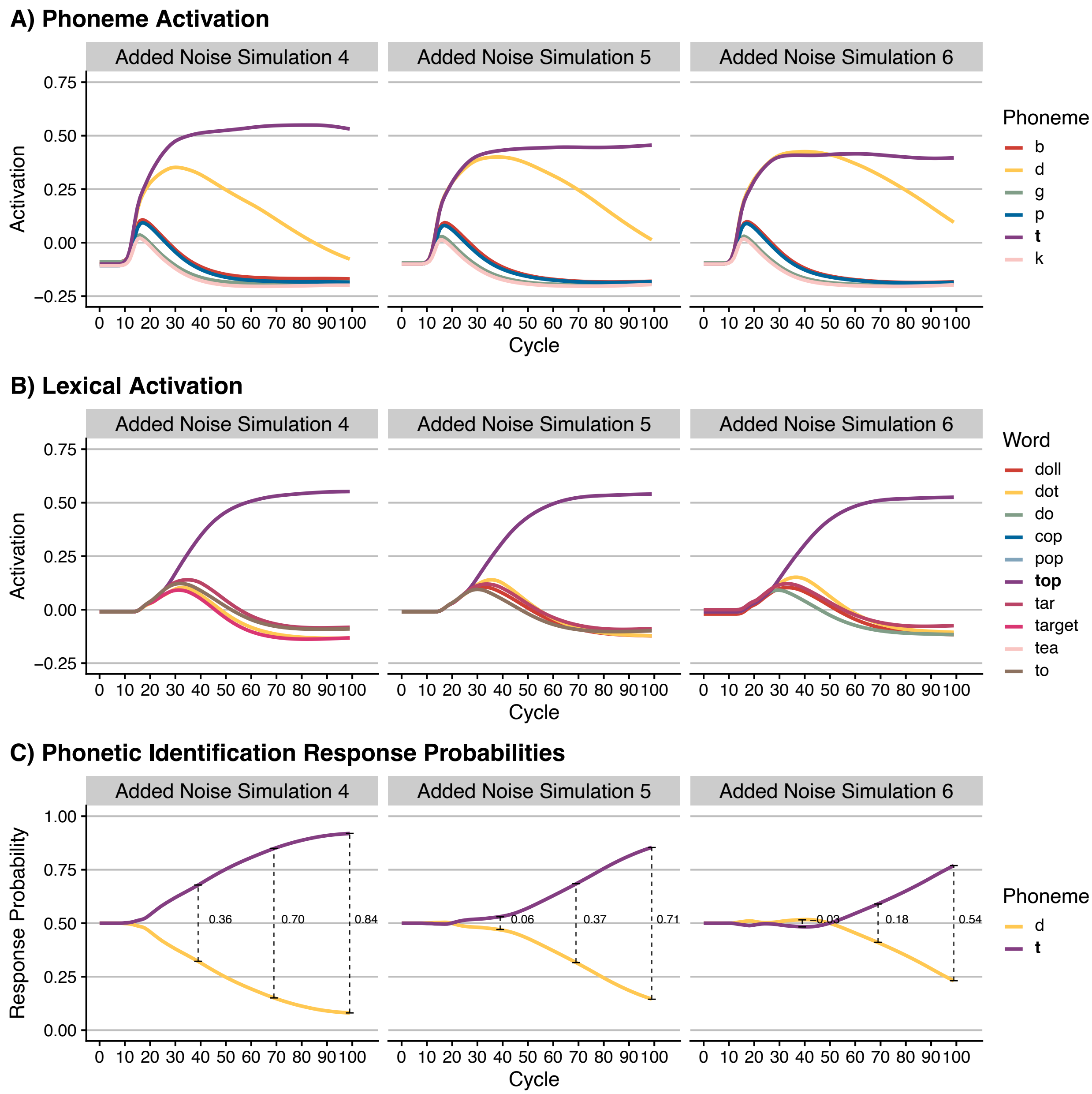

Figure 3. Three of the 10 simulations used to compute the average "Added Noise" activations seen in Figure 2. In all cases, the input for the simulation is the ambiguous midpoint token of a *top-dop* continuum. For all three simulation types, panel A shows phoneme level activation for all six English stop consonants, panel B shows lexical level activation of the top five most highly activated lexical candidates, and panel C shows phonetic identification response probabilities for /t/ and /d/. In panel C, the numbers to the right of the dashed lines indicate the difference between the probability of a /t/ response and the probability of a /d/ response at each time point. In some cases, activations were shifted slightly on the y-axis (by 0.020) to facilitate the visualization of overlapping activations.

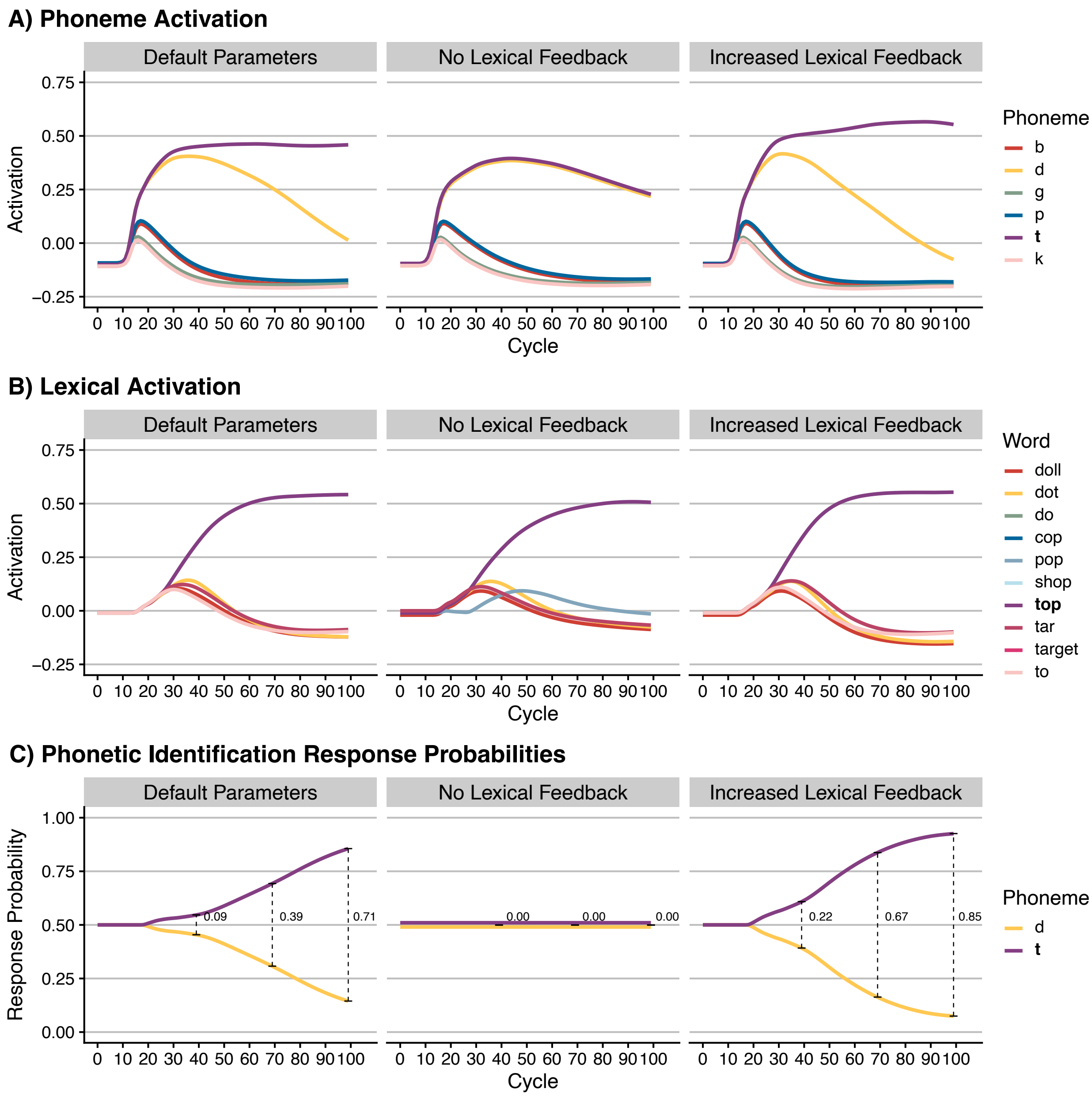

Figure 4. jTRACE simulations modeling differences in lexical feedback and their potential influence on lexical reliance. Each panel contains three simulations: (1) a simulation using default jTRACE parameters (left), (2) a simulation in which the lexical feedback parameter is decreased from its default of 0.05 to 0.00 (middle), and (3) a simulation in which the lexical feedback parameter is increased from its default of 0.05 to 0.07 (right). In all cases, the input for the simulation is the ambiguous midpoint token of a *top-dop* continuum. For all three simulation types, panel A shows phoneme level activation for all six English stop consonants, panel B shows lexical level activation of the top five most highly activated lexical candidates, and panel C shows phonetic identification response probabilities for /t/ and /d/. In panel C, the numbers to the right of the dashed lines indicate the difference between the probability of a /t/ response and the probability of a /d/ response at each time point. In some cases, activations were shifted slightly on the y-axis (between 0.010 and 0.020) to facilitate the visualization of overlapping activations.