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Variations in Phonological Working Memory:
Linking Early Language Experiences and Language Learning Outcomes

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In order to build complex language from perceptual input, children must have access to a powerful information processing system that can analyse, store and use regularities in the signal to which the child is exposed. In this article, we propose that one of the most important parts of this underlying machinery is the linked set of cognitive and language processing components that comprise the child's developing working memory. To examine this hypothesis, we explore how variations in the timing, quality and quantity of language input during the earliest stages of development are related to variations in WM, especially phonological working memory (PWM), and, in turn, language learning outcomes. In order to tease apart the relationships between early language experience, working memory and language development, we review research findings from studies of groups of language learners who clearly differ with respect to these aspects of input. Specifically, we consider the development of PWM in children with delayed exposure to language – children born profoundly deaf and exposed to oral language following cochlear implantation and internationally-adopted children who have delayed exposed to the adoption language; children who experience impoverished language input – children who experience early bouts of otitis media and signing deaf children born to non-signing hearing parents; and children with enriched early language input – simultaneous bilinguals and second language learners.

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Introduction: Early Native Language Development

From remarkably early, children are ready to acquire one or more native languages. During their first twelve months of life (starting from the last trimester of gestation) children are already building the fundamental pieces of what will become a complex language system (e.g., Gervain, 2015). Initially, infants appear to establish language representations that are based on intonation, particularly that of their mother's voice, along with some rudimentary phonotactic properties of their target language(s) (Lany & Safran, 2013). Exposure to specific language(s) allows children to form and fine-tune representations for specific language features, such as phonetic/phonological categories (or handshapes in the case of signed languages), as they zero in on the particular language(s) of their environment (Kuhl, 2004). At the same time, early neural biases as well as changes in underlying neural structure and function take place along with infants' developing language system in a way that aligns with the experiences they encounter (e.g., Dehaene-Lambertz & Spelke, 2015; Gervain, 2015). However, despite the prominent role that even the earliest experiences play in supporting and shaping language development, the influence of such early experiences on language outcomes is not well understood. In the present paper, we explore links between early language experiences and language learning and processing. Specifically, we explore the hypothesis that variation in the timing, quality, and/or quantity of early language input can affect the development of phonological working memory (PWM) via experience-based differences in the representation and processing of phonological elements of language. We further argue that variation in the development of PWM can, in turn, influence language learning in the short and long term.

Our focus on PWM arises from the premise that, in order to build complex language from perceptual input, children must have access to a powerful information processing system that can take in, analyse, and ultimately store the input to which a child is exposed

(Gathercole & Baddeley, 1989). One of the most important parts of this underlying machinery is the linked set of cognitive and language processing components that comprise the child's developing working memory. Working memory, particularly phonological working memory (PWM), supports both the acquisition and subsequent processing of language via the maintenance, processing, and storage of ambient language sounds (e.g., Baddeley, 2000; Gathercole & Baddeley, 1989). Because stimuli processed via PWM are language specific (i.e., phonological elements of a language), the development of PWM might be particularly influenced by language experiences that occur during the earliest stages of development when phonetic/phonological elements of language are initially acquired. Thus, although hypothetical at present, the influence of early experience on later language outcomes is arguably most likely to manifest through variation in phonological representations and their processing via PWM.

However, the relationship between early experience, PWM development, and language acquisition has been difficult to tease apart. Insofar as the development of language and working memory unfold more or less simultaneously, the influence of one on the other is difficult to examine and, thus, the nature of the interaction between the two can go unnoticed. Exacerbating this is the fact that studies of working memory development have often focused on monolinguals learning a single language under "typical" circumstances. In that case, individual differences in language experience may not provide enough variation to tease apart any relationship that might exist between early language input and PWM. In contrast, research on groups of children acquiring language in a broader range of contexts than the typical monolingual language learner might encounter, specifically with respect to the timing, quantity, and quality of early language input, has revealed a pattern of PWM outcomes that seems to suggest a relationship between early experience and PWM development, to be discussed shortly. A close examination of these groups can thus shed light on the relationship between early language experience, the development of PWM, and subsequent language outcomes.

Through the present paper, we will elucidate the role of early experience in language outcomes by 1) examining how the early experiences of different groups of language learners appear to influence the development of PWM in a systematic way, and 2) discussing how variations in WM, specifically PWM, are linked to differences in language learning. Specifically, we consider the PWM development of children with delayed exposure to language (i.e., children born profoundly deaf but only exposed to an oral language; internationally-adopted children), and children who experience either impoverished (i.e., children with otitis media; signing deaf children born to non-signing parents) or enriched early language input (i.e., simultaneous bilinguals and second language learners). We argue that under circumstances such as these, with clear variation in timing, quality and quantity of early input, we can begin to systematically tease apart the relationship between early language experience, working memory and language development.

What do we mean by Working Memory?

There is much current debate concerning how best to characterise working memory (WM) within a set of higher level cognitive processes, termed Executive Functions (EF). We do not attempt to resolve this debate in the current article but instead take WM to be a cognitive system that is involved in language acquisition, among other abilities. Although WM does not function in isolation, in this paper we consider it, for the most part, without discussing other EFs. WM is a process involving the temporary storage and manipulation of incoming information, be it visual, auditory, or otherwise. WM processes are deemed necessary in order to translate incoming information into long-term knowledge. Baddeley and Hitch (1974) first proposed that WM is a multicomponent subsystem, comprised of the following: (1) the visuo-spatial sketchpad, a subsystem responsible for the storage and manipulation of visual information, and (2) the phonological loop that allows for the temporary storage and processing of verbal and/or acoustic information. Responsible for controlling these subsystems is (3) a central executive that relies on attentional mechanisms to control the functioning of each of these “slave” subsystems within working and episodic memory (see Baddeley 2000; 2007). The phonological loop can be broken down further into the phonological store, which can hold phonological content for a few seconds before it fades, and an articulatory rehearsal process where phonological information may be rehearsed in order to refresh the memory trace (Baddeley, 2003; 2009; Repovš & Baddeley, 2006). It has been demonstrated that the different subcomponents of the phonological loop function together to support different aspects of language learning and processing (for reviews see, Baddeley, 2003; Baddeley, Gathercole, & Papagno, 1998; Gathercole, 2006; Juffs & Harrington, 2011).

It is has been proposed that the phonological loop supports language acquisition by allowing incoming (unfamiliar) language-relevant information to be maintained in memory long enough that it can be processed and, over time, transformed into long-term stored knowledge about language, such as vocabulary or grammar. It has been suggested that the phonological store in particular, as opposed to sub-vocal rehearsal, may be involved in the process of language acquisition (e.g., Baddeley et al., 1998) as there is robust evidence for a relationship between PWM capacity and language acquisition as early as 2 years of age; however, sub-vocal rehearsal does not appear to emerge until much later, around roughly age 7 (for reviews, see Cowan & Kail, 1996; Gathercole & Hitch, 1993). Moreover, the ability to perform well on a non-word repetition task, which requires that individuals hear and repeat back an item well within the temporal capacity of the phonological store, and before rehearsal processes are possible, is associated with improved language acquisition. That such a relationship exists further suggests that language acquisition is supported by the creation of adequate phonological representations within the phonological store (Baddeley et al., 1998).

If PWM is necessary for language development, then individual differences in PWM abilities, and/or in the quality of phonological representations supporting PWM, should be linked to variation in language outcomes. Indeed this has been found to be the case in typical language development contexts. PWM capacity predicts children's acquisition of both a first and second language (for reviews see: Baddeley et al., 1998; Gathercole, 2006; Juffs & Harrington, 2011). In children with typical development, PWM is positively associated with vocabulary learning, (Baddeley, 2003; 2009; Gathercole, 2006; Repovš & Baddeley, 2006), grammatical development (Adams & Gathercole, 1995), reading skills (e.g., Goff, Pratt, & Ong, 2005; Nikolopoulos, Goulandris, Hulme, & Snowling, 2006), letter learning (Torppa, Poikkeus, Laakso, Eklund, & Lyytinen, 2006), and phonological skills (Durand, Hulme, Larkin, & Snowling, 2005; Alloway, Gathercole, Willis, & Adams, 2005; van Daal, Verhoeven, van Leeuwe, & van Balkom, 2008). Moreover, this relationship has been found in both naturalistic studies of child second language learners (e.g. Cheung, 1996; Service, 1992; Service & Kohonen, 1995) as well as in carefully controlled experimental studies examining children's acquisition of new vocabulary in a laboratory setting. For example, in a study of school-aged children (12-years-old, on average) who were learning English as a second language (Cheung, 1996), PWM capacity predicted the number of trials necessary to learn new words in English. Interestingly, this was only the case when the children's English vocabulary was low, indicating that once adequate vocabulary is acquired, PWM capacity plays a less dominant role in further vocabulary acquisition (e.g., Gathercole, Willis, Baddeley, & Emslie, 1992).

The Role of Early Experience in PWM Development

While there is robust evidence that PWM capacity is positively associated with both early language learning and later language outcomes, there is less evidence of how initial differences in PWM capacity might emerge. Children's PWM capacity develops rapidly, and with much variability, over the first few years of life (e.g., Gathercole & Adams, 1993). There is relatively little known about developmental changes that occur to support the development of phonological memory (Gathercole, 1999), although limited evidence suggests that working memory develops within the first 6-12 months of life (Nelson, 1995), with evidence for the beginnings of early PWM development typically being reported around 2;6 to 4 years of age, once children are able to repeat words and sentences (Gathercole & Baddeley, 1989; Gathercole & Hitch, 1993). Improvements in WM capacity are then observed during the next few years. As reviewed in the previous section, research that has focused on the role of WM in language acquisition suggests that individual differences in WM capacity are related to various aspects of both first and second language acquisition and processing even from an early age. However, exactly how these individual differences emerge is somewhat of an open question. While some accounts view variability in WM as due to inborn capacity differences (e.g., Baddeley, Gathercole, & Papagno, 1998), here we argue that one critical factor in determining PWM abilities may be early language learning experience (e.g., Gathercole, 2006). Specifically, both timing of language exposure and quality and quantity of language input during an early sensitive period for phonological development might influence children's short and long-term language learning as a result of variations in PWM.

Sensitive periods are common in the brain development of organisms, including humans. They are defined as a period during development when the acquisition of certain abilities or behaviours is facilitated. Following the closure of this period, these abilities can no longer be acquired, or are acquired to a lesser degree and much less efficiently (i.e., through compensatory mechanisms). A great deal of research has delineated sensitive periods for several aspects of visual development (for a review see Hensch, 2005; Werker & Hensch, 2015), with research on language development revealing less consistent results (e.g., Birdsong, 1999; Johnson & Newport, 1989; Krashen, 1973; Lenneberg, 1967; Morgan, 2014). However, there is considerable evidence that a sensitive period, or important-age-related constraints, exists for phonological development. This period lasts until roughly the end of the first year of life, at which point children's language abilities become fine-tuned such that they are better able to distinguish phonemic contrasts in their developing native language (or languages) than those in foreign languages (Kuhl, Williams, Lacerda, Stevens, & Linblom, 1992; Werker & Tees, 1984). During this period, it is suggested that neural architecture is altered so that circuits become specialized to the acoustic and statistical properties of phonetic units in the native language. This facilitates native-language learning, while making second language learning more difficult since the processing of any alternate (i.e., non-native) phonetic units is made less efficient (Kuhl, 2000; 2004). In fact, some evidence suggests that molecular processes are engaged at the end of sensitive periods to prevent specialized circuits from being altered by subsequent experience with similar stimuli (for a review see Werker & Hensch, 2015). Thus, specific distributions of native language phonetic units, in place by 8 to 10 months of age, become increasingly difficult to change and persist into adulthood (Baker, Idsardi, Golinkoff, & Petitto, 2005; Mattock, Molnar, Polka, & Burnham, 2008; Maurer & Werker, 2013; Maye, Werker, & Gerken, 2002; Polka & Werker, 1994; Werker, Gilbert, Humphrey, & Tees, 1981; Yoshida, Pons, Maye, & Werker, 2010).

In light of this, it is interesting to consider the relationship between the sensitive period for phonological development and the establishment of the PWM system. In particular, early experiences might influence phonological development and, in turn, PWM both through the timing as well as through the quality and quantity of language input experienced during or after a sensitive period. Input encountered while a sensitive period is open might be particularly influential in shaping the quality of phonological representations that will later be used by the PWM system, which arguably requires the establishment of adequate and stable phonological representations (Gathercole, 2006) acquired during the earliest stages of language learning.

While evidence for the specific role of children's earliest language experiences on PWM development is limited, there is some evidence from monolingual language learners that experience in general does influence PWM outcomes. For example, several studies report that language familiarity leads to enhanced PWM processing. Adults generally perform faster and more accurately when they are required to repeat words as opposed to non-words (e.g., Chiat & Roy, 2007), and both adults (Coady & Aslin, 2004) and 2;6-3;6 year old children (Thorn & Gathercole, 1999) have been found to repeat non-words more accurately if they are composed of highly familiar, frequent or native-like phonemes, as opposed to non-words constructed of phonemes with low phonotactic probability, demonstrating a relationship between learned phonemic knowledge and PWM capacity. There is also evidence that PWM capacity in children depends on language specific representations. For example, Messer, Leseman, Boom, and Mayo (2010) found phonotactic probability effects in 4-year-olds that were similar to those observed by Coady and Aslin. Messer and colleagues also found that monolingual Dutch-speaking children showed greater phonotactic probability effects in Dutch than did Turkish-Dutch bilinguals. The reverse was also true -- bilingual children for whom Turkish was their L1 showed greater phonotactic probability effects in Turkish than did Dutch monolinguals. Familiarity effects have also been observed in production. Keren-Portnoy and colleagues (2010) found that 26-month-old children who had been producing consonants for longer also performed better on non-word repetition tasks using stimuli that conformed to the regularities of the native language, particularly for consonants that they had individual experience producing compared to consonants not yet in their repertoires.

Evidence of experiential effects on other components of PWM has also been reported. For example, factors affecting sub-vocal rehearsal processes, such as articulation rates, also influence PWM capacity. In a sample of first, third, and fifth graders, the faster children were able to articulate words and digits, the better their PWM (Cowan, Wood, Wood, Keller, Nugent, et al., 1998). This relationship was interpreted as more efficient use of the phonological loop in that the more information that can be rehearsed within a shorter time span, the more information can be maintained at a given time. Importantly, although effects on sub-vocal rehearsal are not evident until later stages of development, they may be influenced by experiences that occurred earlier. For example, early exposure to rich linguistic stimuli may affect general processing speed, which may in turn affect articulation rates and, thus, PWM outcomes as well (e.g., Tallal, Miller, Bedi, Byma, Wang, et al., 1996).

Similarly, experiences that influence the acquisition of long-term stored vocabulary might also influence PWM abilities. By the age of 5 or 6, once children have acquired some proficiency in their native language, vocabulary becomes a much stronger predictor of PWM than the reverse (although there is much variability in this age range; see Gathercole et al., 1992; Jones, Gobet & Pine, 2007). This is important to note because factors that lead to differences in vocabulary size (including early differences in phonological representations underlying PWM) might in turn influence PWM processing at later stages of development. Children who are slower to develop vocabulary due to underspecified phonological representations might show increasingly worse PWM due to the lack of adequate vocabulary to support subsequent PWM processing. At the same time, the development of sufficient vocabulary might mask initial differences in PWM abilities owing to increased support from stored vocabulary knowledge, a point we return to later.

While much of the research reported here focuses on PWM in monolingual language learners, the evidence from this group is limited. Moreover, the influences of early experiences are difficult to tease apart in typically-developing monolinguals because by the time PWM can be measured in these children (i.e., once they are able to repeat words and sentences), the sensitive period for phonological development is likely closed. However, one way to shed light on the influence of the earliest experiences on PWM development is by looking at groups of language learners with more variation in their early language experiences than is usually evident in groups of monolingual learners, particularly variation that occurs during the earliest stages of language acquisition. In the following sections, we review research on different kinds of learners, which we believe provides a rich source of evidence for uncovering the relationship between early experience and PWM development.

A Spectrum of Early Experiences in Language Acquisition

While much research uses monolingual and uninterrupted language acquisition as the default model for studying language development, this is not the only, nor necessarily the most frequently occurring environment in which children acquire language. There is a wide variety of language acquiring populations who experience different learning environments compared to those reported in studies of native monolingual language learners, including bilinguals and internationally-adopted children as well as children with perceptual deficits. Not only has there been a growing interest in how different contexts affect the rate, pattern and ultimate attainment of language, we propose that examining populations with particular variations in early language experience allows us to delineate the influence of early experience on PWM outcomes in greater depth. This also allows us to draw implications for language learning outside those populations to language learning mechanisms more generally. Specifically, in the following sections, we examine the effects of language delay (i.e., internationally-adopted children and oral deaf children with cochlear implants) as well as the effects of relative enrichment or deprivation (simultaneous bilinguals and second language learners versus children with otitis media and deaf signing children born to non-signing parents) on the development of PWM. Based on this review, we argue that language input that is delayed, disrupted, and/or impoverished during an early sensitive period for phonological development will lead to specific disturbances and weaknesses in PWM that may in turn influence the development of more complex aspects of language under particular circumstances. We speculate that disturbances in PWM stem from underspecified phonological representations for the language that experienced the disruption. In contrast, learners who experience early language input that is enriched in some manner, as in bilinguals who learn more than one language, will show selective advantages in PWM owing to stronger, more stable, and/or a greater repertoire of phonological representations and/or possibly as a result of greater availability of executive function mechanisms that arise from exposure to and use of multiple languages. Throughout the following sections, we highlight the general patterns of development that arise in these different populations as well as the differences that can be predicted to arise from each language learning context.

Delayed exposure to language, with or without prior exposure to another language.

The present section reviews research on the development of language and verbal memory abilities of internationally-adopted (IA) children and children with congenital deafness who receive cochlear implants (CIs). Most IA children experience attrition of their birth language and delayed onset of exposure to their adoption language; in contrast, children with CIs who are born of hearing parents receive very restricted input prior to implantation. Despite differences between these groups, both experience delayed onset of language exposure and, as will be explained below, exhibit interesting similarities with respect to the development of language and memory abilities. In particular, both groups appear to show selective deficits in PWM, while general language abilities are disrupted to a lesser degree.

Internationally adopted (IA) children.

The language development of IA children is of interest both theoretically and clinically. Most IA children experience attrition of their first language (L1) and all experience delayed exposure to the adoption language. Exposure to the adoption language has many of the qualities of L1 acquisition insofar as IA children begin to acquire that language during infancy and it is the only language that they are exposed to and learn post-adoption; indeed, the adoption language has been referred to as second first-language (Delcenserie & Genesee, 2014a; DeGeer, 1992). What is interesting in their case is that, although they experience language from birth, the phonological representations laid down during the first months of life differ from those in the language they will ultimately learn. The question thus arises as to how this particular situation influences the development of both PWM and language abilities in the adoption language.

Before moving on to review research on the development of language and memory abilities in IA children, it is important to highlight that the development of these abilities can be affected by several factors above and beyond these specific language acquisition experiences. Country of adoption, for example, can influence the type and the quality of the pre-adoptive care children receive. The reasons for adoption as well as length of institutionalization are additional factors that might affect the development of IA children's language and memory abilities (Delcenserie, 2016). Most of the evidence reviewed here concerns children adopted from East Asian countries who were institutionalized for short periods of time and are known to have received relatively good pre-adoptive care (Pomerleau et al., 2005).

Researchers who have assessed the language development of IA children using standardized tests and/or standardized parent report forms normed on typically-developing monolingual children have found that most IA children score within the typical range on such measures; this is evident as early as 12 to 24 months post-adoption (see Scott & Roberts, 2016, for a review). At the same time, however, evidence indicates that IA children experience language gaps in comparison to non-adopted children as indicated by below average performance on test norms. These gaps are apparent during both the preschool and school years (Delcenserie 2016; Scott, 2009) and are evidenced by a larger than expected subgroup of IA children who perform below average compared to test norms and/or who require special language services (e.g., Delcenserie, Genesee, & Gauthier, 2013; Scott, Roberts, & Krakow, 2008). Lags in language development have also been reported in research that has compared IA children to non-adopted monolingual children matched on variables associated with language acquisition, such as age, gender, and socio-economic status (Cohen, Lojkasek, Pugliese, & Kiefer, 2008; Delcenserie et al., 2013; Delcenserie & Genesee, 2014a; Gauthier & Genesee, 2011; Hoff, 2006). These studies have consistently found that, during preschool, IA children perform significantly lower than matched controls on measures of expressive and receptive language, particularly vocabulary (Gauthier & Genesee, 2011; Scott & Roberts, 2016). During the school years, IA children continue to perform significantly lower than non-adopted controls on measures of vocabulary and also on measures of receptive grammar, knowledge of word definitions, and morphosyntactic abilities such as clitic production (Delcenserie et al., 2013; Delcenserie & Genesee, 2014b; see Delcenserie, 2016, for a review).

Aside from the factors mentioned earlier, such as length of institutionalization, the most important factor reported to influence the development of IA children’s language development is age at the time of adoption; in other words, the length of the delay in exposure to the adoption language. Several studies report that children adopted at earlier ages, before 12 months of age, have better language outcomes as measured by standardized tests (Dalen, 2002; Tan, 2009; van IJzendoorn et al., 2005), make fewer grammatical errors on a narrative task (Scott et al., 2008), and have better reading achievement abilities in comparison to later-adopted children, among other advantages. The effect of age at adoption on language seems to attenuate with time and is not as apparent in school-age IA children and adults (Delcenserie & Genesee, 2014a).

Although few detailed studies on IA children's memory abilities have been done, the evidence available so far suggests that they score significantly lower on tests of memory in comparison to matched control children and that these gaps are specific to language (Delcenserie & Genesee, 2014a). More specifically, it has been found that IA children perform significantly lower than their non-adopted peers on non-word repetition, forward and backward digit recall, and listening recall (Delcenserie & Genesee, 2014a; Eigsti, Weitzman, Schuh, De Marchena, & Casey, 2011). Despite their lower performance in comparison to matched non-adopted children, IA children's verbal memory is usually within age norms on standardized tests (Delcenserie & Genesee, 2014a; Eigsti et al., 2011; Scott et al., 2008), indicating that lags in verbal memory are not of a clinical nature. However, similar to what has been found about IA children's language abilities, emerging evidence suggests that age at adoption is significantly and negatively correlated with measures of verbal memory, such as non-word repetition (Hough, 2005), suggesting that IA children's delayed exposure to their adoption language might impact their verbal memory abilities as well as their language development.

Delcenserie and Genesee (2014a) examined the relationship between IA children's early language experiences and both their language and memory abilities in some detail. They studied 30 IA children from China who were adopted between 6 and 24 months of age by

French-speaking families. The IA children were compared to monolingual non-adopted children matched on age, gender, and socioeconomic status (SES). They found that, despite scoring within standardized test norms for typically-developing monolingual children, the language and memory abilities of the IA children were lower than those of their matched non-adopted peers. They also found that the adoptees' PWM abilities were lower than their language abilities and that both were highly correlated, suggesting that lags in verbal memory underlie lags in language development. Also of interest, using regression analyses that included a number of different predictor measures, they found that the performance of the IA children on tests of PWM was the best predictor of their language scores in contrast to matched non-adopted children where age was the best predictor, again suggesting that differences in WM are related to differences in outcomes in the adoption language. In conjunction with their findings that, on average, IA children score within the typical range on standardized tests, these results suggest that alternative mechanisms that go beyond verbal memory might be engaged in order for them to achieve linguistic parity with test norms.

That IA children's memory weaknesses in comparison to matched controls are related to delayed onset of exposure to the adopted language and not attrition of the birth language is supported by a neuroimaging study by Pierce and her colleagues. That study compared IA children from China adopted into French-speaking families to monolingual French-speaking children and Chinese-French bilinguals (Pierce, Chen, Delcenserie, Genesee, & Klein, 2015). The IA children were 13;7 years of age, on average, and were matched to the other groups on age, gender, and SES. The bilingual children had learned Chinese as an L1 and French as an L2 at the same ages as the IA children. All the children were scanned while performing an n-back task which is thought to reflect PWM, using French pseudo-words. While all groups activated regions associated with PWM processing, the monolingual French speakers, who had been exposed to French since birth, activated certain regions related to PWM, such as left inferior frontal gyrus and left anterior insula, more strongly than the other groups. The monolingual participants also showed greater connectivity between the left anterior insula and other regions associated with PWM processing. In contrast, both the IA children and the Chinese-French bilinguals activated additional regions, such as the right superior and middle frontal gyri, that are typically associated with non-verbal memory and cognitive control processes, particularly as the task got more difficult. That both the bilingual participants and the adoptees exhibited the same pattern of brain activation indicates that it is delayed language exposure and not attrition of the birth language that accounts for the IA participants' results.

Together, findings from Delcenserie and Genesee (2014a) and Pierce et al. (2015) suggest that the different patterns of brain activation observed in IA children, particularly on tasks that implicate PWM, may be due to the fact that they were adopted and began learning the adoption language following the closure of the sensitive period for phonology. In turn, reduced PWM for the adoption language could underlie results indicating that IA children have reduced vocabularies in comparison to non-adopted children. Moving forward, reduced vocabulary size means that less information is available in LTM and that the grammatical constraints and properties of the adoption language are more difficult to retain and use since there is less information available to make rehearsal processes more efficient. This in turn may affect the efficiency with which new linguistic information is acquired through the phonological loop, and this cycle continues. Taken together, this evidence provides support for the necessity of adequate and language-specific phonological representations during the first year of life in order to set up the representations employed by the phonological store for later language learning.

Deaf children learning spoken language.

Congenital deafness can influence both the timing of onset to language and the quality of linguistic input that deaf children are exposed to. Thus, language acquisition in this group can be affected in two ways which we describe in detail throughout this section: as a result of disruption to the typical timeframe of development (i.e., delayed onset of language acquisition) and as a result of varying levels of impoverished input, both in sign and spoken modalities. These effects can be linked to the fact that an estimated 90 to 95% of deaf children are born of hearing parents (DCHPs) who have had very limited previous exposure to signed languages. In this section, we discuss spoken language acquisition in this population, with a discussion of sign language development in the following section.

Spoken language development in children born congenitally deaf is facilitated by cochlear implantation (CI), which is the growing intervention of choice for most DCHPs. However, it is important to note that CIs do not turn a profoundly deaf child into a hearing one. CIs are given to children following a neo-natal diagnosis of deafness, but the age of onset of the implantation can be up to 24 months and in some cases as late as 36 months. At present, this age of CI onset is decreasing and in some countries is happening in the first 12 months. However, even when CI onset is early, there continues to be a period of several months during which the CI becomes fully operational and speech therapy starts to make an impact on the child’s growing linguistic ability. Even with a successful CI and intensive speech therapy, spoken language acquisition is more effortful for a child with a CI than for hearing children. This early period of restricted oral language input means there is often a delay in the onset of language development. Prior to cochlear implantation, DCHPs typically have very little access to language, oral or signed. While many parents continue to speak to their deaf infant after the early diagnosis of deafness and up to the point of the CI procedure, profound deafness is a major barrier to the uptake and storage of spoken phonology during this early sensitive period. Although parents sometimes use a signed language during this early period, the input they provide is typically at a basic level because they usually begin to learn a signed language only after their child is diagnosed with a hearing impairment (Lu, Jones, & Morgan, 2016). Moreover, despite advancing CI technology, these devices provide a reduced version of the auditory signal so that, once hearing is restored, input, although improved, may remain impoverished to some degree. In any case, as a result of delay in CI, the acquisition of spoken language is delayed in comparison to the natural acquisition timetable for PWM and early language learning in hearing children.

Researchers have found that CI children experience lags in comparison to typically-developing hearing children on measures of language ability such as language comprehension, grammar, and vocabulary (Chilosi et al., 2013; Geers, Nicholas, & Sedey, 2003). Although there has been limited research on the morphosyntactic development of DCHPs to date, extant evidence indicates that, like IA children (Delcenserie & Genesee, 2014b), they exhibit morphosyntactic difficulties with the use of free and bound morphemes such as articles, pronouns (including clitics), and verb morphology (Chilosi et al., 2013; Le Normand, Ouellet, & Cohen, 2003). Researchers have also found quite consistently that the language abilities of children with CIs, as a group, are around one standard deviation below that of typically-developing hearing children and, as well, that their development is characterized by slower and more variable language trajectories (Geers, Nicholas, Tobey, & Davidson, 2015; Niparko et al., 2010). In this respect, they are different from and more negatively affected than IA children, likely owing to the fact that children with CIs have no or very little early language input.

Children with CIs also have memory difficulties that persist from childhood into adulthood (Caselli, Rinaldi, Varuzza, Giuliani, & Burdo, 2012). More specifically, children with CIs have been found to perform significantly more poorly on tests of PWM for spoken language than typically-developing hearing children (Burkholder & Pisoni, 2003; Harris et al., 2013; Pisoni & Clearly, 2003). However, although they exhibit slower rates of growth on tests of PWM (Harris et al., 2013; Pisoni, Kronenberger, Roman, & Geers, 2011), their patterns of development are otherwise the same as those of hearing children. Thus, while the memory abilities of children with CIs are significantly lower than test norms, their pattern of development appears to be delayed rather than deviant in comparison to that of typically-developing hearing children.

As has been observed in IA children, a higher than expected percentage of children with CIs experience difficulties in language and PWM abilities. Several factors appear to be implicated in this pattern, including bilateral versus unilateral implantation (Nittrouer, Lowenstein, & Holloman, 2016; Sarant, Harris, Bennet, & Bant, 2014) and, of particular relevance for the issue at hand, age at implantation (except see Dunn et al., 2014 and Nittrouer et al., 2016). Niparko and colleagues looked at the effect of age at implantation on measures of spoken language expression and comprehension over a three-year period (Niparko et al., 2010). The children with CIs' were between 12 and 46 months of age at the start of the study and were sub-grouped according to age at the time of implantation (0-18 months of age, 18-36 months of age, or after 36 months of age). Children implanted prior to 18 months of age performed better on measures of spoken language expression and comprehension, and the longitudinal growth of the abilities of the children implanted at younger ages was more similar to that of typically-developing hearing children. Thus, children with CIs who experience onset of language exposure several months after the closure of the sensitive period for phonological development tended to experience more language difficulties than children who were implanted earlier. In terms of memory abilities, several studies also report that age at implantation is negatively and significantly correlated with performance on measures such as non-word repetition and forward and backward digit recall tasks (e.g., Soleymani, Amidfar, Dadgar, & Jalaie, 2014). In sum, research suggests that deaf children who experience delayed spoken language acquisition not only experience lags in language development in comparison to hearing children, but also lags in PWM.

While much research has examined the PWM skills of children with CIs, what remains unclear is how spoken language and memory influence each other in these children. On the one hand, some studies report that language development mediates memory development in children with CIs. According to this view, the lack of early language experience influences the development of language abilities which, in turn, negatively influences their memory abilities. These studies usually report that the language development of children with CIs is a significant predictor, or a mediator, of memory (e.g., Rhine-Kahlbeck, 2004). On the other hand, there is evidence suggesting that early spoken language deprivation and delay negatively impact the development of memory abilities which then retards language development. According to this hypothesis, the sensory deprivations associated with deafness influence the neural organization as well as the development of domain-general cognitive skills that rely on auditory/spoken experiences (Conway, Pisoni, & Kronenberger, 2009), thus impacting the development and growth of working memory. This would likely have a cascading effect on the development of speech/language skills that heavily depend on working memory and other information-processing abilities (Pisoni et al., 2011). Although there is evidence in favor of both hypotheses, it is important to keep in mind that the relationship between language and memory changes during development, as noted earlier (Gathercole et al., 1992). It is therefore possible that, for children with CIs, the relationship between memory and language changes depending on their chronological age at the time of testing. Nevertheless, it seems reasonable to assume, or at least speculate, that some pre-existing capacity for verbal memory is necessary for the earliest stages of language acquisition to take place.

Overall, evidence indicates that deaf children with CIs who experience delayed onset of language acquisition present with early delays in the acquisition of spoken language phonology and they also exhibit diminished PWM abilities. At the same time, any speech based input that is received prior to CI may be impoverished. Critically, it is not the case that parents of deaf children speak less or change the quality of their spoken language input to their infants (Lederberg, 2006). However, there is a time period before CI and while the CI becomes activated that PWM receives a less than optimal signal. This situation is discussed in more detail in the following section.

Impoverished and enriched language input.

In contrast to the learners discussed in the preceding sections who experience delayed language input, children can receive early language input that is degraded or impoverished in some way, as is the case for children who have multiple bouts of otitis media early in life or deaf children who rely on sign but have non-signing parents. As described in the previous section, language input for deaf children can be both delayed and impoverished. Children who rely on a CI experience early degraded input before and while the CI is becoming functional. If the development of PWM depends on the quality of early language input, PWM abilities following impoverished early language input might, at least to some extent, resemble those of learners who experience delayed exposure to language. In contrast, simultaneous bilingual language learners might be considered to experience enriched input as a result of bi- or multi-language exposure. Not only are bilingual children exposed to a larger distribution of language sounds, they also hear more lexical entries for the same items/concepts and are exposed to greater variability in language input overall insofar as they are exposed to both native and non-native input (e.g., Fennel & Byers-Heinlein, 2014) which they are required to process. Second language learners might also be said to experience enriched language exposure since they are exposed to additional languages after beginning to acquire a first language or languages; however these learners also experience a delay in exposure to their L2. In contrast to the effects of early delay or impoverished language input, enriched early language exposure might lead to selective increases in PWM abilities. To explore these possibilities, cases of impoverished and enriched early input are discussed in the following sections in order to further shed light on how variation in the quality of early language experiences might influence the development of PWM and, in turn, language development.

Impoverished language input: Children with otitis media.

Much research has investigated the language outcomes of children who experience otitis media during infancy and early childhood (for reviews see Ruben, 1997; Whitton & Polley, 2011). Since these children tend to experience discontinuous disruption in language exposure and not total or extended disruption, we consider these children to represent a case of impoverished language input and not delayed input. Research has reported that the general language outcomes of children who experience early otitis media are generally within the typical range. In contrast, studies of these children that have examined fine grained language outcomes related to phonological processing, language comprehension and vocabulary knowledge consistently report that otitis media is associated with delays and specific weaknesses in language ability (e.g., Mody, Schwartz, Gravel, & Ruben, 1999; Pearce, Saunders, Creighton, & Sauve, 1988). Research suggests further that these difficulties may stem from reduced PWM capacity. For example, Mody and colleagues (1999) found that 9-year-old children who experienced otitis media during the first year of life but had normal hearing at the time of testing performed more poorly than control participants on tasks of phoneme recall and temporal order judgments. The authors conjectured that these lags resulted from underspecified phonological representations in working memory due to hearing disruption early in life. Similarly, Majerus et al. (2005) found that 8-year-old children with normal hearing and vocabulary at the time of test who had experienced severe and recurrent otitis media prior to the age of 3 performed lower than control children on tasks of PWM, including speeded non-word repetition and rhyme judgement (Majerus, Amand, Boniver, Demanez, Demanez, & Van der Linden, 2005). Finally, 5-year-olds who had experienced repeated episodes of otitis media prior to the age of 3 but with normal hearing at the time of testing showed reduced performance on tasks of syllable and phoneme awareness as well as on serial recall of word lists and comprehension of syntactically complex sentences (Nittrouer & Burton, 2005). Considering the discussion thus far, it is possible that, due to repeated periods of impaired hearing early in development, these children had formed less accurate phonological representations for the input language.

Impoverished language input: deaf children's acquisition of signed languages.

It is estimated that only 5-10% of deaf children are born of deaf parents (DCDPs); these children are referred to as *native signers*. Research on native signers shows that the acquisition of sign language parallels that of typically-developing hearing children who learn spoken languages with respect to the onset, rate, and pattern of language development. For example, it has been found that native sign language learners use their first signs, make early sign combinations, and master syntax along a timescale that is similar to that of typically-developing hearing children (Chamberlain, Morford, & Mayberry, 2000; Morgan & Woll, 2002; Schick, Marschark, & Spencer, 2005; Morgan, 2015).

In contrast to native signers, the vast majority of children born congenitally deaf are born of hearing parents (DCHPs), as noted earlier. With the advent of the Newborn Hearing Screening Programme in the UK and North America, the vast majority of children with a hearing loss are identified in the first weeks of life. Even so, this does not mean that DCHPs are exposed to sign language at an early age. Because their parents do not know before birth that their child will be deaf they cannot begin to learn a sign language until after a diagnosis has been made. As a result, some time following diagnosis, DCHPs receive non-native sign input from hearing parents who are just learning the language. This means that the majority of deaf children are first exposed to sign after the first few years (Lu et al., 2016) and, in some cases, considerably later (Morford, 2002). Thus, among deaf children who are reliant on a sign language for communication, there is an obvious conflict between the necessary fluent models they require for full acquisition of the language (as evidenced in the case of DCDPs) and the signing skills of their parents (Schick, Marschark & Spencer, 2005). When these children acquire sign language, after a delay of several months or even years, they become *non-native learners* of their first language.

Lu and colleagues (2016) studied the signed input from both deaf and hearing parents to their deaf infants during the first 24 months of life. Deaf parents signed with their infants from birth onwards in the same way hearing parents talk to hearing infants. However, hearing parents with deaf infants had to begin the laborious task of learning BSL (British Sign Language) before they began to sign to their infants. Parental reports indicated this occurred between 3-12 months after the diagnosis of deafness but the quality of this input was not native like to any degree. While both sets of parents used BSL with their children as the main language of communication, there were systematic differences in the quantity (number of handshape types) and quality (clarity of signed articulation) of signs used by the deaf and hearing parents. These variations in the signed input were mirrored in the signing output of their deaf infants, especially with regard to the children's phonological systems, even though the DCHPs had been exposed to BSL relatively early in their development (from between 3-12 months of age). Thus, the DCHPs, although still in the sensitive period for phonological development when their parents began signing with them, were shown to have less developed phonologies than the DCDPs. In other words, the advantage of early exposure to a signed first language can be modulated by the effects of non-optimal input and this is more likely the older the age of acquisition of the learner and the quality of the signed language input provided by caregivers or others in the learners' environment. A child who receives non-native language input from their primary caregiver who decides to speak her second language to the child will be simultaneously hearing much native language input from siblings, neighbours, television, etc. However a DCHP will typically only get signed input during the early stages of language acquisition from their non-native signing parents.

Marshall and colleagues (2015) report that children aged 6-11 years of age who had restricted exposure to fluent models of sign language also have working memory delays in comparison to hearing children and native signers of the same ages, again suggesting that the quality of early language experience, either signed or spoken, affects working memory abilities. This study used measures of non-verbal working memory rather than PWM. The only studies that have examined PWM specifically in signers who experienced impoverished input early in life looked at outcomes in adulthood. Deaf adults who were DCHPs have been shown to have language processing abilities that resemble the level of phonological sensitivity attained by second language learners of spoken languages. These studies taken together provide evidence that non-native sign input during the sensitive period for phonological development can have lasting effects on L1 abilities, particularly in the realm of PWM. For example, Mayberry (1993) examined adults who had been born deaf to hearing parents and began learning American Sign Language (ASL) as an L1 sometime between early infancy and late childhood (i.e. 0-13 years). She compared the language abilities of these ASL learners to those of adults who had been born with normal hearing (and thus normal spoken-L1 acquisition onset), but who lost their hearing later in life and then acquired ASL as an L2. She found reduced sentence recall abilities in the late onset L1 learners of ASL relative to both native ASL speakers and late onset learners of ASL as an L2.

Thus, studies on sign language acquisition show that impoverished early signed input leads to language difficulties in adult signers, particularly with respect to phonological and lexical processing. Deaf adults who experienced impoverished early signed language input have also been found to have difficulties in the acquisition of English as an L2 (e.g., Mayberry, 2007; Mayberry & Lock, 2003; Wake, Poulakis, Hugues, Carey-Sargeant, & Rickards, 2005). For example, Mayberry and Lock (2002) tested English reading in deaf adults (*n* = 31; 17-53 years of age) who had been exposed to ASL as a primary language at different points in childhood. Results showed that adults who had experienced very early and consistent native exposure to ASL achieved higher levels of sign language proficiency. This group was also more skilled at reading English as a second language than adults whose ASL proficiency was poorer, suggesting that, even when languages involve different modalities, strong L1 skills facilitate L2 learning.

Enriched language input: simultaneous bilingual and second language learners.

We treat simultaneous bilingual and second language learners as cases of enriched language input because they have exposure to more than one language and, most importantly from the perspective of our thesis concerning a sensitive period for phonological development, exposure to more than one phonological system. Our working assumption is that, since bilinguals, simultaneous and successive, can achieve high levels of proficiency in additional languages, enriched exposure to two phonological systems constitutes a stimulus for phonological development and PWM. However, and in contrast, bilingual learners might be at a disadvantage since, on average, they have reduced exposure to each language in comparison to monolinguals and, at least in the case of successive bilinguals, by definition they begin acquisition of the second language following the sensitive period for phonological development.

In support of the assumption that exposure to more than one language is a form of enrichment, evidence suggests that there is an executive function advantage for bilinguals in comparison to monolingual speakers which is thought to be due to their experience managing more than one language (Baum & Titone 2014; see, Morton, 2014, for an opposing point of view). Evidence suggests further that this advantage extends to working memory and verbal memory in particular (e.g. Blom, Küntay, Messer, Verhagen, & Leseman, 2014; Delcenserie & Genesee, 2016; Kaushanskaya, 2012; Kroll, Michael, Tokowicz, & Dufour, 2002; Kudo & Lee Swanson, 2014; Yoo & Kaushanskaya, 2012; but see also Engel de Abreu, Cruz-Santos, Tourinho, Martin, & Bialystok, 2012; Ratiu & Azuma, 2015); although these advantages may be evident only after a certain amount of exposure. For example, Kaushaskaya and colleagues (2014) found that 5 – 7 year old Spanish/English bilingual children had greater verbal WM abilities than English monolingual children once the bilingual children had had two years of exposure to Spanish and English. Similarly, Blom and colleagues (2014) found that while 5-year-old Turkish-Dutch bilingual children did not differ from matched monolingual children on measures of verbal WM when initially tested, they performed better than the monolingual children when they were tested at a one-year follow-up. Finally, in a study of 22-month-old Spanish-English simultaneous bilingual children, Parra, Hoff, and Core (2010) demonstrated that amount of English in the homes of Spanish-English bilingual children was positively correlated with accuracy for non-word repetition for English-like, but not Spanish-like stimuli. However, exposure and proficiency are often confounded and, thus, these findings might better be interpreted to reflect the importance of proficiency.

Indeed, proficiency has been found to predict verbal memory in both bilingual children (e.g., Kudo & Swanson, 2014) and adults (Linck, Osthus, Koeth, and Bunting, 2014; Luk, 2015; Service, Simola, Metsänheimo, & Sini Maury, 2002). Thorn and Gathercole (1999) examined performance on non-word repetition and digit span tasks in 5-6 year-old children who were either English monolinguals, simultaneous French-English bilinguals (learned both French and English from birth), or French second language learners (learned English from birth and French after the age of 3, matched for French vocabulary knowledge with the simultaneous bilinguals). Her results showed that the groups who performed better on the English non-word repetition and digit span tasks were those who had larger English than French vocabularies (i.e. English monolinguals and second language learners of French). Simultaneous bilingual children who had equivalent English and French vocabularies performed equivalently on tasks in each language. Furthermore, the two bilingual groups (matched for French vocabulary) performed equivalently to each other and better than the monolingual English speakers on the French PWM tasks. In a second experiment, 4-8 year old simultaneous and sequential French/English bilinguals (not matched for vocabulary) were compared. In this case, simultaneous bilinguals, who had equivalent vocabularies in each language, performed equivalently on non-word repetition tasks in their two languages. In contrast, sequential bilinguals, who had greater vocabulary knowledge in their L1, performed better on the non-word repetition task in that language. Thus, in one sense, evidence suggests that L2 acquisition can be treated as a case of delayed exposure to a language if acquisition begins at some point after L1 onset. However, increased proficiency in a language, even an L2, might support the development of verbal memory abilities in bilinguals (as in other learner groups) because increasing proficiency implies that individuals have more vocabulary items stored in long term memory on which they can draw to support PWM processes.

This leaves open the question of age of acquisition (AoA), which is also often confounded with proficiency, but which may uniquely influence the development of PWM because L2 learners are exposed to the L2 after the sensitive period for phonological development. Vejnovic and colleagues (2010) examined whether AoA influenced verbal memory abilities in bilingual speakers by testing equally proficient groups of adult successive bilinguals who acquired their L2 at age 4 or age 9, on average. They found that, while both groups performed similarly on verbal memory tasks in their L1, the bilinguals who acquired their L2 earlier performed better on L2 verbal memory tasks than the group who acquired their L2 later. Delcenserie and Genesee (2016) addressed the issue of AoA and WM further by examining both simultaneous and successive bilinguals on both verbal and non-verbal memory. Specifically, they tested groups of highly proficient English-French bilinguals who had either acquired both languages simultaneously from birth or had acquired English as an L2 "early" (i.e., between 3 and 6 years of age) or "late" (i.e., after 6 years of age); these groups were compared to English monolinguals. They found that all bilingual groups performed better than the monolingual group on verbal and non-verbal WM tasks, supporting a bilingual WM advantage. However, the simultaneous bilinguals scored significantly better than both L2 groups, despite the fact that all groups had equally high proficiency in English, suggesting that it is early exposure to enriched language input that is especially advantageous.

Putting it All Together

In the preceding sections, we reviewed studies that indicate, unsurprisingly, that very early language experiences shape children's later language learning. In particular, we proposed that early cognitive underpinnings, namely the development of PWM, play a key role in this relationship. Here, we consolidate that evidence in order to discuss how variations in the timing, quality and amount of language exposure after birth might modulate effects on later language development as a result of their effects, short- and long-term, on phonological processing and, in particular, PWM.

The first thing we note about the language development patterns of the specific groups we have reviewed is that, while early experiences can affect all aspects of language development, phonological aspects of language (including PWM) appear to be particularly vulnerable. As reviewed, deaf adults who experience delayed exposure to L1 signed language as children exhibit particular difficulties in phonological processing in sentence repetition tasks in comparison to adults with early L1 sign exposure (Mayberry, 2007), and children who experience delay in L1 sign language exposure exhibit greater difficulties acquiring and processing phonological information than late L2 sign language learners who become deaf after early acquisition of spoken language. Similar patterns have also been found in oral deaf children's rapid processing of English phonotactics (Geers et al., 2015). Similarly, while IA children often score within the typical range on standardized tests of language such as vocabulary and grammar, they score significantly lower in comparison to both test norms and matched control groups on tests of sentence recall and working memory involving phonological processing (Delcenserie & Genesee, 2014a). These outcomes arguably occur due to a disruption in the phonological input during an early sensitive period for phonological development and, in the case of signing deaf children, these effects might also reflect the impoverished nature of the input that delayed sign language exposure entails (Lu et al., 2016), a point we return to later. Other groups who experience impoverished language input during the sensitive period for phonological development also exhibit reduced performance on tasks dependent on phonology. For example, children with otitis media early in life have been shown to exhibit lags on tasks assessing PWM while often scoring in the typical range on other tests of language including expressive and receptive vocabulary, although subtle effects on these measures have also been reported (see Roberts et al., 2005, for a review).

Similar patterns also appear in children who learn a second language. L2 learners who, by definition, exhibit lags in exposure to an L2 but normal exposure to their L1 at birth, in some cases perform more poorly on phonological processing tasks in the language that they acquire later (e.g., Abrahamsson & Hyltenstam, 2009; Parra, Hoff, & Core, 2010); these effects can persist into adulthood, though lags may be masked with increasing proficiency in that language, potentially through the recruitment of additional cognitive abilities (Delcenserie & Genesee, 2016). Such effects are more evident in L2 learners with less proficiency in the L2 than in highly proficient L2 learners (Delcenserie & Genesee, 2016), although they can be evident even in L2 learners who can pass for native speakers during oral conversations if sufficiently sensitive language tests are used (Abrahamsson & Hyltenstam, 2009). In contrast, L2 learners and simultaneous bilinguals who achieve high levels of L2 proficiency – on par with monolinguals, do not necessarily exhibit such lags and may even exhibit advantages in PWM in comparison to monolingual learners (Delcenserie & Genesee, 2016). Of particular note, simultaneous bilinguals who have exposure to two languages from birth score significantly higher than L2 learners with equally high levels of proficiency in the target language on tests of PWM, arguing again that it is early experience with language that is especially consequential for phonological processing and language learning.

At the core of our hypothesis is the speculation that the development of PWM is tied to the establishment of language-specific phonological representations insofar as there is evidence that phonological representations form the basis for what is most efficiently processed by the PWM system (Gathercole, 2006). We argue more specifically that the maturation of the WM system itself is modulated by the same types of language experience that facilitate the brain's specialization for its developing native language. In this argument, the sensitive period for language is therefore tied into a shared timeframe for the activation and instantiation of the PWM component. Moreover, because native-language specific phonological representations are established early and remain robust over time, we propose that subsequent PWM processes that are active beyond the initial stages of language acquisition continue to be influenced by that early experience.

Evidence from the language learning groups we have reviewed supports this claim and suggests how these effects might be substantiated in the brain and, thereby, how they might influence language development. Beginning with IA children, perceptual attunement typically occurs during a time when they are exposed to a language they will subsequently discontinue learning. Thus, by the time they are adopted – often between 12 and 24 months of age in the case of children from China, the object of much research – IA children have become at least partially, if not completely, specialized at discriminating the speech sounds of their birth language but will not have acquired phonological representations and full maturation of PWM for specific sounds in the adoption language. If early-acquired phonological representations for the birth language persist -- as suggested by Pierce and colleagues (2014), they might interfere with or otherwise impact acquisition of phonological representations for sounds in the adoption language (Pierce et al., 2015).

The findings from Pierce and colleagues (2015) support this argument and suggest further that this is the case for typically-developing L2 learners as well. Of particular relevance to the current discussion, IA children who began acquiring their “second first language” from between 6 and 25 months of age exhibited similar patterns of brain activation during the PWM task as same-age Chinese-French bilinguals who had acquired French as an L2 at approximately the same ages as the adoptees, but who continued to learn and use Chinese, their birth language. While all groups activated regions associated with PWM, the IA children and the Chinese-French bilinguals activated additional regions that are typically associated with non-verbal memory and cognitive control processes. Pierce and colleagues interpreted these results to indicate that the adoptees and the bilingual participants recruited regions of the brain that differed from those activated by the French monolinguals in order to compensate for the fact that phonological representations in the brain had been fine tuned to Chinese but the current language environment was French. As a result, it may be that subsequently acquired phonological representations for the adoption language were weaker or less precise than those acquired by L1 learners. In turn, acquisition of the adoption language after the sensitive period for phonological development, along with maintenance of phonological representations from the birth language, may account for the persistent PWM lags exhibited by IA children. These factors may in turn contribute to specific behavioral difficulties observable in IA children’s acquisition of the adoption language, as evidenced by their performance on tasks of verbal memory and vocabulary that implicate those representations (see Scott & Roberts, 2016; and Delcenserie, 2016, for reviews).

Turning now to deaf children of hearing parents -- weaker PWM for spoken language has been found in profoundly deaf children born of hearing parents who receive CIs. However, in contrast to IA children, these children receive no or greatly reduced sensory input during the sensitive period for phonological development before and during the CI process. Thus, influences from a previously acquired language and, in particular, early-acquired phonological categories and relationships, cannot account for the language and verbal memory outcomes of deaf children with cochlear implants. How then can we account for their patterns of language development? There are at least two possibilities. One possibility is that they acquire unstable or underspecified phonological representations of spoken language because they are acquired after the sensitive period for phonological development. In other words, the phonological representations of the input language that congenitally deaf children establish and use for language learning following implantation may be unstable or weak because they were not laid down during the sensitive period for phonological development.

Another possibility is that, because they acquire spoken language after the sensitive period for phonological development, children with cochlear implants, like IA children, draw on alternative, more general cognitive systems to acquire the phonological representations that support their developing PWM system. In support of this, an increasing number of studies suggest that individual differences in speech-language outcomes after cochlear implantation in deaf children may be due to underlying differences in core neurocognitive processes (e.g., Harris et al., 2013). That reliance on alternative cognitive systems results in different outcomes in comparison to CI children’s hearing peers and deaf native signers comes from evidence that a significant number of deaf children with cochlear implants continue to exhibit weaknesses in language development, particularly phonological processing skills, following implantation. This suggests that phonological processing and PWM that relies on alternative neurocognitive processes may be less than optimal (Spencer & Tomblin, 2008; Geers & Hayes, 2010; Miller Lederberg & Easterbrooks, 2013).

Additional evidence supports the hypothesis that alternative cognitive systems (i.e., those not typically active during early language acquisition) might be activated for processing phonological information in a language that is acquired after the sensitive period for phonological development, with or without prior sensory input. For example, Barone and colleagues (2013) have found that the auditory cortex of congenitally deaf, but not hearing, cats received unique inputs from visual and somatosensory brain regions, which the authors viewed as compensatory (see Campbell et al., 2014, for a review of issues surrounding cortical reorganization during and after deafness in humans). In humans, this may imply that alternative brain networks take over, or supplement, phonological processing for a language that was not acquired during the earliest stages of development. Supporting this, Logan, Lively and Pisoni (1991) report that adult L2 learners are able to learn non-native phonemic contrasts through extensive training (see also Bradlow, Pisoni, Akahane-Yamada, & Tohkura, 1997; Ingvalson, Holt, & McClelland, 2012; Lively, Pisoni, Yamada, Tohkura, & Yamada, 1994; and McCandliss, Fiez, Protopapas, Conway, & McClelland, 2002) and that this learning occurs through the use of compensatory mechanisms that are highly task-dependent (Gervain & Werker, 2008; Werker & Tees, 2005). Despite such improvements, however, it is rare for the phoneme discrimination abilities of late L2 learners to reach the level of native-speakers or to generalize outside the training context; nor is there evidence that newly acquired phonemes are used during word recognition (e.g., Bradlow et al., 1997; Ingvalson et al., 2011; Pallier, Bosch & Sebastián-Gallés, 1997). These findings, along with results from research on children with CI, are compatible with our hypothesis that language exposure that happens during the sensitive period sets up a reciprocal relationship between the building blocks of language and PWM. If both systems are set up from very early in development, the ensuing language skills may be most efficient. However, if development is disrupted, as illustrated in the populations reviewed previously, compensatory mechanisms might be used to enable language development to progress, although this may come at some cost.

Evidence that early language exposure in any form is better than no language exposure at all comes from studies of native sign language learners (deaf children born of deaf parents who are exposed to a natural signed language during an early sensitive period). In this case, a WM system with full processing capacities can be developed (Marshall et al., 2015). While native signers are extremely rare, their language development profiles point to the importance of early language exposure in some modality (even if it is not speech) as a crucial factor in PWM development. In contrast, the results we reviewed suggest that if initial language exposure is in a language that is ultimately discontinued (the case of IA children) or if early input is impoverished (DCHPs, children with otitis media, to be discussed next), phonological processing and PWM are affected to some degree later in development.

While IA children likely develop phonological representations for a language they will ultimately discontinue and CI children may miss the early opportunity to establish optimal phonological representations, children with impoverished language input during the first years of life fall somewhere in between. Specifically, and on the one hand, children who experience multiple bouts of otitis media early in life and deaf children who rely on sign language input but are born to hearing parents just learning a signed language both receive language input from birth or, often, by the time they are 6 months of age. On the other hand, their early exposure to language is often degraded or impoverished. Despite early exposure to language, the language outcomes observed in these groups and, in particular, their lags in tasks requiring phonological processing and/or PWM (e.g., Otitis Media: Mody et al., 1999;

Pearce, et al., 1988; DCHP's sign language skills as adults: Emmorey, 1995; MacSweeney, et al, 2008; Orfanidou et al, 2010) resemble those of both CI and IA children. Although beyond the scope of this article, it is also interesting to note that similar weakened PWM abilities are thought to underlie the particular deficits observed in children with specific language impairment (SLI; e.g., Archibald & Gathercole, 2006). While PWM deficits in SLI are proposed to stem from neuro-cognitive impairments (e.g., Ullman & Pierpont, 2005), in the present populations we propose that similar lags can be caused by environmental disruption. Specifically, the pattern of reduced PWM abilities observed in children with otitis media and DCHPs may be due to degraded language input during the earliest stages of development when phonological representations are typically acquired. Thus, the input that DCHPs and children with otitis media are exposed to may not be consistent or precise enough to establish phonological representations that are on par with those of children who have continuous and non-degraded language exposure from birth. As a result, children with impoverished early language experiences may have under-represented or weak phonological representations that are less efficient for supporting PWM processes.

In contrast to the preceding cases of delayed and impoverished input, bilinguals acquire language under conditions that might be considered enriched insofar as they are exposed to and acquire two language systems, including two different phonological systems. That dual language exposure constitutes a form of enrichment that can enhance phonological processing and, in particular, PWM is attested by a number of studies, to be reviewed shortly, but these effects are conditional on proficiency and age of acquisition. With respect to proficiency, research that has examined the development of PWM in bilinguals, simultaneous and successive, suggests that bilinguals exhibit greater working memory in the language in which they are more proficient (see, for example, Parra et al., 2010, for a case of simultaneous bilinguals, and Gathercole, 1999, for a case of successive second language learners). That proficiency is important also comes from research demonstrating that successive bilinguals perform significantly better on PWM tasks than monolinguals once they have had several years exposure to the L2 and, thus arguably, some minimal level of proficiency in that language (Blom et al. 2014; Delcenserie & Genesee, 2016; Kaushaskaya et al., 2014). In a related vein, simultaneous bilinguals who are matched on proficiency with native speakers have been found to actually outperform monolinguals on tasks of PWM (e.g., Delcenserie & Genesee, 2016; Blom et al., 2014). Delcenserie and Genesee's finding that the advantages of bilingualism with respect to PWM are most evident in simultaneous bilinguals in comparison to second language learners whose exposure to the L2 begins after the sensitive period for phonological development attests to the importance of early experience, once again.

While there is no clear explanation for the bilingual advantage with respect to PWM, one possibility that has gained some empirical support, although it is strongly contested by others (e.g., Morton, 2014), is that working memory is advantaged in bilinguals owing to the positive effects of bilingualism on executive functions. More specifically, there is growing evidence that complex mental activities that "promote mental stimulation" have positive cognitive outcomes (Kramer & Mota, 2015, p. 311). It has been argued that bilingualism entails complex cognitive processes that can enhance executive functions and, of particular relevance to the present discussion, working memory, a component of executive functions, through the effects of cognitive control. It has been argued further that the acquisition and management of two languages during communication may enhances bilinguals' working memory abilities because they need to pay careful attention to and process information about context, the interlocutor, and the discourse in memory in order to use their languages appropriately and effectively, all tasks that implicate executive functioning. That cognitive processes related to attention and the control of information might play a role in accounting for working memory advantages in bilinguals is compatible with the findings we discussed earlier that such additional cognitive processes might be activated to compensate for delays in language exposure in IA children or for impoverished linguistic input in deaf children of hearing parents and cases of repeated bouts of otitis media.

Up to this point, we have focused on the role of early experience on phonological development and PWM. The acquisition and processing of complex language might also be influenced by early language experience owing to the foundational nature of native-language phonology and its cascading effects on more complex language skills that are built on phonological representations. In this regard, there is evidence that once sound categories for the native language have been formed, infants can use these categories to help with word learning and segmentation (Jusczyk & Aslin, 1995; Stager & Werker, 1997; Swingley & Aslin, 2002; Werker, Fennell, Corcoran, & Stager, 2002). Similarly, more accurate native language speech sound discrimination in infancy (from newborn to 20 months) has been positively associated not only with early vocabulary skills at 24 months of age (Tsao, Liu, & Kuhl, 2004) but also with word knowledge at 3 years of age (Molfese & Molfese, 1985), verbal fluency, language comprehension and production abilities at 4 years of age (Bernhardt et al., 2007), and reading abilities at 5 years of age (Kuhl, 2010). Thus, there is considerable evidence that the nature of the input received during the earliest stages of language acquisition, and arguably during an early sensitive period for phonological development, may establish a long-lasting foundation for phonological processing that has cascading effects on the acquisition of higher order language skills.

Before concluding, it is important to note that children in all of the groups whom we have discussed, even those who experience delayed and/or impoverished early language input, can develop high levels of language proficiency. In fact, in some cases they even may perform at the same level as children who were exposed to language continuously from birth when tested using general measures of language, such as vocabulary and grammar (e.g., Delcenserie, 2016). It is difficult to establish the exact extent to which this is true at present owing to a lack of sufficient and appropriate evidence -- differences often emerge only when fine grained analysis of vocabulary and grammar are examined and, at present, this kind of testing is not common (e.g., Abrahamsson & Hyltenstam, 2009; Chilosi et al., 2013; Delcenserie & Genesee, 2014b; Delcenserie & Genesee 2014c).

Nevertheless, we would argue that achievement of high levels of language proficiency, although perhaps not “like that of monolingual native speakers”, is compatible with the view that early phonological/PWM development is uniquely and differentially affected by early language exposure because proficiency can be achieved in other ways. First, and as discussed earlier, individuals may be able to recruit additional or alternative neural processes in order to support the acquisition and processing of phonological elements that were not acquired during early language acquisition (e.g., Pierce et al., 2015). Second, it may be possible to re-open phonological sensitive periods at a later-than-usual point in development. In partial support of this possibility, there is some evidence that sensitive periods can been reinstated in the auditory (Engineer, Riley, Seale, & Vrana, 2011) and visual cortices (Maya Vetencourt, Sale, Viegi, Baroncelli, De Pasquale, O’Leary, et al., 2008; Maya Vetencourt, Tiraboschi, Spolidoro, Castrén, & Maffei, 2011; Silingardi Scali, Belluomini, & Pizzorusso, 2010) of adult rats. With respect to humans and language acquisition, Werker and Hensch (2015) have suggested that specific training paradigms might lead to the re-opening of a sensitive period, possibly due to the deployment of focused attention (Kaliman, Alvarez-Lopez, Cosin-Tomas, Rosenkranz, Lutz, & Davison, 2014; Slagter, Davidson, & Lutz, 2011). This in turn, they speculate, might activate biological changes and allow for the creation of neural circuits that subserve phonological acquisition to once again become plastic. Extant evidence suggests that if, in fact, a sensitive period can be re-opened as a result of exposure to critical acoustic input (e.g., deaf children with CI) or enriched input (late L2 learners), there may be limits on the level of proficiency that can be attained subsequently.

In a related vein, early language experience itself (or lack thereof) may play a role in determining the onset, duration, and offset of the sensitive period for phonological acquisition. For example, IA and CI children might experience extension of the sensitive period for phonological development as a result of delayed exposure to a new or first language, respectively. In the case of IA children – because they are exposed to language from birth, the onset of the sensitive period for phonological development should be opened as expected. If onset of the adoption language does not occur early enough, the period might also close as expected since, as far as their language systems are concerned, they are following a typical trajectory for a monolingual language learner. However, if IA children get input in the adoption language before the period closes, the added linguistic variability or the change in repertoire of input sounds entailed by the adoption language might keep the window open longer, as has been argued to occur in bilingual language learners (e.g., Petitto, Berens, Kovelman, Dubins, Jasinka, & Shalinksy, 2012; Werker, Byers-Heinlein, & Fennell, 2009). Indeed, as reported earlier, there is a significant negative correlation between age of exposure to the adoption language and PWM capacity and language outcomes, at least during the first several years following adoption (Scott et al., 2008). Thus, an extended sensitive period for phonological development might explain later high levels of language proficiency in some cases.

Critically, differences in sensitive period timing might lead to different PWM outcomes at different points in development. For example, if the sensitive period for phonological development is extended, but PWM is measured early in development (shortly after IA children switch to the adoption language) it may be the case that observed lags are due to phonological acquisition starting at a later point in development, and/or that IA children are still in the process of acquiring phonological representations for their new language. In this case, however, phonological acquisition would utilize learning mechanisms that are typically active during the sensitive period, and thus initial lags may resolve at some later point in development. In contrast, if adoption language acquisition truly begins outside of a sensitive period for phonological development, then those IA children might rely on alternative mechanisms to support phonological development and PWM processing. In that case, lags in PWM processing may be observed indefinitely, except in cases where the compensatory mechanisms or adaptations are able to mask underlying differences in phonological processing.

The case for children with CIs is quite different. Since input is required to begin the cascade of processes involved in opening and holding a sensitive period open (e.g., Cyander & Mitchell, 1980; Fagiolini, Pizzorusso, Berardi, Domenici, & Maffei, 1994; Mower, 1991; Philpot, Sekhar, Shouval, & Bear, 2001, for examples from the visual system), the very reduced phonological input experienced by deaf children with CIs might delay the opening of the sensitive period and then ultimately hold it open later in development than expected, up to a point, following implantation (e.g., Kral & Sharma, 2012; for a review see Werker & Hensch, 2015). Thus, CI children may be able to acquire phonological representations once their cochlear implant is functioning via similar means as native language learners, if they receive input early enough. However, even the newest cochlear implant technology cannot reproduce the quality of input experienced by children with normal hearing. Moreover, given their later stage of general maturation at the time of CI, it is possible that other factors might influence phonological acquisition that occurs later than expected. At present, we lack sufficient evidence to explicate these possibilities further but they remain theoretically viable and interesting.

Conclusions

During the earliest stages of language acquisition, children’s brains grow and change at a remarkable pace. Early optimal periods of heightened neuroplasticity allow for periods of rapid learning, during which the foundation for sensory and perceptual systems are formed (e.g., Kuhl, 2010; Maurer & Werker, 2014; Werker & Hensch, 2015). In this paper, we have argued that variation in the timing, quality, and/or quantity of early language input can affect the development of PWM through their effects on the establishment of native-language phonological representations during this early period. Because PWM development is closely linked to language acquisition (e.g., Baddeley et al., 1998), early instantiated differences in phonological representations and PWM go on to influence language acquisition in the short and long term.

Understanding the neurocognitive processes involved during language acquisition can help to elucidate early age-related effects on language and may help to explain the wide variability in language attainment across individuals generally, beyond the groups we have discussed here. The evidence we reviewed suggests that even brief delays in exposure to a language, or early periods of impoverished language input, have a lasting impact on both behavior and the brain. Thus, even monolinguals with no clinical concerns, who experience less variation in early language input than other language learning groups, experience a critical input threshold below which phonological input is less than adequate or optimal for full development of phonological categories and, in turn, PWM. Although evidence for this is currently limited, factors that are influenced by experience, such as language familiarity (Coady & Aslin, 2004), vocabulary size (Gathercole et al., 1992) and time spent in school (Roberts et al., 2015), have been found to predict verbal memory abilities in monolingual children. Understanding subtle differences in early language environments will therefore help to further elucidate the role of experience on PWM and language development.

Critically, although evidence suggests that lags in PWM influence language outcomes, these lags do not appear to preclude the achievement of high levels of proficiency in either the L1or an L2. This achievement may be due to the use of adaptive or compensatory mechanisms that are developed with increasing language proficiency, to the extension or re-opening of sensitive periods for phonological acquisition, or to some other mechanism. However, the implication of this is that there is not only one but, in fact, multiple ways to become proficient in language. Thus, the notion of a “native speaker” that is typically defined with reference to monolingual language learners who hear a single language from birth needs to be rethought. Instead, understanding the individual context in which language is acquired and ultimately used, as well as how the brain is altered by and responds to environmental input at different points in development, will enable us to acquire a more nuanced and broadly applicable understanding of language learning. In turn, this approach may uncover the particular conditions or learning environment that could best facilitate individual learners’ language development at various points across the life span.

While the approach we have taken has highlighted a relationship between early experience and language outcomes, unresolved issues remain. For example, the precise nature of the phonological representations that develop to support PWM in each subgroup we considered remains unclear. As well, while evidence suggests that alternative cognitive strategies may be employed to support the acquisition and processing of language to very high levels of proficiency following delayed or impoverished input, the precise nature of those strategies, the mechanisms involved, and the contexts under which they are required and used have received little attention. It may be that, once they are established, compensatory mechanisms are recruited in all contexts by all individuals who make use of them. Alternatively, it may be that certain language environments, such as those that are more cognitively demanding, are more likely to elicit the use of alternative strategies than others.

Finally, while even the earliest language experiences appear to influence language outcomes, the limits of the influence of sensitive periods remain to be determined. Given that even prenatal language experiences can influence the developing brain (e.g., May, Byers-Heinlein, Gervain, & Werker; see Dehaene-Lambertz & Spelke, 2015 for a review), it is reasonable to ask if any delay, no matter how short, will impact PWM and language outcomes in some way; or are very short delays resistant to such influence?

Notwithstanding these unresolved issues, the present review provides tantalizing albeit preliminary evidence for a working memory system that is highly active during early stages of language development and that is highly dependent upon experience. Knowledge gained through this system is used reciprocally to support ongoing language development and processing. We hope we have also been able to show that experiences encountered by children from very early in development can provide insights into both how brain systems are established (e.g., through early plasticity and sensitive periods) and how early cognitive foundations can impact ongoing language development.

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