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Flexible, rapid and automatic neocortical word form acquisition mechanism in children as revealed by neuromagnetic brain response dynamics

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ABSTRACT

Children learn new words and word forms with ease, often acquiring a new word after very few repetitions. Recent neurophysiological research on word form acquisition in adults indicates that novel words can be acquired within minutes of repetitive exposure to them, regardless of the individual's focused attention on the speech input. Although it is well-known that children surpass adults in language acquisition, the developmental aspects of such rapid and automatic neural acquisition mechanisms remain unexplored. To address this open question, we used magnetoencephalography (MEG) to scrutinise brain dynamics elicited by spoken words and word-like sounds in healthy monolingual (Danish) children throughout a 20-min repetitive passive exposure session. We found rapid neural dynamics manifested as an enhancement of early (~100 ms) brain activity over the short exposure session, with distinct spatiotemporal patterns for different novel sounds. For novel Danish word forms, signs of such enhancement were seen in the left temporal regions only, suggesting reliance on pre-existing language circuits for acquisition of novel word forms with native phonology. In contrast, exposure both to novel word forms with non-native phonology and to novel non-speech sounds led to activity enhancement in both left and right hemispheres, suggesting that more wide-spread cortical networks contribute to the build-up of memory traces for non-native and non-speech sounds. Similar studies in adults have previously reported more sluggish (~15–25 min, as opposed to 4 min in the present study) or non-existent neural dynamics for non-native sound acquisition, which might be indicative of a higher degree of plasticity in the children's brain. Overall, the results indicate a rapid and highly plastic mechanism for a dynamic build-up of memory traces for novel acoustic information in the children's brain that operates automatically and recruits bilateral temporal cortical circuits.

Introduction

By early adulthood, humans have acquired vocabularies of between 15,000 and 20,000 words (D'Anna et al., 1991), enabling efficient and accurate linguistic communication. However, to obtain such an extensive vocabulary, word learning in childhood has to be extremely rapid. Indeed, behavioural studies indicate that children learn words with apparent ease and new word forms are added into active vocabulary after only a handful of repetitions (e.g. Dollaghan, 1985). Although estimates for the rate of lexical acquisition in childhood vary depending on various factors, for example, the meaning of the new words (e.g. Goldfield and Reznick, 1990), some studies suggest the learning rate to be as high as 10–20 words per week (e.g. Ganger and Brent, 2004).

How are new words learned? The mainstream views maintain that consolidation of new word form representations and their integration into the mental lexicon is a lengthy process, which is preceded by a initial encoding stage that appears to be a swift and largely automatised process (e.g. Kimppa et al., 2015), with consolidation requiring at least an overnight sleep period (Gaskell and Dumay, 2003; Davis and Gaskell 2009). This initial process of rapid acquisition of a novel word form seems to be highly important for language learning, as behavioural studies have indicated that good performance in such tasks predicts improved language proficiency in children (e.g. Gathercole, 2006).

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However, despite the fact that rapid acquisition of novel word forms has been studied behaviourally for decades (see, e.g., Carey and Bartlett, 1978), the neurobiological foundations of both children's and adults' rapid learning abilities are poorly understood. Consequently, a recent line of research has strived to illuminate the neurophysiology of online word form acquisition (for a review, see Shtyrov, 2012). Indeed, recent studies in adults have shown that formation of neural memory traces for novel spoken word forms with native phonology takes place after mere 15–30 min of passive exposure to them (e.g. Shtyrov et al., 2010; Yue et al., 2014; Kimppa et al., 2015). In these studies, lexical memory trace formation is reflected as an early (~50–150 ms after recognition point) amplitude increase in the brain's event-related responses (ERPs) as a result of exposure to novel word forms. In adults, this enhancement takes place regardless of the individual's focused attention on the speech input and appears to be specific to novel word forms with native phonology only (e.g. Kimppa et al., 2015; see also Weber-Fox and Neville, 1996). Furthermore, this enhanced neural responsiveness as a result of exposure to novel word forms has been clearly associated with behavioural learning outcomes and individual learning profiles (Kimppa et al., 2015, 2016), supporting the notion that such activity is a genuine neural correlate of the acquisition process. Given that the neural changes reflecting acquisition of novel word forms in adults are very rapid, and given that children acquire new words in an extremely short time span (Dollaghan, 1985; Carey and Bartlett, 1978), it seems plausible to assume that the neural correlates of novel word form acquisition in children may manifest as adult-like – or even more efficient – plastic changes in brain activity. However, to the best of our knowledge, this hypothesised speed of brain activity change in children has never been tested empirically.

Even though it is plausible to expect children to exhibit neural processes reflecting memory trace formation for novel word forms comparable to adults, there is ample evidence to suggest that children's brain is much more malleable than that of adults. Thus, while neural processes underlying rapid and automatic word form acquisition in adults have revealed no evidence for rapid acquisition of novel word forms with non-native phonology (Kimppa et al., 2015), children's innate ability to acquire a new language from scratch is superior to that of adults (for a review, see Birdsong, 2006), at least prior to puberty (Johnson and Newport, 1989). Therefore, one might expect that this superior ability of children to acquire a new language may also be reflected as rapid formation of new neural memory traces for items with non-native phonology as well.

Similarly to non-native word forms, the question of rapid memory trace build-up can be asked about non-speech sounds as well. Previous research indicated that acoustically matched complex sounds do not elicit the same fast plastic changes in adult neocortex as word forms in native speech (Shtyrov et al., 2011). However, children's ability to acquire new word forms may differ from that of adults and could possibly be at least partially based on a more general learning mechanism. Thus, an open question remains as to whether children's brain is capable of rapidly forming novel representations for any acoustic events, or whether this phenomenon is restricted to language only.

On the neural sources of rapid acquisition of novel word forms reflected in the memory-trace related enhancement of neural activation, regions in the left perisylvian cortices, including left temporal and inferior frontal regions, seem to be most frequently activated when examining adults. However, it is unclear whether children exhibit activation in the similar brain regions when processing speech. While a recent meta-analysis comprising of fMRI studies on language processing in children between 0–18 years of age reported that adults and children utilise similar cortical regions, differences in activation patterns between, for example, low-level sensory regions and higher-level control regions, may change with age (Weiss-Croft and Baldeweg, 2015). These age-related differences between both children of different ages and between children and adults are consistent with the Skill Learning Hypothesis (Johnson, 2001) postulating that the activity in fronto-parietal regions, responsible for, e.g., top-down processing and forming a part of the attention network (Posner and Rothbart, 2007; Ptak, 2012), diminishes with increasing age. In contrast, an opposite effect of activity increase is seen in temporal sensory regions, associated with the increased automatisation of speech processing and categorisation. Thus, the present evidence from fMRI studies on language processing in childhood suggests that, at least for neural processes involving native language processing, similar cortical regions should be activated in children and adults. However, when a child's brain is acquiring novel items that include sounds that do not exist in her native language, the developing brain might still need to recruit different cortical regions in the acquisition process. For instance, it may involve higher-order fronto-parietal regions, reflecting the degree of resource-intense top-down processing required to process the incoming speech signal (Brauer and Friederici, 2007) in order to enable formation of a new memory trace in the brain's mental lexicon. Thus, a question arises on which neural network children's ability to acquire word forms with non-native phonology may rely.

Adult studies on processing of non-native versus native speech have shown similar brain regions being activated, i.e. mainly perisylvian regions (Wilson and Iacoboni, 2006; Golestani and Zatorre, 2004). Some studies suggest, however, that the areas utilised for speech processing may depend on the cues that are required to identify the speech sounds (Zhao et al., 2008), suggesting different activation patterns for native and non-native speech. Furthermore, studies investigating learning or acquisition of novel word forms have shown that even right-hemispheric perisylvian structures are involved in the acquisition of novel items (Paulesu et al., 2009), which may reflect either genuine lexicalisation or lexical retrieval of specific items (Damasio et al., 1996), or additional attentional or working memory processes required during stimulus processing (Vigneau et al., 2011). Thus, partially different neural structures might be utilised during acquisition of novel words with native versus non-native phonology, possibly due to the different acoustic cues required to process these words and different degrees of top-down processing of non-native sounds. However, in the absence of experimental evidence, only tentative hypotheses can be made.

Given the lack of research on the neural processes underlying novel word form acquisition in children, we designed the current experiment to fill these gaps. To assess the automatic word form acquisition, we presented 5–12 year old children with real words, novel word forms incorporating either native or non-native phonology, and equally complex non-speech control sounds. Non-speech sounds mimic the complex acoustic properties of a speech signal but cannot be interpreted as human speech. To accurately capture the dynamics associated with online exposure to novel word forms, we used magnetoencephaphology (MEG), a neuroimaging method optimally combining spatial and temporal resolution, allowing us to specify the neural memory trace formation process in both space and time. In our analyses, we scrutinised the brain dynamics elicited by these sounds throughout the 20-min passive exposure session. Cortical generators of neural activity underlying surface MEG dynamics were analysed using distributed source reconstruction techniques (weighted minimum-norm current estimates). In accordance with the results previously obtained with adults, we expected to find changes in neural dynamics, reflecting putative formation of neural memory traces for novel word forms, in left perisylvian regions. Regarding exposure to new items with non-native phonology, we expected that partially different neural networks would be recruited during acquisition of these items, possibly reflecting the increased need for top-down processing of such items and involving other sources, including those in the right hemisphere.

Material and methods

Participants

Twenty three monolingual native Danish-speaking children suc-