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Predictors of spoken language learning

Patrick C.M. Wong [a,b,c,*], Marc Ettlinger [a]

[a] Roxelyn and Richard Pepper Department of Communication Sciences & Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208, USA
[b] Department of Otolaryngology - Head and Neck Surgery, Feinberg School of Medicine, Northwestern University, 676N St Clair, Suite 1325, Chicago, IL 60611, USA
[c] Hugh Knowles Center for Clinical and Basic Science in Hearing and Its Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208, USA

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ABSTRACT

We report two sets of experiments showing that the large individual variability in language learning success in adults can be attributed to neurophysiological, neuroanatomical, cognitive, and perceptual factors. In the first set of experiments, native English-speaking adults learned to incorporate lexically meaningfully pitch patterns in words. We found those who were successful to have higher activation in bilateral auditory cortex, larger volume in Heschl's Gyrus, and more accurate pitch pattern perception. All of these measures were performed before training began. In the second set of experiments, native English-speaking adults learned a phonological grammatical system governing the formation of words of an artificial language. Again, neurophysiological, neuroanatomical, and cognitive factors predicted to an extent how well these adults learned. Taken together, these experiments suggest that neural and behavioral factors can be used to predict spoken language learning. These predictors can inform the redesign of existing training paradigms to maximize learning for learners with different learning profiles.

Learning outcomes: Readers will be able to: (a) understand the linguistic concepts of lexical tone and phonological grammar, (b) identify the brain regions associated with learning lexical tone and phonological grammar, and (c) identify the cognitive predictors for successful learning of a tone language and phonological rules.

1. Introduction

A particularly challenging aspect of clinical and learning sciences is the large individual differences observed in treatment and training responses. While gold standards of treatment or learning have been reported for different communication disorders or types of learning, these reports focused on group results without detailing the fact that only some patients or learners were responsive. For example, adult spoken language learning—the type of learning that our research focuses on—shows large variability of learning success using high variability training, which has been reported to result in the best learning outcome overall (Bradlow, Akahane-Yamada, Pisoni, & Tohkura, 1999; Lively, Logan, & Pisoni 1993). However, the fact that not all participants learn successfully in these studies means that learners might benefit from redesigned training or treatment that accommodates learners of potentially different learning profiles. This requires first identifying factors that can best predict individual differences in learning/treatment ahead of time. Here we report two sets of experiments conducted in our laboratory that examined predictors of learning success in two types of spoken language learning. In the first set of experiments, native English-speaking adults learned to incorporate a foreign phonetic contrast in lexically

* Corresponding author at: Roxelyn and Richard Pepper Department of Communication Sciences & Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208, USA. Tel.: +1 847 491 2416; fax: +1 847 491 2429.
E-mail address: pwong@northwestern.edu (Patrick C.M. Wong).

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meaningful contexts and behavioral and neural measures were obtained before training in order to understand what factors distinguish successful from less successful learners. In the second set of experiments, we focused on simple and complex phonological grammar learning and identified cognitive and neural factors that were predictive of learning success.

2. Foreign phonetic learning

Extensive research in speech learning has found the learning of many foreign phonemes to be difficult for adults. For example, native Japanese-speaking adults have difficulty learning the English/r/and/l/(Bradlow, 2008; Callan, Jones, Callan, & Akahane-Yamada, 2004; MacKain, Best, & Strange, 1981). Studies in speech learning often focus on how to train adults by altering the training program without a careful consideration of why some adults are more successful than others. Our research specifically focuses on finding factors that could explain, to an extent, variance in learning success. In our research on foreign phonetic learning, we focused on the learning of lexical tones, which are pitch patterns that are used to mark word meaning. For example, in Mandarin Chinese, a tone language, the syllable/ma/can have four different lexical meanings depending on the pitch of the syllable. A large number of world's languages use pitch to contrast word meaning (Yip, 2002), although English is not one of these languages. Lexical tone learning is especially useful for understanding neural differences in speech learning because hypotheses could be developed based on the large body of scientific work on pitch processing. For example, it has been found that the anterolateral portion of Heschl's Gyrus contains a "pitch center" in primates (Bendor & Wang, 2005) and the rostral auditory brainstem faithfully tracks pitch pattern (Greenberg, Marsh, Brown, & Smith, 1987; Krishnan, Xu, Gandour, & Cariani, 2005).

In the first of a series of lexical tone training studies, native English-speaking adults learned to incorporate pitch in lexically meaningful contexts (Wong & Perrachione, 2007). For example, they learned that the syllable [pɛʃ] spoken with a high-level and rising pitch pattern means 'glass' and 'pencil,' respectively. As predicted, we found a range of learning success in these adults. We classified them into two groups based on whether they achieved a 95% accuracy learning criterion. We found that the successful learners showed better performance in a pitch pattern perception task in which they identified the pitch patterns embedded in vowels spoken by multiple talkers.

Our learners also participated in a functional MRI experiment in which they discriminated the pitch patterns of words they learned before and after training (Wong, Perrachione, & Parrish, 2007). When all learners were examined regardless of learning success, increased activation was observed in the left hemisphere including the auditory cortex and prefrontal cortex including Broca's area, similar to what we observed when native tone language speakers perceived lexical tones (Wong, Parson, Martinez, & Diehl, 2004). Most interestingly, successful and less successful learners showed differences both before and after training. After training, successful learners showed a more streamlined brain network that included stronger activation in the left posterior auditory cortex, whereas less successful learners activated a more diffused network including the prefrontal cortex. Most importantly, differences were also observed before training such that successful learners activated bilateral auditory cortex more strongly. Not only did we find neurophysiological (cerebral hemodynamic) differences, but also neuroanatomical differences. As discussed earlier, the Heschl's Gyrus in primates contains a pitch center (Bendor & Wang, 2005). We manually measured the volume of the Heschl's Gyrus of our learners and found that successful learners had larger volume in both grey and white matter only on the left (Wong, Warrier, Penhune, Roy, Sadehh, & Parrish, 2008). When we considered our three predictors, including pitch pattern perception, bilateral auditory cortex activation, and volume of left Heschl's Gyrus, all measured before training, we found about 61% of the variance in learning explained.

We also considered other factors that could be predictive of learning. For example, we found that more successful learners had musical training (Wong, 2007), perhaps partially due to the fact that musicians showed more faithful pitch tracking as early as the auditory brainstem (Wong, Skoe, Russo, Dees, & Kraus, 2007). We also found that successful learners attended to pitch directional cues more so than less successful learners (Chandrasekaran, Sampath, & Wong, 2010). In our ongoing research, we are examining whether neuroanatomical connectivity, resting-state activation, as well as large-scale functional brain connectivity (Sheppard, Wang, & Wong, 2009) could also be predictive.

3. Phonological grammar learning

Successful spoken language communication not only involves using phonemes in isolation, but also involves learning the rules governing their combination to form words (phonological grammar). For example, in English, the realization of the plural suffix, *-s*, is governed by a phonological grammar such that it is realized as [s] after voiceless consonants (e.g., *cats*) and [z] after voiced segments (e.g., *dogs*) to avoid combining voiced and voiceless consonants, and as [əz] to avoid consecutive alveolar fricatives (e.g., *dishes*). These rules and constraints are specific to each language and there is variability across types of patterns and across individuals in terms of when they are learned in first and second language acquisition (Berko, 1958; Brown, 1973). As with sound learning, we have sought to partially explain this individual variation in learning success by appealing to cognitive, neurological and genetic factors.

Our phonological grammar training studies involve teaching participants an artificial language based on a natural language (Shimakonde, a Bantu language spoken in Mozambique) (Liphola, 2001). The language consisted of two types of words: simple words requiring only affixation to form new words (e.g., *cat* → *cats*) and complex words which also require an additional set of phonological rules to form new words (e.g., *dish* → *dishes*). The phonological rules we used (vowel harmony and vowel reduction) target the vowels of the words and are not present in English, but are relatively common in other languages all around the world (Van der Hulst & van de Weijer, 1995). Therefore, participants learned the artificial language as naïve second language learners. Training involved exposure to word-picture pairings, which exposed participants to both words of the language and the phonological grammar. Assessment of grammatical learning success involves testing participants on their ability to extrapolate the grammatical patterns to new, untrained words in a *wug* test (Berko, 1958).

In one study, we correlated learning success with standardized measures of domain-general memory capacity (Ettlinger, Bradlow, & Wong, 2009). We found that success in the acquisition of the simple grammatical pattern correlated with procedural memory (memory for sequences), while success on the acquisition of the complex pattern correlated with declarative memory (memory for associations), controlling for general intelligence or working memory in both cases.

The neural substrates supporting these memory subsystems are relatively well understood, so these behavioral findings motivated conducting a neuroimaging study to explore the mechanisms underlying these correlations. The fMRI results corroborate the behavioral findings: When participants are acquiring simple patterns, the basal ganglia and Broca's area, which are associated with procedural memory (Knowlton, Mangels, & Squire, 1996), are active, while the hippocampus, which is associated with declarative memory (Eichenbaum & Cohen, 2001), is more active during the acquisition of complex patterns (Ettlinger et al., 2009). Subsequent analyses show that volumetric measures of relevant cortical areas show the same correlations, and that people who can learn the complex pattern show greater efferent connectivity from the hippocampus to Broca's area (Ettlinger, Novis, Wang, & Wong, 2010).

Because the frontostriatal pathway contains a high concentration of dopaminergic neurons, our ongoing research considers whether polymorphism of genes that are tied to the dopamine system could explain some of the variance in learning.

Combined, these results provide insight into the cognitive mechanisms underlying the acquisition of phonology, suggesting that even the most complex elements of grammar are explainable via domain-general capabilities. Furthermore, by looking at the acquisition of a language very different from English, we can go beyond understanding grammar as procedural rules processed in Broca's area as has been previously argued (Marslen-Wilson & Tyler, 1997; Paradis, 1994; Pinker, 1999; Pinker & Ullman, 2002; Tyler, Marslen-Wilson, & Stamatakis, 2005; Ullman, 2004), to a more complete understanding of phonological grammar as involving the hippocampus as well.

4. Conclusion

Although spoken language learning in adulthood shows large individual variability in success, we found in both speech sound and phonological grammar learning that success can be predicted by neural, perceptual, and cognitive factors to an extent. With these predictors, we are designing experiments to examine altering training paradigms that might enhance the learning of different learners. For example, for lexical tone learning, we have found that certain types of high-variability training could be detrimental to the learning of learners who showed poor pitch pattern perception (Lee, Perrachione, Dees, & Wong, 2007). For phonological grammar learning, we are examining how presentation order for stimuli of different complexity could result in better learning for learners with poor procedural and/or declarative memory. Because of our focus in individual differences and differences in learning success, we hope our results could also be applied to treatment of communication disorders where large individual differences in recovery are often observed.

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Appendix A. Continuing education

1. In primates, where is the "pitch center" located?
   a. Broca's area
   b. Wernicke's area
   c. Heschl's Gyrus
   d. Prefrontal cortex
2. Which one of the following statements about lexical tone learning is true?
   a. All adult learners can learn very successfully
   b. Adult learners who do not speak a tone language as their native language cannot learn
   c. Some adults can learn very successfully, some not so successfully
   d. Only children can learn
3. Which one of the following factor(s) have been found to correlate with lexical tone learning?
   a. Larger right Heschl's Gyrus
   b. Higher activation in auditory cortex
   c. Better pitch pattern perception
   d. b and c

4. "Grammar" can refer to which of the following?
   a. Syntax
   b. Phonology
   c. A list of phonemes usable in a language
   d. a and b
5. Which of the following memory subsystems account for a significant amount of variance in acquiring phonology in the cited studies?
   a. Procedural memory and working memory
   b. Procedural memory and declarative memory
   c. Declarative memory and working memory
   d. None of the above

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