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The time course of auditory perceptual learning: neurophysiological changes during speech-sound training

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HERE we report that training-associated changes in neural activity can precede behavioral learning. This finding suggests that speech-sound learning occurs at a pre-attentive level which can be measured neurophysiologically (in the absence of a behavioral response) to assess the efficacy of training. Children with biologically based perceptual learning deficits as well as people who wear cochlear implants or hearing aids undergo various forms of auditory training. The effectiveness of auditory training can be difficult to assess using behavioral methods because these populations are communicatively impaired and may have attention and/or cognitive deficits. Based on our findings, if neurophysiological changes are seen during auditory training, then the training method is effectively altering the neural representation of the speech/sounds and changes in behavior are likely to follow *NeuroReport* 9: 3557–3560 © 1998 Lippincott Williams & Wilkins.

Key words: Cortical plasticity; Electrophysiology; Mismatch negativity

Introduction

Listening training can change the neurophysiological responses of the human central auditory system. We and others have measured behavioral and neurophysiologic responses pre- and post-training and found that the magnitude of neurophysiological responses increases as perception improves.[1–3] However, the relative time course of the neurophysiological changes and behavioral learning is unknown. Some visual training studies propose that changes in neurophysiology may precede changes in behavior.[4,5] That is, if a time lag exists between neural changes and improved behavioral performance, there may be a period of consolidation when neural networks are thought to assemble to form meaningful codes which are later retrieved and manifested as behavior.[6] However, no neurophysiological data exist to support this theory.

Pre-perceptual learning in people has been a challenge to evaluate because non-invasive recording techniques are required in order to monitor changes in neurophysiology. By using event-related cortical potentials, which provide a means for measuring learning-related neural changes objectively, we examined the time course of learning neurophysiologically and behaviorally. Our hypothesis was that training-associated neurophysiological changes would precede behavioral learning.

Subjects and Methods

Procedure: Subjects were six male and four female normal-hearing, right-handed monolingual speakers of English (age range 21–31 years). Over a period of 10 days we trained the subjects to identify two novel speech contrasts. Identification training occurred on days 3, 5, 7, and 9. Neural activity and behavioral identification ability were measured on the days following training, that is, on days 4, 6, 8, and 10. Days 1 and 2 provided test re-test measures to establish the day-to-day variability of identification and neurophysiological measures.

Subjects were trained to differentiate between two stimuli differing in voice onset time (VOT). Although both stimuli sounded like /ba/ prior to training, subjects learned to identify the −20 ms VOT stimuli as /mba/ and the −10 ms VOT stimuli as /ba/. The event-related cortical response used to evaluate neurophysiological change was the mismatch negativity (MMN). The MMN is a passively elicited (not requiring subject participation) physiological response to an acoustically different (deviant) stimu-

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lus when presented in a series of homogeneous standard stimuli.[7] The MMN reflects the neurophysiological processes that underlie auditory discrimination.[8] In this experiment, the –10 ms VOT stimulus was the standard stimulus and the –20 ms VOT stimulus was the deviant stimulus. In order to determine when a significant change in neurophysiology and behavior occurred for each individual, 90% confidence intervals were established by estimating pre-training variability by subtracting day 1 (pre-test 1) from day 2 (pre-test 2). Any subsequent day-to-day changes had to exceed the 90% confidence intervals in order to be considered significant.

Stimuli: The stimuli were synthesized speech tokens from an eleven item /ba/-/pa/VOT continuum in which VOT varied from –50 ms to +50 ms in 10 ms steps. The stimuli were generated using a Klatt digital speech synthesizer.[9] The steady-state portion of the stimuli consisted of the vowel /a/, which varied in duration relative to the VOT so that the overall duration for each stimulus remained constant at 180 ms. Format and bandwidth values have been described previously.[3]

Electrophysiology testing (days 1, 2, 4, 6, 8 and 10): Electrophysiological methods have been reported previously.[3] The MMN was defined according to duration, area and onset latency of the response.

Behavioral testing: Identification testing was performed on days 1, 2, 4, 6, 8 and 10. During the behavioral tests, the subjects were seated in a sound-treated booth in front of a computer monitor with a 15-inch screen. On day 1, to gain familiarity with the identification task, each subject listened to the –50 ms and +50 ms continuum and identified the sound they heard from three choices /mba/ /ba/ or /pa/. No feedback was provided. Once the subject demonstrated that he/she understood the task, during the remainder of the experiment, each subject was presented with either the –20 or –10 ms VOT stimuli and asked to identify the speech token as either /mba/ or /ba/. Fifty trials without feedback were given. The response was scored correct if the subject assigned a /mba/ to the –20 ms VOT stimulus and /ba/ to the –10 ms VOT stimulus. These results served as identification measures.

Identification training was performed on days 3, 5, 7 and 9. On day 3, subjects participated in a fading task that was designed to emphasize the temporal cue (VOT) to be trained.[3] Following the fading session, each subject participated in identification training. Identification training sessions consisted of four blocks of 50 trials in which either a –10 ms or –20 ms VOT stimulus was presented. Positive feedback (green reinforcement light) was given when the –20 ms VOT stimuli was labeled as /mba/ and the –10 ms VOT labeled as /ba/. Each stimulus was presented randomly with an equal probability of occurrence.

Results

Group and individual results show that subjects learned to identify the –20 ms VOT stimuli as /mba/ and the –10 ms VOT stimuli as /ba/ (t = 4.53, df = 9, $p < 0.001$; Fig. 1). Moreover, as subjects learned to differentiate between the two stimuli, the duration (t = 5.03, df = 9, $p < 0.001$) and area (t = 4.03, df = 9, $p < 0.001$) of the MMN increased as onset latency decreased (t = 1.96, df = 9, $p = 0.05$; Figs 1,2). Indivi-

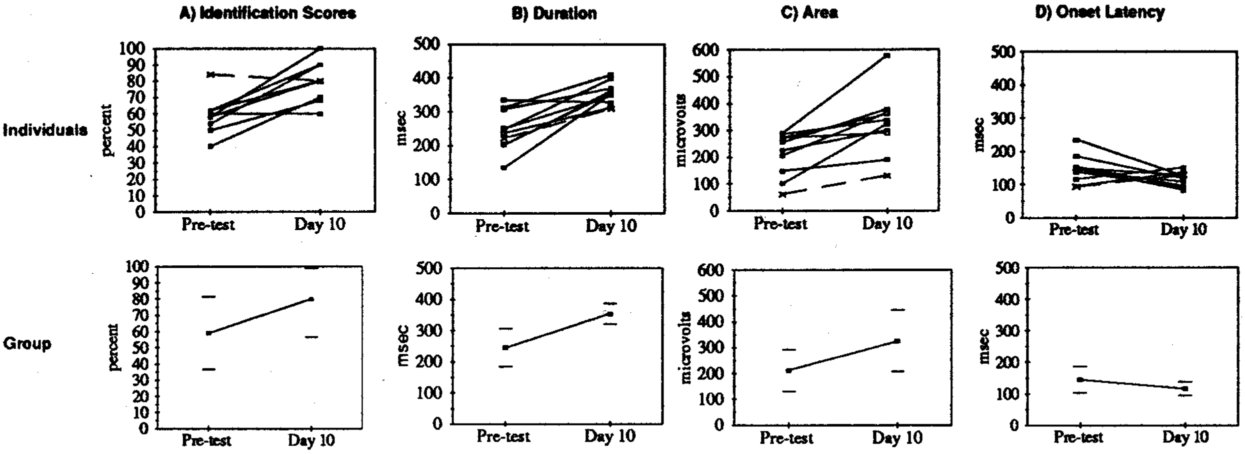

FIG. 1. Training-induced changes. There was significant improvement in the identification scores following training from pre-test (day 2) to post-test (day 10) (t = 4.53, df = 9, $p < 0.001$). There was a significant change in MMN duration (t = 5.03, df = 9, $p < 0.001$), area (t = 4.03, df = 9, $p < 0.001$) and onset latency (t = 1.96, df = 9, $p = 0.05$). 1 s.d. is shown above and below each grand mean. Note: subject 3 shown as x– – –x appears as a non-learner; however identification scores improved across training days with performance reaching 100% (exceeding the confidence interval) on day 8.

dual subject results are summarized in Fig. 3. Nine of the 10 subjects learned to identify the novel stimuli. All 10 subjects showed significant changes in the MMN. Whereas, individuals showed variable time courses for behavioral learning, all subjects showed significant changes in at least one of the neurophysiological measures (MMN duration, area and onset latency) by day 4. Therefore, the time course of significant behavioral and neurophysiological learning was not the same. Significant changes in identification ability were measured either on the same day, or days following, the day of change in the MMN. In no case did changes in behavior precede changes in neurophysiology. Specifically, four of the 10 subjects (3, 5, 6, 9) showed significant changes in neurophysiology prior to changes in identification ability. Five of the 10 subjects (4, 7, 8, 10, 11) showed significant changes in both neurophysiology and identification ability on day 4. Subject 2 never demonstrated a significant change in identification performance and therefore was labeled a non-learner.

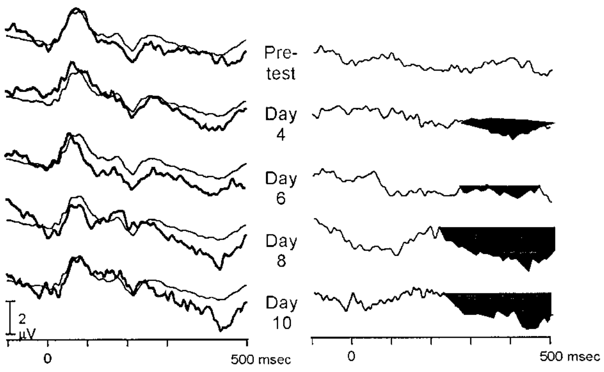

FIG. 2. Group grand average MMN responses shown for each test day. The thin lines on the left are the responses to the –20 ms VOT stimuli when presented alone. The thick lines are the responses to the –20 ms VOT stimulus presented as the deviant stimulus in a homogeneous series of –10 ms VOT stimuli. The MMN responses are the shaded areas in the subtraction waves on the right.

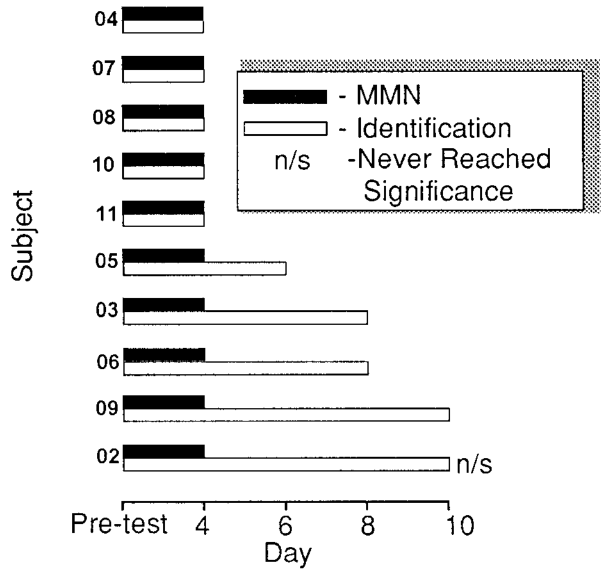

FIG. 3. First day of significant change. The first day of significant change in the MMN and identification scores are plotted for each individual. A significant change in the MMN was observed for each individual following the first training session (day 4). Subjects 3, 5, 6, and 9 show delays in time before significant improvements in identification were observed.

Discussion

Neurophysiological change occurred immediately following the first day of training. We speculate that this change may reflect fast learning theories put forth in earlier training studies.[6] According to this theory, fast learning could have taken place in the auditory system during training while the brain was selecting optimal sensory units to represent VOT as a unique population of cells firing in synchrony. Reinforcement in the form of feedback probably aided the encoding of the two contrasting VOT stimuli. Put another way, without conscious awareness, an ensemble of cells responding in the same manner to both stimuli may have begun to differentiate between the stimuli by establishing distinct synchrony patterns for the –20 ms and –10 ms VOT stimuli. Once these codes became efficient, the task became automatic. This process would have been pre-attentive because, during the initial stage of training, not all subjects were aware of the salient feature that distinguished the two stimuli. Based on the proposed generators of the MMN, this learning probably took place in, but was not limited to thalamo-cortical association areas of auditory cortex.[10–14]

Subsequent to the fast learning period, the synchronized events consolidate and carry biologically meaningful information. Therefore, neural processing switches from a storage mode to an information processing mode, from passive to active. If the neural information is sufficient to be recognized and integrated cognitively, behavioral demonstration of this knowledge can take place. This second stage may be representative of the slow component to learning that occurs off-line.[6] Therefore, it is possible that the sensory architecture provides the code, but the integration and cognitive retrieval system that recognizes this code as being meaningful and sufficient to execute a behavioral perceptual task requires attention and reflects slower learning. Hence the behavioral learning lags behind the pre-attentive neurophysiological change.

Of particular interest is the case of one nonlearner. Subject 2 did not demonstrate significant improvement in identification, yet showed significant change in the MMN. For this individual, training appeared to modify the neurophysiological response, but for some reason this information was not integrated into functional behavior. It is possible that this person required additional training for behavioral performance to improve. This possibility is reinforced by subjects 3, 6 and 9 who did not show significant changes in behavior until days 8 and 10, yet demonstrated changes in the neurophysiology on day 4.

Why do some individuals learn while others do not? Variables that could account for differences in rate of learning are probably governed by higher cognitive processes beyond the pre-attentive stage of the MMN. Improving our understanding of attentive information processing systems such as memory retrieval and integration may also help explain why some individuals learn faster than others.

In summary, these results suggest that auditory training alters the neural activity that provides the necessary coding for speech-sound learning, that changes in neural activity occur rapidly during training, and that these changes are later integrated into functional behavior. There may be slow behavioral learners, fast behavioral learners, and even some non-learners who are unable to retrieve and integrate neurophysiological codes into functional behavior. A neurophysiologic tool could help pinpoint the source of the learning difficulty. As more non-invasive techniques become available to assess learning-related changes in the human brain, our understanding of human physiologic plasticity will be enhanced. This study establishes that neurophysiological changes can be measured before behavior and that learning-related neural changes can be systematically assessed in humans using non-invasive techniques. Combining behavioral and neurophysiological measures provides a window to both processes.

Conclusion

Understanding the time course of neural and behavioral learning is useful for determining the efficacy of (re)habilitation among the communicatively impaired. For example, if changes in neurophysiology of a hearing/language impaired child occur following a series of auditory training sessions, this would imply that the brain's representation of sound is changing neurally and therefore the clinician should continue with the current (re)habilitation strategy. However, a change in neurophysiology without a change in behavior may suggest that the intervention method being used is successfully altering the brain's ability to code the sounds, but that behavioral changes may be lagging in time, or impaired due to other intervening issues such as cognition, motivation etc.

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