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Neural stability: A reflection of automaticity in reading

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ABSTRACT

Automaticity, the ability to perform a task rapidly with minimal effort, plays a key role in reading fluency and is indexed by rapid automatized naming (RAN) and processing speed. Yet little is known about automaticity's neurophysiologic underpinnings. The more efficiently sound is encoded, the more automatic sound processing can be. In turn, this automaticity could free up cognitive resources such as attention and working memory to help build an integrative reading network. Therefore, we hypothesized that automaticity and reading fluency correlate with stable neural representation of sounds, given a larger body of literature suggesting the close relationship between neural stability and the integrative function in the central auditory system. To test this hypothesis, we recorded the frequency-following responses (FFR) to speech syllables and administered cognitive and reading measures to school-aged children. We show that the stability of neural responses to speech correlates with RAN and processing speed, but not phonological awareness. Moreover, the link between neural stability and RAN mediates the previously-determined link between neural stability and reading ability. Children with a RAN deficit have especially unstable neural responses. Our neurophysiological approach illuminates a potential neural mechanism specific to RAN, which in turn indicates a relationship between synchronous neural firing in the auditory system and automaticity critical for reading fluency.

1. Introduction

Reading fluency requires the fast, effortless recognition of text and simultaneous retrieval and integration of phonological, orthographic, and semantic information. Automaticity, an ability to perform a task rapidly with minimal effort and attentional energy, promotes reading fluency by facilitating reading subskills and integrating these skills. Should any of these subskills be impaired, automaticity and integration in turn could be compromised. Rapid automatized naming (RAN), a task requiring naming common stimuli such as letters, digits, and colors as rapidly as possible, requires integrative reading processes such as phonological processing, visual-spatial processing, and working memory (Wolf et al., 2000). Thus, RAN is commonly used as an index of automaticity in the context of reading. Many studies show that it is one of the strongest predictors of successful reading across multiple languages (reviewed by Norton and Wolf, 2012). Together with RAN, processing speed is another index of automaticity that explores the speed of mental activity with non-linguistic stimuli such as timed visual matching and timed object semantic comparison of objects (Kail, 1991; Woodcock et al., 2001). Processing speed is regarded as a cardinal part of the cognitive system (Kail and Salthouse, 1994); therefore, this capacity helps support the automatization of learning that is crucial for successful reading. Although processing speed and RAN share characteristics of automaticity, researchers generally agree that reading is associated with the unique demands of processing speed for linguistic skills rather than general processing speed (Kail and Hall, 1994; Neuhaus et al., 2001). This highlights the uniqueness of RAN as a proxy of automaticity in reading; in studies of reading disabilities, RAN has been widely used to differentiate a specific reading profile: a RAN deficit.

Apart from RAN, phonological awareness (PA), defined as sensitivity to and ability to manipulate the sound structure of spoken language, is another powerful predictor of successful reading in many languages, including English (Ziegler and Goswami, 2005). There is an

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ongoing debate in reading research whether RAN and PA should be subsumed under one factor, phonological processing (Norton and Wolf, 2012; Wagner and Torgesen, 1987), or if they are independent. Because RAN performance and PA performance tend to correlate highly and relate to some of the same cognitive skills, using behavioral measures to disentangle these two abilities is difficult.

Neuroimaging studies support the idea that RAN relies on the automatic integration of multiple cognitive functions. For example, neuroanatomic systems associated with RAN performance overlap with those identified as the "reading network," including inferior frontal cortex, frontal cortex, left-hemisphere dorsal posterior regions, and the ventral visual pathway (Schwartz et al., 2012; Saur et al., 2008). Additionally, RAN performance correlates with activity in brain regions including occipital, temporal, parietal, and frontal cortices (He et al., 2013), and dyslexic children with RAN deficits displayed smaller right cerebellar anterior lobes compared to typical developing children (Eckert et al., 2003). While these studies point to the neuroanatomic systems that are associated with RAN, further investigation into neural mechanisms is required to better understand the process and role of RAN in reading. Recent evidence found that the left inferior frontal and inferior parietal regions were associated with impairment in phonological awareness, whereas the right cerebellar lobule VI was more specific to RAN deficits, suggesting a dissociation between PA and RAN (Norton et al., 2014). The present study aims to understand whether the dissociation can also be applied to trial-by-trial auditory processing that helps explain the relationship among RAN, PA, and reading fluency. Should we identify a common mechanism underlying RAN and PA it would support the view that they reflect a similar factor; in contrast, if we identify a neural mechanism that only pertains to one it would support the independence of RAN and PA.

Auditory-neurophysiological processing plays a crucial role in children's literacy acquisition; deficiencies in speech-sound processing can increase likelihood of reading difficulties (Carr et al., 2014; Liberman et al., 1974; Pugh et al., 2013). A healthy auditory system facilitates efficient encoding of speech sounds; in turn, it allows explicit knowledge of phonemes to integrate effectively with other cognitive skills that support reading. The frequency-following response (FFR) to speech sounds offers a unique window of the auditory system into reading skills (Banai et al., 2009, Chandrasekaran et al., 2009; Hornickel and Kraus, 2013; White-Schwoch et al., 2015). The FFR is thought to predominantly reflect activity in the auditory midbrain that faithfully captures the encoding of acoustic characteristics of speech sounds (Chandrasekaran and Kraus, 2010; White-Schwoch et al., 2016) with recent evidence also suggesting a contribution from auditory cortex (Coffey et al., 2016). Apart from capturing the acoustic characteristics of speech sounds, the FFR can also be examined in terms of its neural stability, capturing how consistently an individual's brain responds to speech sounds (Centanni et al., 2013, 2014; Hornickel and Kraus, 2013). Neural stability has often been associated with children's reading ability (Hornickel and Kraus, 2013; White-Schwoch et al., 2015), with poor readers showing more variable FFR. Also, neural stability is dependent on experience, implying a potential reciprocal relationship between neural stability and reading fluency. An intervention study (Hornickel et al., 2012) demonstrated that a classroom assistive-listening device intervention boosts both reading skills and neural stability. As a whole, these studies suggest that neural stability facilitates efficient speech-sound processing to support successful reading; skillful reading, in turn, could further reinforces neural stability. Recent evidence demonstrates that trial-by-trial timing jitter in the inferior colliculus is a potential source of neural stability in the FFR, potentially underlying perceptual difficulties in listening to speech sounds (White-Schwoch et al., 2016). Thus, the stability in neural encoding can help support effective auditory processing of speech that plays a pivotal role in reading. Indeed, animal studies have supported the hypothesis that speech processing in the central auditory system ties to neural stability of the FFR. For example, Centanni and colleagues (2014) found that a rat model of dyslexia exhibits unstable cortical processing of speech sounds. This suggests that impairment in speech-sound processing in poor readers could be due to the increasing neural firing variability in the auditory cortex (Centanni et al., 2013, 2014).

When sounds can be stably represented, they can be more efficiently encoded (Centanni et al., 2013, 2014). Efficient encoding of sounds could help facilitate automatic processing of sounds. In turn, this automaticity helps support reading fluency as it helps facilitate the allocation of cognitive skills important for reading by freeing up cognitive resources such as attention and working memory (LaBerge and Samuels, 1974; Berninger, 1999). Given the relationship between neural stability and the integrative function in the central auditory system, we hypothesized that automaticity and reading fluency correlate with stable representation of sounds. To test the hypothesis, we first examined automaticity-related tasks (RAN and processing speed) and reading fluency in relation to neural stability. If neural stability and automaticity relate to each other, then we expect that both RAN and processing speed positively relate to neural stability. Secondly, building upon previous research that has shown the link between neural stability and reading fluency, we employ mediation analyses to examine whether or not automaticity mediates this link. Although mediation analyses cannot draw a causal inference of the variables, this statistical approach can serve to examine a potential conceptual direction that connects neural stability and reading fluency. Lastly, given that a RAN deficit is prevalent in dyslexic children (Norton and Wolf, 2012; Wolf and Bowers, 1999), we examined whether children with poor RAN performance in our study exhibit with unstable representation of sounds, compared to children with good RAN performance. Given the presumed relationship between neural stability and automaticity, we expect that children with a RAN deficit will have unstable responses to sounds.

2. Materials and methods

2.1. Participants

Eighty-seven children (52 females, mean age = 10.8 years (range: 8.03–13.67), SD = 1.5, 20 diagnosed with reading impairment based on parental reports) were sampled from a project that examined auditory processing and children's reading abilities. The participants had to meet the following inclusion criteria: (1) normal hearing thresholds (< 20 dB nHL bilaterally for octaves between 125 and 8000 Hz; ANSI, 2009), (2) normal IQ (standard score of Vocabulary and Matrix reasoning ≥ 85 on WASI; Wechsler 1999), (3) no history of developmental disorders such as autism, ADHD, or other neurological disorders. All experiments were approved by the Northwestern University Institutional Review Board, and informed consent was obtained from parents and assent from children.

2.2. Behavioral measures

2.2.1. Automaticity and phonological awareness

To measure automaticity, we used both rapid automatized naming (RAN) and processing speed tasks. The RAN tasks included letter and color naming from the subtest of the Comprehensive Test of Phonological Processing (CTOPP, Wagner et al., 1999). A processing speed task was also used because it captures an automatic process needed in reading but minimizes processing of linguistic information. This skill is measured by using the Visual Matching subtest from the Woodcock-Johnson Test of Cognitive Abilities III (Woodcock et al., 2001), requiring participants to identify and circle two identical digits in each row within 3 min. In addition, phonological awareness was assessed with the Elision and Blending Words subtests of the CTOPP. Age-normed standardized scores were calculated for each subtest.

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