Neuropsychologia 103 (2017) 162–167

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Neural stability: A reflection of automaticity in reading

Silvia Siu-Yin Lam[a,b], Travis White-Schwoch[a,b], Steven G. Zecker[b], Jane Hornickel[a,b,1], Nina Kraus[a,b,c,d,e,*]

[a] Auditory Neuroscience Laboratory, Northwestern University, Evanston, IL, USA
[b] Department of Communication Sciences, Northwestern University, Evanston, IL, USA
[c] Institute for Neuroscience, Northwestern University, Evanston, IL, USA
[d] Department of Neurobiology and Physiology, Northwestern University, Evanston, IL, USA
[e] Department of Otolaryngology, Northwestern University, Evanston, IL, USA

ARTICLE INFO

Keywords:
Automaticity
Rapid automatized naming
Neural stability
Reading fluency

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

* Corresponding author at: Department of Communication Sciences, Northwestern University, 2240 Campus Drive, Evanston, IL 60208, USA.
E-mail address: nkraus@northwestern.edu (N. Kraus).
URL: http://www.brainvolts.northwestern.edu/ (N. Kraus).
[1] Jane Hornickel is now Data Visualization Analyst at Schoolzilla, Oakland, CA, USA.

http://dx.doi.org/10.1016/j.neuropsychologia.2017.07.023
Received 17 September 2016; Received in revised form 11 May 2017; Accepted 20 July 2017
Available online 21 July 2017
0028-3932/

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.

2.2.2. Reading fluency

Reading was assessed through word and non-word reading fluency using the Test of Word Reading Efficiency (TOWRE; Torgesen et al., 1999). These tasks require reading aloud a list of high-frequency words or non-words as accurately and quickly as possible within 45 s. A standardized composite score was calculated based on these two subtests.

2.2.3. Neurophysiological measures

The frequency-following responses were collected using a vertical montage (active Cz, forehead ground, ipsilateral earlobe reference) using Ag-AgCI electrodes with impedances < 5 kΩ. 6000 artifact-free responses (3000 for each polarity) were obtained for each sound. During the recording, children sat quietly watching a movie and heard the soundtrack in their unoccluded left ear presented at 40 dB SPL. Movie watching encouraged compliance during the passive recordings. Data were recorded through the Compumedics NeuroScan Stim 2 presentation software at a rate of 4.35 Hz, presenting two stimuli, 170 ms [ba] and [ga] syllables each with a 50-ms formant transition and a 120-ms steady-state vowel synthesized by a Klatt-based software (Klatt, 1980). Stimuli were presented at 80 dB SPL in alternating polarities monaurally to the right ear through insert earphones (ER-3, Etymotic Research). Responses were collected in Compumedics NeuroScan Acquire, digitized at 20,000 Hz, and off-line bandpass filtered from 70 to 2000 Hz (12 db/octave roll off). Responses were epoched into 230 ms windows (40 ms of pre-stimulus activity), and responses greater than ± 35 μV were rejected as artifact.

2.2.4. Analysis of neural stability

Stability of the FFR across trials was calculated by correlating two subaverage waveforms from the first 3000 and last 3000 events of the response recording, with r values closer to 1 indicating more morphologically coherent responses. The FFR neural stability calculations were made specifically for responses to the formant transition region (7–60 ms) as past research demonstrated that the formant transition from consonants to vowels is a crucial time window in examining children's reading ability (Hornickel et al., 2009). For statistical analyses, neural stability was collapsed across the two stimuli to form one metric. All data were Fisher transformed before statistical analyses (see Hornickel and Kraus, 2013 for additional details); however, values reported in Figs. 2 and 3 were converted back to correlation coefficient *r* for visual purposes. Prestimulus amplitude was also collected prior to the presentation of the stimulus sounds, which was thought to reflect resting neurophysiological noise (Hornickel and Kraus, 2013).

2.2.5. Statistical analyses

The central aim of this study was to examine neural mechanisms that associate with automaticity and reading fluency. First, correlation analysis was used for a preliminary test of the relations between neural stability and the behavioral measures (i.e. RAN, PA, processing speed, and reading fluency). The correlational results were also used as a reference for follow-up statistical analyses when appropriate. Secondly, we were interested in the extent to which automaticity mediates the relation between neural stability and reading fluency. In other words, does neural stability relate to RAN ability such that it, in turn, relates to reading fluency performance? To address this question, two sets of mediation analyses were conducted, using RAN and processing speed as a mediator, neural stability as a predictor, and reading fluency as the outcome. When evaluating a mediation model, three components are evaluated: the indirect effect, direct effect, and total effect. Here, the indirect effect represents the relation of neural stability to RAN, and, in turn, how it explains the relation of RAN to reading fluency. The direct effect represents the relation of neural stability to reading fluency adjusted for the influence of RAN. The total effect represents the relation of neural stability to reading fluency; technically, it is the combination of the indirect effect and the direct effect. If both RAN and processing speed are mediating variables, this suggests that the mediating effect transmitting the influence of neural stability on reading fluency is due to automaticity in general. In contrast, if only one of RAN or processing speed are mediating variables, this suggests a role for the non-linguistic or linguistic content of the test in mediating the relation between neural stability and reading fluency.

Lastly, we investigated whether or not poor RAN performance potentially associates with unstable representation of sounds through analysis of covariance (ANCOVA) which compared the neural stability of children with poor- vs. good- RAN. Children who scored 1 SD below or above the mean score of 100 (i.e. < 85 or > 115) were characterized as the "poor-RAN" group and the "good-RAN" group, respectively. To ensure that the poor-RAN group's performance reflected solely the contributions of RAN (rather than the influence of PA), only children who were within of the normal range on phonological awareness performance (i.e. score > 85) were included.

3. Results

Analyses highlighted the relationships between neural stability and reading-related behavioral measures. Children with more stable neural responses to speech had faster processing speed ($r = .308$, $p = .004$) and better rapid automatized naming (RAN) performance ($r = .318$, $p = .003$), but there was no link between neural stability and phonological awareness (PA) ($r = .122$, $p = .259$). Consistent with previous work, children with more stable responses were more fluent readers ($r = .321$, $p = .002$). We also found that all three reading-related cognitive measures including processing speed, RAN and PA positively related to reading fluency (processing speed: $r = .488$, $p < .001$; RAN: $r = .748$, $p = < .001$; PA: $r = .375$, $p < .001$). All correlations among these tasks are reported in Table 1.

The first mediation analysis revealed that neural stability positively relates to RAN, and in turn, RAN positively ties to reading fluency. In this mediation model, RAN was used as a mediator to examine if the link between neural stability and reading fluency could be explained by RAN. Because IQ performance was correlated with RAN as well as reading fluency, IQ was entered as a covariate in the model. Additionally, to isolate the effect of processing speed in this model because it was highly correlated with RAN, $r = .458$, $p < .001$, processing speed, along with IQ, was entered as a covariate. The results

Table 1
Correlations among the behavioral measures and neural stability.

	Phonological awareness	Rapid automatized naming	Processing speed	Reading fluency	Neural stability
Phonological awareness	1.00				
Rapid automatized naming	.327**	1.00			
Processing speed	.270*	.458***	1.00		
Reading fluency	.375***	.748***	.488***	1.00	
Neural stability	.122	.318**	.308**	.321**	1.00

* $p < .05$.
** $p < .005$.
*** $p < .001$.

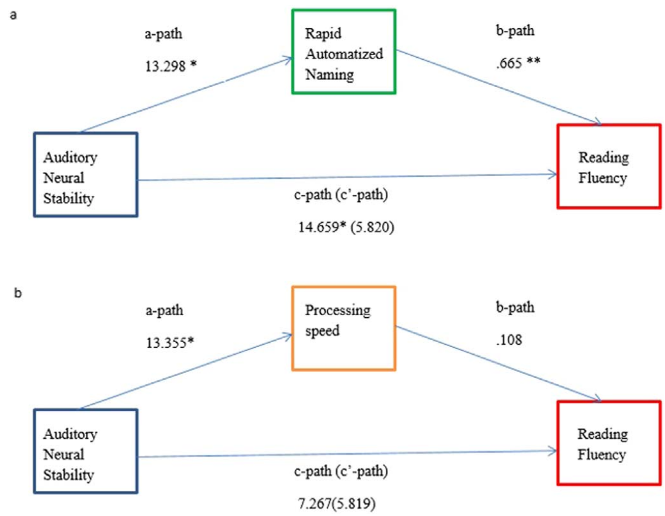

Fig. 1. a demonstrates that rapid automatized naming (RAN) significantly mediates the effect of neural stability in reading fluency. Neural stability predicts RAN ability and RAN ability predicts reading fluency, represented in the a-path and b-path respectively. Neural stability predicts reading fluency, represented in c-path as the total effect. The indirect effect (a*b path) is significant, confirming that the influence of neural stability on RAN, which in turns promote reading fluency. Meanwhile, when considering RAN as a mediator, the direct effect of neural stability in reading fluency is weakened, represented in c′-path in parenthesis. Although both processing speed and RAN tap on automaticity and relate to neural stability, processing speed did not act as a mediator carrying the influence from neural stability to reading fluency. b shows that although neural stability predicts processing speed (represented in a-path), all other effects in this mediations model fall short of significance, implying neural stability does not transmit processing speed and in turn improves reading fluency. *Note: all numbers are beta in the mediation analyses. *p = .05; **p < .001.*

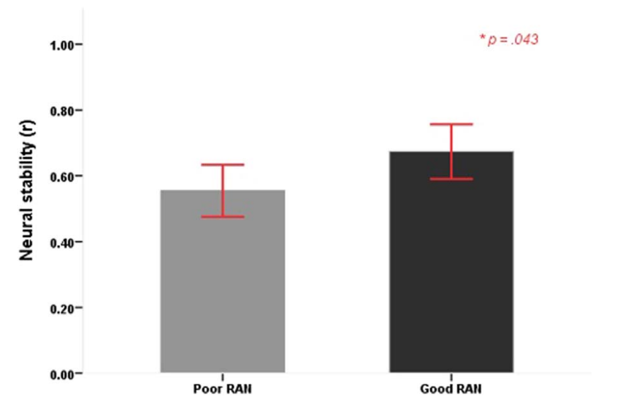

Fig. 2. Poor RAN performers (N = 15) have more variable responses (lower *r* values) than good RAN performers (N = 14) when examining trial-to-trial response variability between the first half of the frequency-following-response (FFR) recordings and the second half, F (1, 26) = 4.523, *p* = .043, η_p^2 = .148, controlling for IQ performance.

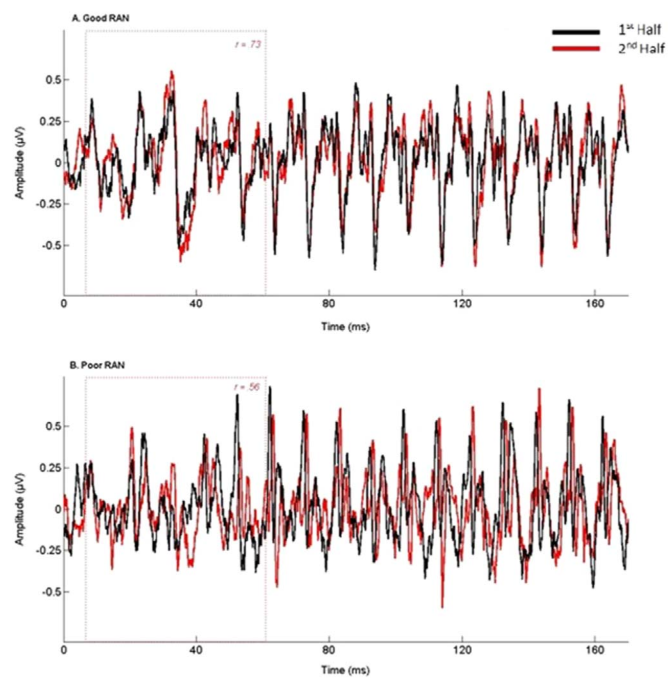

Fig. 3. The frequency-following-response (FFR) of good RAN performers are less variable than poor RAN performers. The FFR from a representative good RAN performer (top) and poor RAN performer (bottom) are plotted to illustrate the neural stability in children with good and poor-RAN performance.

showed that neural stability predicted RAN, as indicated in Fig. 1a (indicated as a-path, b = 13.298, SE = 6.349, p = .039); and RAN predicted reading fluency (indicated as b-path, b = .665, SE = .085, p < .001). The total effect measuring the influence of neural stability on reading fluency is significant (indicated as c-path in the same figure, b = 14.659, SE = 6.469, p < .026). We used a bootstrap estimation approach with 1000 samples (Preacher and Hayes, 2008) and then a 95% confidence interval (CI) was computed by determining the mediating effect; this effect emerges if neural stability promotes RAN, and if, in turn, RAN improves reading fluency. The results confirmed the indirect effect, with CI between .666 and 18.579, implying a significant effect as CI does not fall below zero. The direct effect (c′-path) of neural stability in reading fluency was weakened when adjusting for the effect of RAN as a mediator in the model, b = 5.820, SE = 5.062, p = .254, suggesting the significant link revealed in the total effect (c-path) of neural stability in reading fluency may be driven primarily by RAN.

The second mediation analysis revealed that processing speed does not mediate the effect of neural stability on reading fluency. In the second mediation analysis, to isolate the effect of RAN in this model, RAN, along with IQ, was entered as a covariate. Although neural stability predicted processing speed, as indicated in Fig. 1b as a-path, b = 13.355, SE = 6.579, p = .045, processing speed failed to predict reading fluency adjusted for the influence of neural stability, indicated in b-path, b = .108, SE = .082, p = .192. Hence, there is no mediation effect of processing speed on the relation between neural stability and reading fluency.

Lastly, the ANCOVA analysis further confirmed the relation between neural stability and RAN. The good-RAN group displayed better auditory neural stability than the poor-RAN group, with IQ score controlled, F (1, 26) = 4.523, p = .043. To ensure that the observed group difference was not due to neurophysiological noise as shown in Hornickel and Kraus (2013), we conducted ANCOVA to examine whether or not there was a difference between the groups in their neurophysiological noise, with IQ as a covariate. There were no group differences, F (1, 26) = 1.023, p = .321. Fig. 2 shows the mean scores of the two groups and Fig. 3 displays the FFR from a poor-RAN representative and a good-RAN representative.

In sum, the results support predictions that neural stability associates with automaticity including RAN and processing speed; RAN is the unique mediator for understanding the process or mechanism that interconnects neural stability and reading fluency. Furthermore, poor-RAN performers have variable neural stability of FFR.

4. Discussion

4.1. The relationship between neural stability and automaticity in reading

Neural stability captures the consistency of neural responses to speech, which supports an essential building block for successful reading. We hypothesized that neural stability is related to automaticity by virtue of stable speech-sound encoding, given the close relationship between neural stability and integrative functions in the central auditory system that help facilitate cognitive processing and integration of resources important for reading. Consistent with our hypothesis, neural stability, measured by trial-to-trial response stability for speech syllables, associated with key measures of automaticity - RAN and processing speed. However, neural stability did not relate with PA.

A major contribution of automaticity in reading is the facilitation of efficient cognitive processing (LaBerge and Samuels, 1974; Berninger, 1999). Reading is a complex task comprising multiple domains, with phonology, orthography, and semantics processing playing particularly important roles (Berninger et al., 2006). When a subskill becomes automatized, it allows more effective allocation of attentional resources to other cognitive domains as well as better integration of all reading resources. For example, when children become fluent in the coordination of phonological-orthographic processing, the perceptual processing needed for the task could be less taxed, freeing resources for higher-order processing such as passage comprehension and idea generation (Berninger, 1999; Berninger et al., 2006). With respect to speech-sound processing, the assumption is that the more reliably sound information is processed, the more automatic speech-sound processing can be; thus, more resources are freed for higher-order processing, ultimately contributing to fluent reading.

The FFR reflects an integrative system auditory-cognitive system that is subject to modification by the corticofugal system (Kraus and White-Schwoch, 2015). Thus, the FFR can indicate the influence of non-auditory cognitive processes, for better or worse. This idea is supported by studies demonstrating that the integrity of the FFR aligns with cognitive skills such as attention and executive control (reviewed by Krizman et al., 2014). Therefore, a top-down failure of cognitive systems involved in RAN could propagate into the auditory system, which would mean that the unstable FFR we observe here could be a consequence, and not a direct cause, of poor automaticity. This hypothesis can be explored more thoroughly in a longitudinal study of the FFR and literacy development that tracks neural stability before children are old enough to exhibit automatic and integrated literacy skills.

4.2. RAN mediates the relation between neural stability and reading fluency

This study highlights the unique role of RAN as a mediator connecting auditory neural stability and reading fluency. Our mediation analysis suggests a potential conceptual direction of these variables: neural stability relates to RAN ability, which in turn may facilitate reading fluency. Interestingly, although processing speed is related to both auditory neural stability and reading fluency, processing speed alone does not mediate the stability-reading link. Thus, the results highlight the role of RAN beyond that accounted for by speed of processing, which is compatible with past research (Kail and Hall, 1994; Neuhaus et al., 2001). While processing speed is a core component in naming, highlighting the automatization aspect, RAN itself is uniquely connected to other reading processes such as visual-lexical access, visual-attention processing and serial processing (e.g., Jones et al., 2010; Wolf and Bowers, 1999). The current results suggest that the influence of auditory neural stability is channeled through RAN, a skill set incorporating multiple literacy-related cognitive skills, to impact reading fluency.

Consistent with our prediction, children with poor-RAN ability showed more auditory neural variability than children with good-RAN ability, as shown in Fig. 2. Fig. 3 also shows the FFR from representatives of the poor- and good-RAN groups. The response of a poor-RAN individual was distinctly less reliable. Together, these results suggest that Hornickel and Kraus's (2013) discovery that poor readers have unstable neural responses could be primarily driven by RAN deficits in the poor reading group.

4.3. Distinct neural mechanisms for RAN and phonological awareness

The results of this study help to differentiate the roles of phonological awareness and RAN in reading. The data show no evidence of a link between phonological awareness and neural stability. Our findings are in line with neurophysiologic studies which suggest distinct neural mechanisms for phonological awareness and RAN. A recent functional-MRI study conducted by Norton et al. (2014) found that 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. Our data are in line with the notion of separate neural mechanisms underlying phonological awareness and RAN.

The neural signature specific to a RAN performance bolsters the multi-etiology view of reading impairment, proposed by Wolf and Bower in their Double-Deficit Hypothesis (1999). In the future, neural mechanisms specific to phonological awareness and RAN could potentially serve as literacy and pre-literacy biological markers, providing insight into more effective and targeted intervention for children with distinct reading-subtypes.

4.4. Limitations and future directions

One limitation of this study is that we quantified neural variability by correlating subaverages representing the first and second halves of our recording sessions; this means that we cannot rule out neural fatigue as a potential factor underlying these effects. Although Hornickel and Kraus (2013) showed that multiple ways of quantifying neural variability yield similar results, future work should replicate our findings using alternate approaches. Moreover, we cannot completely exclude the influence of attentional control in changes of neural stability and future investigation is warranted (Hairston et al., 2013; Krishnan et al., 2005; White-Schwoch et al., 2015). In addition, scalp-recorded neurophysiological responses are inherently ambiguous, and future work aimed at understanding what neural events manifest as a variable FFR can provide clarity to these findings. The present study measured responses to two speech syllables; although we expect that neural stability to other speech sounds should generate converging outcomes, future studies should probe generalization to other speech sounds. Nonetheless, converging evidence confirms that these stimuli are useful in understanding auditory processing in reading (Chandrasekaran et al., 2009; Hornickel et al., 2009). Lastly, neural stability, phonological awareness and automaticity measures such as RAN and processing speed change with development (Benasich et al., 2014; Kail and Hall, 1994; Wagner et al., 1997; Skoe et al., 2013); interactions among variables could vary with age. Examining these relationships in preschool children could help determine how neural stability supports automaticity as reading development, and the extent to which response stability predicts future literacy.

Declaration of interest

Nina Kraus has financial interest in Synaural, a company working to develop a user-friendly measure of auditory processing.

Acknowledgements

This research is funded by NIH R01 DC01510, R01 HD069414, and the Knowles Hearing Center, Northwestern University.

References

Banai, K., Hornickel, J., Skoe, E., Nicol, T., Zecker, S., Kraus, N., 2009. Reading and subcortical auditory function. Cereb. cortex 19 (11), 2699–2707.
Benasich, A.A., Choudhury, N.A., Realpe-Bonilla, T., Roesler, C.P., 2014. Plasticity in developing brain: active auditory exposure impacts prelinguistic acoustic mapping. J.

Neurosci. 34 (40), 13349–13363.
Berninger, V.W., 1999. Coordinating transcription and text generation in working memory during composing: automatic and constructive processes. Learn. Disabil. Q. 22 (2), 99–112.
Berninger, V.W., Abbott, R.D., Jones, J., Wolf, B.J., Gould, L., Anderson-Youngstrom, M., Apel, K., 2006. Early development of language by hand: composing, reading, listening, and speaking connections; three letter-writing modes; and fast mapping in spelling. Dev. Neuropsychol. 29 (1), 61–92.
Carr, K.W., White-Schwoch, T., Tierney, A.T., Strait, D.L., Kraus, N., 2014. Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. Proc. Natl. Acad. Sci. USA 111 (40), 14559–14564.
Centanni, T.M., Engineer, C.T., Kilgard, M.P., 2013. Cortical speech-evoked response patterns in multiple auditory fields are correlated with behavioral discrimination ability. J. Neurophysiol. 110 (1), 177–189.
Centanni, T.M., Chen, F., Booker, A.M., Engineer, C.T., Sloan, A.M., Rennaker, R.L., Kilgard, M.P., 2014. Speech sound processing deficits and training-induced neural plasticity in rats with dyslexia gene knockdown. PLoS One 9 (5), e98439.
Chandrasekaran, B., Kraus, N., 2010. The scalp-recorded brainstem response to speech: neural origins and plasticity. Psychophysiology 47 (2), 236–246.
Chandrasekaran, B., Hornickel, J., Skoe, E., Nicol, T., Kraus, N., 2009. Context-dependent encoding in the human auditory brainstem relates to hearing speech in noise: implications for developmental dyslexia. Neuron 64 (3), 311–319.
Coffey, E.B., Herholz, S.C., Chepesiuk, A.M., Baillet, S., Zatorre, R.J., 2016. Cortical contributions to the auditory frequency-following response revealed by MEG. Nat. Commun. 7.
Eckert, M.A., Leonard, C.M., Richards, T.L., Aylward, E.H., Thomson, J., Berninger, V.W., 2003. Anatomical correlates of dyslexia: frontal and cerebellar findings. Brain 126 (2), 482–494.
Hairston, W.D., Letowski, T.R., McDowell, K., 2013. Task-related suppression of the brainstem frequency following response. PLoS One 8 (2), e55215.
He, Q., Xue, G., Chen, C., Chen, C., Lu, Z.L., Dong, Q., 2013. Decoding the neuroanatomical basis of reading ability: a multivoxel morphometric study. J. Neurosci. 33 (31), 12835–12843.
Hornickel, J., Kraus, N., 2013. Unstable representation of sound: a biological marker of dyslexia. J. Neurosci. 33 (8), 3500–3504.
Hornickel, J., Skoe, E., Nicol, T., Zecker, S., Kraus, N., 2009. Subcortical differentiation of stop consonants relates to reading and speech-in-noise perception. Proc. Natl. Acad. Sci. USA 106 (31), 13022–13027.
Hornickel, J., Zecker, S.G., Bradlow, A.R., Kraus, N., 2012. Assistive listening devices drive neuroplasticity in children with dyslexia. Proc. Natl. Acad. Sci. USA 109 (41), 16731–16736.
Jones, M.W., Branigan, H.P., Hatzidaki, A., Obregón, M., 2010. Is the 'naming'deficit in dyslexia a misnomer? Cognition 116 (1), 56–70.
Kail, R., 1991. Developmental change in speed of processing during childhood and adolescence. Psychol. Bull. 109 (3), 490.
Kail, R., Hall, L.K., 1994. Processing speed, naming speed, and reading. Dev. Psychol. 30 (6), 949.
Kail, R., Salthouse, T.A., 1994. Processing speed as a mental capacity. Acta Psychol. 86 (2), 199–225.
Klatt, D.H., 1980. Software for a cascade/parallel formant synthesizer. J. Acoust. Soc. Am. 67, 971–995.
Kraus, N., White-Schwoch, T., 2015. Unraveling the biology of auditory learning: a cognitive–sensorimotor–reward framework. Trends Cogn. Sci. 19 (11), 642–654.
Krishnan, A., Xu, Y., Gandour, J., Cariani, P., 2005. Encoding of pitch in the human brainstem is sensitive to language experience. Cogn. Brain Res. 25 (1), 161–168.
Krizman, J., Skoe, E., Marian, V., Kraus, N., 2014. Bilingualism increases neural response consistency and attentional control: evidence for sensory and cognitive coupling. Brain Lang. 128 (1), 34–40.
LaBerge, D., Samuels, S.J., 1974. Toward a theory of automatic information processing in reading. Cogn. Psychol. 6 (2), 293–323.
Liberman, I.Y., Shankweiler, D., Fischer, F.W., Carter, B., 1974. Explicit syllable and phoneme segmentation in the young child. J. Exp. Child Psychol. 18 (2), 201–212.
Neuhaus, G., Foorman, B.R., Francis, D.J., Carlson, C.D., 2001. Measures of information processing in rapid automatized naming (RAN) and their relation to reading. J. Exp. Child Psychol. 78 (4), 359–373.
Norton, E.S., Wolf, M., 2012. Rapid automatized naming (RAN) and reading fluency: implications for understanding and treatment of reading disabilities. Annu. Rev. Psychol. 63, 427–452.
Norton, E.S., Black, J.M., Stanley, L.M., Tanaka, H., Gabrieli, J.D., Sawyer, C., Hoeft, F., 2014. Functional neuroanatomical evidence for the double-deficit hypothesis of developmental dyslexia. Neuropsychologia 61, 235–246.
Preacher, K.J., Hayes, A.F., 2008. Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. Behav. Res. Methods 40, 879–891.
Pugh, K.R., Landi, N., Preston, J.L., Mencl, W.E., Austin, A.C., Sibley, D., Molfese, P., 2013. The relationship between phonological and auditory processing and brain organization in beginning readers. Brain Lang. 125 (2), 173–183.
Saur, D., Kreher, B.W., Schnell, S., Kümmerer, D., Kellmeyer, P., Vry, M.S., Huber, W., 2008. Ventral and dorsal pathways for language. Proc. Natl. Acad. Sci. USA 105 (46), 18035–18040.
Schwartz, M.F., Faseyitan, O., Kim, J., Coslett, H.B., 2012. The dorsal stream contribution to phonological retrieval in object naming. Brain 135 (12), 3799–3814.
Skoe, E., Krizman, J., Anderson, S., Kraus, N., 2013. Stability and plasticity of auditory brainstem function across the lifespan. Cereb. Cortex (bht311).
Torgesen, J.K., Wagner, R., Rashotte, C., 1999. TOWRE–2 Test of Word Reading Efficiency. Pro-Ed, Austin, TX.
Wagner, R.K., Torgesen, J.K., 1987. The nature of phonological processing and its causal role in the acquisition of reading skills. Psychol. Bull. 101 (2), 192.
Wagner, R.K., Torgesen, J.K., Rashotte, C.A., Hecht, S.A., Barker, T.A., Burgess, S.R., Garon, T., 1997. Changing relations between phonological processing abilities and word-level reading as children develop from beginning to skilled readers: a 5-year longitudinal study. Dev. Psychol. 33 (3), 468.
Wagner, R.K., Torgesen, J.K., Rashotte, C.A., 1999. Comprehensive Test of Phonological Processing: CTOPP. Pro-ed.
White-Schwoch, T., Carr, K.W., Thompson, E.C., Anderson, S., Nicol, T., Bradlow, A.R., Kraus, N., 2015. Auditory processing in noise: a preschool biomarker for literacy. PLoS Biol. 13 (7), e1002196.
White-Schwoch, T., Nicol, T., Warrier, C.M., Abrams, D.A., Kraus, N., 2016. Individual differences in human auditory processing: insights from single-trial auditory midbrain activity in an animal model. Cereb. Cortex.
Wolf, M., Bowers, P.G., 1999. The double-deficit hypothesis for the developmental dyslexias. J. Educ. Psychol. 91 (3), 415.
Wolf, M., Bowers, P.G., Biddle, K., 2000. Naming-speed processes, timing, and reading: a conceptual review. J. Learn. Disabil. 33 (4), 387–407.
Woodcock, R.W., McGrew, K.S., Mather, N., 2001. Woodcock-Johnson Tests of Achievement. Riverside Publishing, Itasca, IL.
Ziegler, J.C., Goswami, U., 2005. Reading acquisition, developmental dyslexia, and skilled reading across languages: a psycholinguistic grain size theory. Psychol. Bull. 131 (1), 3.