RESEARCH REPORT

Examining the neural and cognitive processes that underlie reading through naming speed tasks

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Abstract

We combined fMRI with eye tracking and speech recording to examine the neural and cognitive mechanisms that underlie reading. To simplify the study of the complex processes involved during reading, we used naming speed (NS) tasks (also known as rapid automatized naming or RAN) as a focus for this study, in which average reading right-handed adults named sets of stimuli (letters or objects) as quickly and accurately as possible. Due to the possibility of spoken output during fMRI studies creating motion artifacts, we employed both an overt session and a covert session. When comparing the two sessions, there were no significant differences in behavioral performance, sensorimotor activation (except for regions involved in the motor aspects of speech production) or activation in regions within the left-hemisphere-dominant neural reading network. This established that differences found between the tasks within the reading network were not attributed to speech production motion artifacts or sensorimotor processes. Both behavioral and neuroimaging measures showed that letter naming was a more automatic and efficient task than object naming. Furthermore, specific manipulations to the NS tasks to make the stimuli more visually and/or phonologically similar differentially activated the reading network in the left hemisphere associated with phonological, orthographic and orthographic-to-phonological processing, but not articulatory/motor processing related to speech production. These findings further our understanding of the underlying neural processes that support reading by examining how activation within the reading network differs with both task performance and task characteristics.

KEYWORDS

eye tracking, fMRI, naming speed, orthography, phonological processing

1 | INTRODUCTION

Despite reading being a crucial skill for one's economic, social and academic success (Norton & Wolf, 2012), it remains controversial how reading skills and reading difficulties develop (Araújo, Reis, Petersson, & Faísca, 2015). Furthermore, due to the multiple and complex components that are involved during reading, the neuroanatomical

mechanisms that support the behavioral differences in reading ability are not well understood. To simplify the study of the complex processes involved in reading, we use naming speed (NS) tasks, in which participants are required to name sets of simple stimuli (e.g., letters or objects) as quickly and as accurately as possible. NS has been described as a "microcosm" of reading (Wolf & Bowers, 1999) and is a powerful predictor of current and future reading ability (Kirby et al., 2010). Furthermore, the simple NS paradigm is a valuable tool for studying the numerous cognitive, articulatory and oculomotor processes underlying reading and the efficiency of their timing mechanisms (see Al Dahhan, Kirby, & Munoz, 2016, for a review; Cutting & Denckla, 2001; Wolf, Bowers, & Biddle, 2000).

Successful performance on NS tasks requires automatic visual recognition of familiar stimuli, access to phonological codes from the lexical store and rapid articulation of stimulus names (Gordon & Hoedemaker, 2016). In order to rapidly name stimuli in a NS task and minimize interference between successive items, sustained attention is required to manage vocal execution and manage perceptual encoding of stimuli according to available working memory capacity. Variation in task performance depends upon these various cognitive task components and their coordination (Gordon & Hoedemaker, 2016). Furthermore, factor analyses have shown that NS tasks load onto two separate factors according to their stimuli, with letters and digits loading onto alphanumeric NS and objects and colors loading onto non-alphanumeric NS (Narhi et al., 2005; van den Bos, Zijlstra, & Spelberg, 2002). Alphanumeric NS tasks have been found to be more strongly correlated with reading ability than non-alphanumeric NS tasks (Bowey, McGuidan, & Ruschena, 2005; Savage & Frederickson, 2005) and have been found to be performed much faster and become automatized earlier in development (Cronin & Carver, 1998; Cummine, Szepesvari, Chouinard, Hanif, & Georgiou, 2014; Di Filippo et al., 2005; Georgiou & Stewart, 2013; Mazzocco & Grimm, 2013).

Two key cognitive processes shared by reading and NS are phonological processing and orthographic processing. However, there is disagreement as to which of these processes relates NS to reading. Some researchers have proposed that NS reflects automaticity of phonological processing (Torgesen, Wagner, & Rashotte, 1994; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997), whereas others have suggested that NS is an indication of the automaticity of the recognition of visual symbols (Bowers, 1995; Bowers & Wolf, 1993). To address this, NS task stimuli can be manipulated to increase their phonological and/or orthographic similarity (Compton, 2003). If performance relies primarily on phonological processing, increasing the phonological difficulty of a NS task by selecting stimuli whose names rhyme with one another should impair

task performance. However, if NS relies primarily on orthographic processing, increasing orthographic difficulty by selecting stimuli that are visually similar to one another should impair performance. Based on these hypotheses, letter NS tasks have been utilized to identify orthographic processing as the main cognitive process underlying NS task performance in both adults and young children (Al Dahhan et al., 2014; Al Dahhan, Kirby, Brien, & Munoz, 2017).

The pattern of neural activity during NS tasks includes areas involved in the left cerebral hemisphere reading network (Cummine, Chouinard, Szepesvari, & Georgiou, 2015; Cummine et al., 2014; Misra, Katzir, Wolf, & Poldrack, 2004). This network, consisting of six key regions that are the focus of this paper, includes a dorsal stream, which maps orthographic information onto phonological representations, and a ventral stream, which involves a whole word identification system (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Cummine et al., 2013; Hickok & Poeppel, 2004; Price, 2012; Pugh et al., 2000; Saur et al., 2008). The dorsal stream projects anteriorly from the visual cortex toward the parietal lobe and frontal regions and includes the posterior superior temporal gyrus, angular gyrus, and supramarginal gyrus; the ventral stream projects ventrolaterally and includes the inferior occipito-temporal regions, fusiform gyrus and the medial temporal gyrus (Borowsky et al., 2006; Pugh et al., 2000). Within this network, there is greater activity for alphanumeric than non-alphanumeric tasks, with non-alphanumeric stimuli primarily activating regions in the ventral pathway and alphanumeric stimuli activating regions in both the dorsal and ventral pathways (Cummine et al., 2014; Misra et al., 2004). A number of these key reading regions also play important roles in speech acquisition and production processes during both overt and covert tasks: articulation (precentral gyrus, supplementary motor area, cerebellum), visual/orthographic processing (inferior temporal gyrus) and sound/phonological decoding (supramarginal gyrus and the superior temporal gyrus) (Cummine et al., 2016; Price, 2012; Sato, Tremblay, & Gracco, 2009; Simmonds et al., 2014). These findings indicate that fluent reading requires automatic and efficient activation of regions involved with phonological, orthographic and articulatory processes (Cummine et al., 2016).

Overall, while previous research has identified the left-hemisphere reading network and shown differences in neural activity between alphanumeric and non-alphanumeric NS tasks, it remains unknown how this network is modulated with various stimulus manipulations. To address these important gaps, we combine fMRI with eye tracking and speech recording in average adult readers and examine how manipulating stimulus composition of NS tasks affects performance. The results from this approach allow for a more comprehensive understanding of the underlying components supporting

reading, which will allow researchers to refine existing models of NS and how these processes are affected by various task stimuli. This could also lead to establishing biomarkers to help identify children who may be at risk for developing reading difficulties in order to provide them with early assessment and effective interventions.

To examine behavioral performance and cognitive processing, we analyze participants' articulations and eye movement performance. During NS tasks, researchers typically only measure overall naming times. However, total naming time does not show important individual differences in reading-related processes, such as attentional control, or allow for the ability to adequately determine the underlying cognitive processes of NS tasks (Araújo et al., 2011; Araújo et al., 2015; Clarke, Hulme, & Snowling, 2005; Georgiou, Parrila, & Kirby, 2009; Georgiou, Parrila, Kirby, & Stephenson, 2008; Lervag & Hulme, 2009; Neuhaus, Foorman, Francis, & Carlson, 2001). Therefore, as an attempt to understand the processes that underlie NS, researchers have separated naming times into the articulation times of stimulus names and pause times between these articulations (Jones, Obregon, Kelly, & Branigan, 2008; Neuhaus et al., 2001; Norton & Wolf, 2012). Pause times represent a marker for the response preparation aspect of executive control (Araújo et al., 2011; Clarke et al., 2005; Georgiou, Parrila, & Kirby, 2006; Georgiou et al., 2009; Kirby et al., 2010; Li et al., 2009; Neuhaus et al., 2001). Furthermore, we use video-based eye tracking to measure the number of saccades to look from one stimulus to the next, backwards saccades, or regressions, and fixation durations (Olitsky & Nelson, 2003; Rayner, 1997; Starr & Rayner, 2001). Pause time and fixation duration have been found to be the most powerful predictors of reading ability, with shorter pause times and fixation durations being associated with higher reading ability (Al Dahhan et al., 2014, 2017). Longer fixation durations and pause times reflect deficits in gaining automaticity during the task as more time is required to acquire visual/orthographic information from stimuli and prepare the correct response. Increasing the visual similarity of letters had the greatest effect on performance: decreased letter naming efficiency and increased naming errors, saccades, regressions, pause times and fixation durations (Al Dahhan et al., 2014, 2017). Researchers have yet to examine whether these patterns are similar to non-alphanumeric stimuli.

Simultaneous recordings of eye movements and vocalizations during fMRI studies allow for a more fine-grained understanding of brain–behavior relationships and how performance is influenced by the coordination of vocal and visual processes, providing greater insight into the response preparation aspect of executive control (Araújo et al., 2011; Clarke et al., 2005; Georgiou et al., 2006, 2009; Kirby et al., 2010; Li et al., 2009; Rayner, 1997). However, when studying reading or general language processes, behavioral studies often use tasks which rely on spoken responses, such as reading aloud. Speech production during fMRI studies presents the possibility of creating task-related motion artifacts (Soltysik & Hyde, 2006). Thus, fMRI studies have predominantly used covert naming to study reading processes, but relying on covert responses presents issues of its own. For example, during covert naming it is unclear whether participants are performing the task according to the instructions they were given, whether they are performing the task at all, or how accurately they are performing the task. To address this issue, we include both an *overt* session in which task stimuli were named aloud, and a *covert* session in which stimuli are named silently. For each session, we examine the neural and cognitive processes involved in NS tasks by first examining the sensorimotor processes involved in the serial processing and naming of simple stimuli. This involves key oculomotor regions involved in saccade control, such as the frontal, supplementary and parietal eye fields (FEF, SEF, PEF), dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC) and the caudate nucleus (CN) (Brown, Vilis, & Everling, 2007; Connolly, Goodale, Goltz, & Munoz, 2005; Connolly, Goodale, Menon, & Munoz, 2002; Ford, Goltz, Brown, & Everling, 2005); key speech areas, such as the inferior frontal gyrus, insula and primary motor cortex (Guenther, Ghosh, & Tourville, 2006); and key visual regions involved in reading along the ventral visual pathway, such as the cuneus, lingual gyrus and the fusiform gyrus (Indefrey & Levelt, 2004; Price, 2012). We then examine the differences in behavioral performance and neural activation between alphanumeric and non-alphanumeric NS tasks, and the effects of manipulating stimulus composition. This design allows us to control for sensorimotor processes when examining task differences and ensures that any differences found between the tasks are not driven by false positives caused by motion artifacts that may be present during the overt session.

When comparing the two sessions, we hypothesize that there will be no differences in behavioral performance, sensorimotor activation (except in regions involved in the motor aspects of speech production) or neural activation in the left-hemisphere neural reading network. Furthermore, we hypothesize that behavioral performance will overall be more negatively affected by object stimuli than the letter stimuli, and increasing the visual similarity of letters and the phonological similarity of the objects will negatively affect performance.

2 | MATERIALS AND METHODS

2.1 | Participants

Participants were recruited from the Queen's University graduate student community who provided their written and informed consent. Nineteen participants, ages 21–26 years, were recruited for this study. All participants were performing

well at university and did not report having any language or reading difficulties. Descriptive statistics for raw scores on the reading and nonverbal ability measures are presented in Table 1. Scores are equivalent to two standard deviations above the norm for 21- to 26-year-olds. Data from one participant were removed due to excessive head motion (>2 mm) during scanning. The remaining eighteen participants (mean age = 24.1 years, SD = 1.89; 16 female) were right-handed, as assessed by the Modified Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected to normal vision, reported English as their native language, and had no history of head injuries or neurological illnesses.

2.2 | Reading and cognitive measures

2.2.1 | Reading and decoding ability

Reading ability was assessed with three tasks: Word Identification, Sentence Reading Fluency and Passage Comprehension (Schrank, McGrew, Mather, & Woodcock, 2014). In *Word Identification,* participants were asked to read aloud up to 106 words that increased in difficulty until they either attempted all the words or made six consecutive errors. *Sentence reading fluency* was assessed by examining participants' ability to rapidly read and comprehend simple sentences within a 3-min time limit, in which they were required to circle "Yes" or "No" whether the sentence was true or false. *Passage comprehension* was assessed by examining participants' ability to silently read up to 52 passages, comprehend the information in each and provide a missing word to complete a sentence within each passage. Participants' decoding ability was assessed with *Word Attack* (Woodcock, 1998) in which they were asked to read aloud 45 pseudowords that increased in difficulty until they either attempted all the words or made six consecutive errors. For each task, participants' scores were the number of correct responses.

TABLE 1 Descriptive statistics of group performance on reading and nonverbal ability measures

	Controls (n = 18)	
Variable	**M**	**SD**
Word identification	76.83	1.25
Passage comprehension	46.50	1.20
Sentence reading fluency	106.89	2.14
Word attack	24.78	0.94
Phoneme elision	32.00	1.50
Phoneme isolation	28.28	1.56
Word blending	26.67	1.24
Matrix reasoning	28.11	2.21

2.2.2 | Phonological awareness

Phonological processing was assessed with three tasks from the Second Edition of the Comprehensive Test of Phonological Processing battery (Wagner, Torgesen, Rashotte, & Pearson, 2013): *Elision* measures the ability to remove phonological segments from spoken words to form other words (34 items), *Phoneme Isolation* measures the ability to isolate individual sounds within words (32 items), and *Word Blending* measures the ability to synthesize sounds to form words (33 items). For each task, participants' scores were the number of correct responses.

2.2.3 | Nonverbal ability

Nonverbal ability was assessed with the Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999). Thirty-five incomplete visual patterns, each with five possible pieces to complete the patterns, were shown to participants one at a time. Participants were asked to point to the piece that would best complete the pattern. Participants' scores were the number of correct answers.

2.2.4 | Naming speed tasks

Four versions of a letter NS task and two versions of an object NS task, with two trials/version, were administered (Figure 1a,b). For the letter NS tasks, single letter substitutions of the letter *o* in a control task (LC; Denckla & Rudel, 1976) with the letter matrix of *a, d, o, p* and *s* were made to make the letter matrix more phonologically similar (PS: *o* replaced with *v*), visually similar (VS: *o* replaced with *q*), or both visually and phonologically similar (VPS: *o* replaced with *b*; Compton, 2003). Similarly, for the object NS tasks, the object control task (OC; Denckla & Rudel, 1976) had pictograms of the stimuli *dog*, *hat*, *chair*, *cat* and *star*, and in the object phonologically similar condition (OPS), *chair* was replaced with *bat,* to rhyme with *hat* and *cat*. Each NS task presented 50 letters/objects simultaneously with ten repetitions of the five letters/objects arranged semi-randomly in five rows of ten letters/objects each.

2.3 | Procedure

Before the study began, all participants completed four practice NS trials outside of the MRI environment. The first two practice trials, which were counterbalanced for order, involved participants naming the eight letters and six objects that were used in the study (i.e., *a, d, b, p, s, q, o, v, dog, hat, chair, cat, star,* and *bat*) to ensure that they were familiar with the stimulus
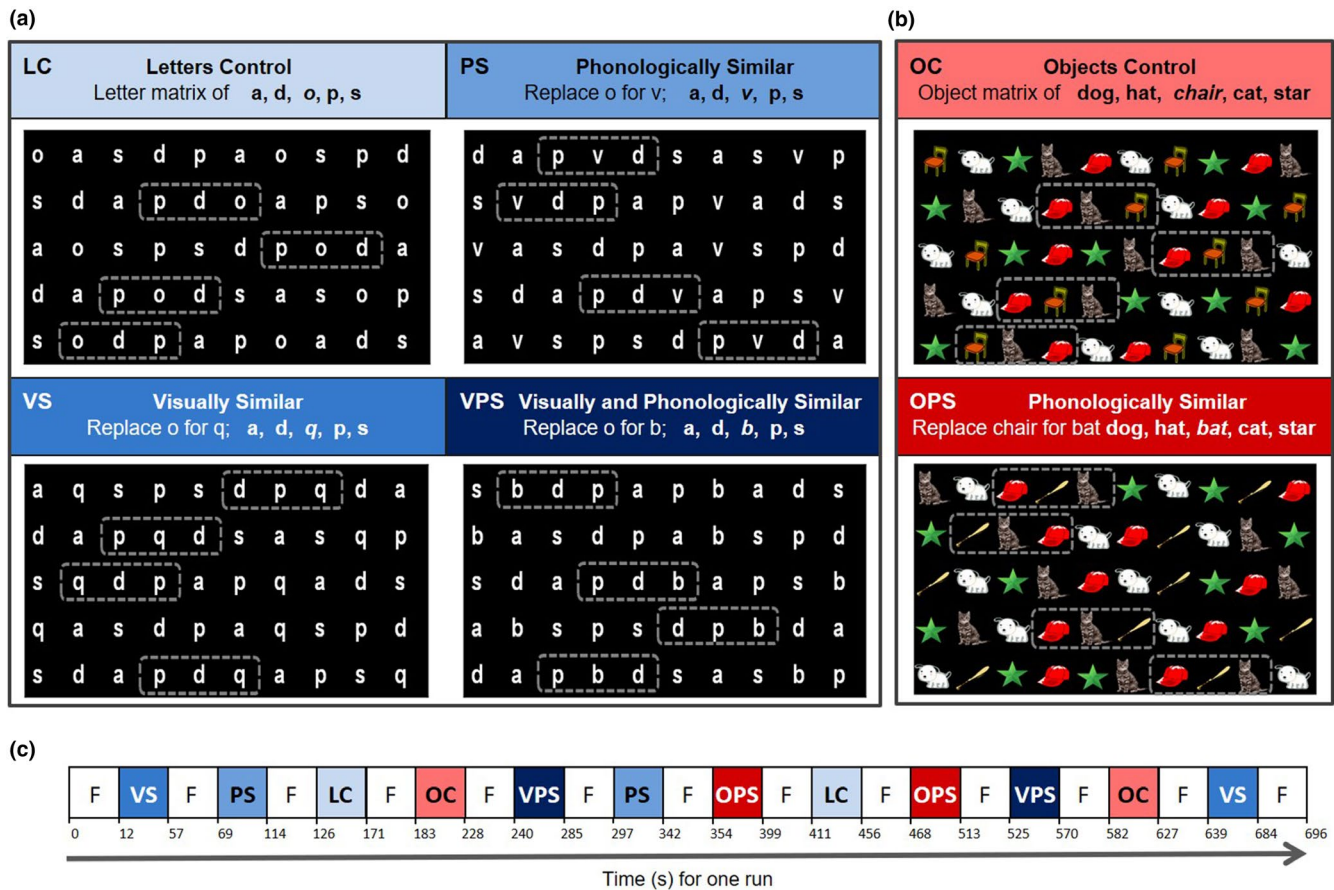
FIGURE 1 Naming speed (NS) stimuli. (a) Letter NS tasks. The letters control (LC) NS task was developed by Denckla and Rudel (1976). The phonologically similar (PS), visually similar (VS), and visually and phonologically similar (VPS) tasks were developed by Compton (2003). (b) Object NS tasks. The object control (OC) NS task was developed by Denckla and Rudel (1976). (c) fMRI block paradigm during one run. The four versions of the letter NS task and two versions of the object NS task, with two trials/version, were counterbalanced for order. Dashed boxes indicate regions in which the letters or objects became similar to one another [Colour figure can be viewed at wileyonlinelibrary.com]

names. The third and fourth practice trials, also counterbalanced for order, involved participants performing NS tasks consisting of 20 letters and 20 objects each presented in four rows, to ensure participants understood the task requirements.

We employed two fMRI sessions, a *covert* session and an *overt* session, counterbalanced for order, that were 24 hr apart, each lasting approximately 1.5 hr, in which all participants completed the same four fMRI runs, with each run lasting 11.6 min. In the *overt* session, participants were instructed to name aloud as many letters or objects in the array as quickly and accurately as possible from left to right and top to bottom, and to go back to the beginning of the task and start over if they finished before the end of the time. In the *covert* session, the same instruction was given to participants except they were asked to silently name the letters or objects. Having two sessions in which participants perform an overt and a covert version of the same tasks allowed for a direct assessment of motion artifacts, sensorimotor patterns of activation and potential differences in eye movement behavior and neural activation within key regions of the reading network.

2.4 | Visual display, eye tracking and articulatory recordings

Visual displays were generated using Experiment Builder (SR Research Ltd., version 10.10.1630) running on a Windows 7 PC and were back-projected onto a high-contrast rear projection screen (DA-LITE), positioned at the head of the magnet bore, using a NEC LT265 DLP video projector (Tokyo, Japan) with a refresh rate of 60 Hz and a resolution of 1,024 × 768 and an Avotec SV-6011 color LCD Projection System (Florida, USA). A mirror situated on top of the head coil angled at approximately 45° allowed participants to view the screen.

Eye position was recorded throughout all tasks using an EyeLink 1,000 fiber optic camera (SR Research Ltd.), all recordings and calibrations were done monocularly based on the right eye while viewing was binocular. The camera was positioned next to the screen approximately 60 cm from the bore of the magnet to view the right eye of the participant in the mirror. Horizontal and vertical positions of the right pupil were digitized at 500 Hz and average gaze position error of <1°. Before each functional run, the eye tracker was

calibrated using nine randomly presented target locations on the screen (eight around the periphery and one central). The targets were flashed sequentially, and participants were instructed to fixate on each one. After calibration, the process was repeated to validate that the average error between fixation and target was <1° and that no loss of eye tracking occurred. The array of letters was presented in white print (Angsana New font, size 60) on a black background, with a 1.7° viewing distance between each letter and 2.4° viewing distance between each row. The horizontal and vertical dimensions of each letter stimulus were $0.47° \times 0.63°$, respectively. The array of objects was matched for luminance, 50 cd/m^2, with a 1.7° viewing distance between each object and 2.3° viewing distance between each row. The horizontal and vertical dimensions of each object stimulus were $1.4° \times 1.4°$.

During the overt session, articulations were recorded via an MRI compatible optical microphone (Optoacoustics Ltd.) and an ASIO compatible sound card at a sampling rate of 24 kHz. Eye position and articulations were recorded continuously from the start to end of each fMRI run and were synchronized through Experiment Builder.

2.5 | fMRI experimental design

Imaging data were acquired using a Siemens 3-Tesla Magnetom Trio system (Erlangen, Germany) fitted with a 12-channel receive-only head coil with participants lying supine. Functional images were acquired axial oblique with 40 horizontal slices (3.3 mm thick) covering the whole brain. High-resolution T1-weighted whole-brain structural scans were performed on each participant using a 3D MP-RAGE sequence (repetition time, TR = 1,760 ms; echo time, TE = 2.2 ms; flip angle, FA = 9°; field-of-view, FOV = 256 × 256 mm; matrix size 256 × 256 mm; 1-mm isovoxel resolution; 176 volumes). Functional data were collected using T2*-weighted echo-planar image (EPI) volumes sensitive to blood oxygen-level-dependent (BOLD) contrast (Kwong et al., 1992; Ogawa, Lee, Kay, & Tank, 1990) acquired in an interleaved fashion (TR = 2,750 ms, TE = 30 ms, FA = 84°, FOV = 211 × 211 mm, matrix size 64 × 64, 3.3-mm isovoxel resolution, 192 volumes). Four functional runs consisting of 192 volumes, including two discarded volumes to compensate for T1 saturation effects, were acquired for each participant.

A block design was used to administer the four versions of the letter NS task and two versions of the object NS task, with 12-s blocks of fixation separating each version of the task (Figure 1c). For each run, there were two trials/NS task, with each task presented on the screen for 45 s. These NS tasks were interleaved with 12-s fixation blocks in which participants were instructed to fixate at a single dot in the middle of the screen. Each run began with an additional fixation period (3 TR), while MR images were acquired in order to allow the fMRI signal to reach steady-state longitudinal magnetization, and each run ended with a 12-s fixation period to allow the hemodynamic response to return toward baseline before commencing the next run.

2.6 | Data analysis

2.6.1 | Behavioral data

Articulations and eye movements were analyzed using a combination of custom MATLAB software (version R2011a; MathWorks Inc.) and built-in saccade detection tools from SR research.

To avoid the possibility of practice effects, for both sessions, behavioral data were only analyzed for each participant's first pass through the task. For the overt session, eye position and articulations were digitized from the start to end of each trial. An eye movement was counted as a saccade based on the built-in saccade detection algorithm of the SR Research software. Specifically, a saccade was marked when it reached either a threshold velocity of 30°/s or a threshold acceleration of 8,000°/s^2. We used these start and end points in all subsequent analysis. Amplitude was calculated as the Euclidean distance in degrees of visual angle between eye position at the start and end of each saccade. Fixations were calculated as the time intervals between saccades, and fixation duration was calculated for each trial by averaging the length of all the fixations made in the trial. Regressions were defined as leftward saccades less than 10° in amplitude and within a horizontal visual angle of 30° in order to exclude leftward eye movements made from the end of one line of the array to the beginning of the next line. Eye tracking data associated with skips or naming errors were removed manually from the behavioral data analyses. For the covert session, the same algorithms were used to define eye movements. However, due to the inability to detect errors made during the tasks, fixation duration was defined as the average duration of all fixations made and the end of the first pass of the task was detected by the last eye movement made during the last row of the task.

For the overt session, the sound files containing the letter and object naming responses for each participant were analyzed using custom software developed in MATLAB. Data extraction from the audio files was completed using procedures described previously (Georgiou et al., 2006) designed to normalize the volume of the audio recordings across participants and remove background noise (also see Al Dahhan et al., 2017). In detail, for each wave file (sampling rate of 44.1 kHz) of audio recording, we performed a simple normalization algorithm to extract absolute amplitude. First, taking

the absolute value of the waveform, we removed any extreme loud spikes using a threshold of 7 standard deviations above the mean amplitude and then normalized to the maximum amplitude. We then used a rectangular box filter of 200 sample points to remove high frequency noise. Empirically, we found that this produced a clean waveform, but some loud spikes remained so we repeated the spike removal at a threshold of 4 standard deviations above the mean. After re-normalizing, a clean waveform of articulation amplitude was produced. To mark the onset and offset of articulations, we applied a simple threshold filter of 15% of the normalized amplitude. The amplitude had to remain above this threshold for 2,000 sample points to be counted as an articulation, in order to avoid short spurious noises from being falsely detected. The sounds files were separated into pause and articulations based on this automated method. We found that this automated threshold also agreed with our empirical segmentation upon listening to each articulation.

Some manual segmentation of articulations was also required, and a custom software interface in MATLAB was used for this process. This interface displayed the articulations, the corresponding saccades over the letters and the onset/offset times for articulations. It allowed for further manual annotation. First, some participants would slur articulations or not pause between the articulation of stimuli names. During these instances, these articulations were manually split in places in which the amplitude would dip to a minimum, but still above threshold, between these continuous utterances and pause times were marked as 0 between these articulations. Second, spurious articulations such as unrelated talking, coughing or other utterances were manually removed. Third, end points of articulations rarely had to be manipulated if other noises interfered with the proper detection via the automated method. However, overall we found that little manual intervention was required in most cases and every effort was made to rely on objective and automated marking.

Articulations were manually scored to calculate an error score from the participants' responses, corresponding to the number of naming errors made per trial. NS efficiency was then calculated by dividing the number of items named correctly in a trial by the total time spent naming items on that trial. Pause time for each trial was calculated as the mean of the pause times between two correctly identified items, and articulation time was calculated as the mean of the articulation times for correctly identified items. These parameters were calculated after removing the pauses and articulations associated with task errors. More specifically, incorrect articulations and their bordering pauses were removed from the data. If participants corrected themselves following a naming error, the incorrect articulation and the bordering pauses were removed. If participants skipped an item, the pause time between the articulations of the two neighboring items, as well as the articulation of the item following the skipped item, was removed (Georgiou et al., 2006).

2.6.2 | fMRI preprocessing

All fMRI preprocessing and statistical analyses for both sessions were conducted using BrainVoyager (version 1.10, Brain Innovation). The first two functional volumes acquired from each run were removed for steady-state magnetization, and then, preprocessing steps were performed including slice scan time correction with cubic spline interpolation, 3D motion correction to the first volume of the remaining volumes in each run, 3D spatial smoothing with a 6 mm full width half maximum (FWHM) Gaussian kernel (i.e., twice the between-plane distance of 3.3 mm; Skuldarkski et al., 1999) and temporal filtering (high-pass filter with cutoff of two cycles/run and linear trend removal). For each participant, functional data were screened for motion artifacts exceeding 2 mm translation or 2° rotation by examining the motion correction plots of each functional run. Functional images were coregistered to the structural images. 3D structural images were normalized into standard Talairach space (Talairach & Tournoux, 1988) by aligning them first into the anterior commissure–posterior commissure (AC-PC) plane and then using trilinear interpolation to warp the structural images into Talairach coordinates. These parameters were then applied to the coregistered functional data.

2.6.3 | fMRI whole-brain mean activation analysis

After preprocessing the data, a random-effects multi-subject general linear model (RFX GLM) with separate participant predictors and Z-normalization was generated to localize significant differences in neural activity during the tasks. Functional data from all NS tasks were first subtracted from fixation (*main contrast*) to examine sensorimotor activation, and group-level statistical maps were generated at a threshold of $p < .01$, $t(17) = 2.90$, then corrected for multiple comparisons across the voxel population using a cluster threshold correction at $p < .05$ (yielding a cluster threshold of 10 contiguous voxels, as estimated by BrainVoyagers's Cluster-level Statistical Threshold Estimator at 1,000 iterations). Various contrast maps were produced to compare the four-letter NS tasks and two object NS tasks to examine whether there were significant differences in neural activity between the tasks after correction for multiple comparisons. These statistical contrast maps were superimposed on an average high-resolution 3D anatomical scan in Talairach space created from each participant's T1 scan. All contrasts were tested in both directions.

2.6.4 | fMRI region of interest (ROI) analyses

Six key regions of the left-hemisphere reading network were selected from the *main contrast* as the 125 contiguous voxels (5 × 5 × 5) within a cubic cluster centered on the point of peak activation: the inferior frontal gyrus, supramarginal gyrus, angular gyrus, middle temporal gyrus, superior temporal gyrus and fusiform gyrus. The ROIs were extracted from the *main contrast* to investigate how the pattern of signal in these key regions changes across the letter and object NS conditions, and how activation within these regions is correlated with the behavioral measures of the tasks.

2.7 | Statistical analysis

Statistical analysis of data was completed using SPSS Statistics v19.0 (IBM, Chicago, IL, USA). Paired samples Bonferroni-corrected t tests were conducted to compare the NS tasks with one another to examine whether performances on the task versions were significantly different from one another, and to examine whether there were task differences in behavioral performance and neural activation between the overt and covert sessions. Separate analyses were conducted for NS performance (NS efficiency), NS components (articulation and pause times), eye movement measures (fixation durations, and number of saccades and regressions) and beta weight values (GLM parameter estimates) for comparisons described in the Results and figure legends. Bivariate correlations were further conducted to describe the relationships between the dependent variables. The significance levels of all correlations were corrected by dividing alpha (0.05) by the number of unique correlations in each analysis.

3 | RESULTS

To examine the neural and cognitive processes that underlie NS tasks, we first examined differences in behavioral performance during the overt and covert sessions between alphanumeric and non-alphanumeric stimuli, and the effects of stimulus composition had on these tasks. We next examined whether those behavioral differences were also reflected at the neural level in regions involved in sensorimotor processing and the reading network.

3.1 | Behavioral task performance

We first examined the differences in behavioral performance during the overt session because this is the session which resembles previous studies and the only one in which all of the behavioral comparisons can be made. For the letter NS tasks, the combined visually and phonologically similar task (i.e., the VPS condition) had the greatest effect on performance: decreased NS efficiency (Figure 2a), increased number of errors (Figure 2b), longer articulation times (Figure 2c), pause times (Figure 2d), and fixation durations (Figure 2e), and more saccadic regressions (Figure 2f) (all $p's$ < .05; see Figure 2 for the few comparisons that were not significant). For the object NS tasks, there were significantly longer articulation times for the OC task (Figure 2c; $t(17) = 6.01$, $p < .001$, $r = 0.89$), but longer pause times for the OPS task (Figure 2d; $t(17) = 4.54$, $p < .001$, $r = 0.84$). There was also a significant difference between the letter and object NS tasks on all measures (all $p's$ < .001; Figure 2). None of these measures was possible during the covert session.

To simplify further analyses, composite scores for the letter and object NS tasks were computed for each of the constructs (efficiency, articulation and pause times, fixation durations, and saccade and regression counts) by averaging the z-scores for the individual tasks. These composite scores are justified by the high correlations for each construct across tasks. For the letter NS tasks, the correlations between NS efficiency scores ranged from 0.79 to 0.94, for articulation times from 0.78 to 0.94, for pause times from 0.69 to 0.90, for fixation duration from 0.75 to 0.95, for saccade count 0.64 to 0.85 and for regression count from 0.55 to 0.81. For the object NS tasks, the correlations between NS efficiency scores were 0.78, 0.89 for articulation times, 0.84 for pause times, 0.94 for fixation duration, 0.79 for saccade count and 0.83 for regression count. All of these correlations were significant at the 0.05 level when correcting for the number of correlations for each construct; for the letter NS constructs, alpha was divided by four because there were four-letter NS tasks; for the object NS constructs, alpha was divided by two because there were two object NS tasks. These behavioral results replicate our previous behavioral studies analyzing these letter NS tasks outside of the magnet (Al Dahhan et al., 2014, 2017).

Lastly, we examined whether there were differences in eye movement performance during the covert session among the tasks and how performance differed compared to the overt session (descriptive statistics are in Table 2). Due to the lack of oral responses made during the covert session, the only behavioral measures that were obtained during this session were eye movement performance, specifically fixation duration and regression count. Paired samples t tests showed that similar to performance during the overt session, there was a significant difference between the letter and object NS tasks for fixation duration (Figure 2g) and regression count (Figure 2h) ($p < .05$). There were significant correlations between the overt and covert sessions among the individual NS tasks after correcting for multiple correlations by dividing alpha by six because there were six NS tasks; these ranged from 0.54 to 0.65 for fixation duration and 0.56 to 0.68 for regression count for the letter NS tasks ($p < .05$), and 0.57 for fixation duration and 0.62 for regression count for the object NS tasks ($p < .05$). Furthermore, paired

FIGURE 2   Effect of task version on task performance, NS components and eye movement measures. (a) Efficiency score on the NS tasks. (b) Errors in naming. (c) Average articulation time per trial. (d) Average pause time per trial. (e) Average fixation duration during overt naming. (f) Regression count during overt naming. (g) Average fixation duration during covert naming. (h) Regression count during covert naming. NS, naming speed task; LC, letters control NS task; PS, phonologically similar NS task; VS, visually similar NS task; VPS, visually and phonologically similar NS task; OC, object control NS task; OPS, phonologically similar object NS task. Blue bars represent performance on the letter NS tasks, and red bars represent performance on the object NS tasks. Stripped bars represent performance during the covert session. Standard errors are shown; *$p < .05$; **$p < .01$; ***$p < .001$ [Colour figure can be viewed at wileyonlinelibrary.com]
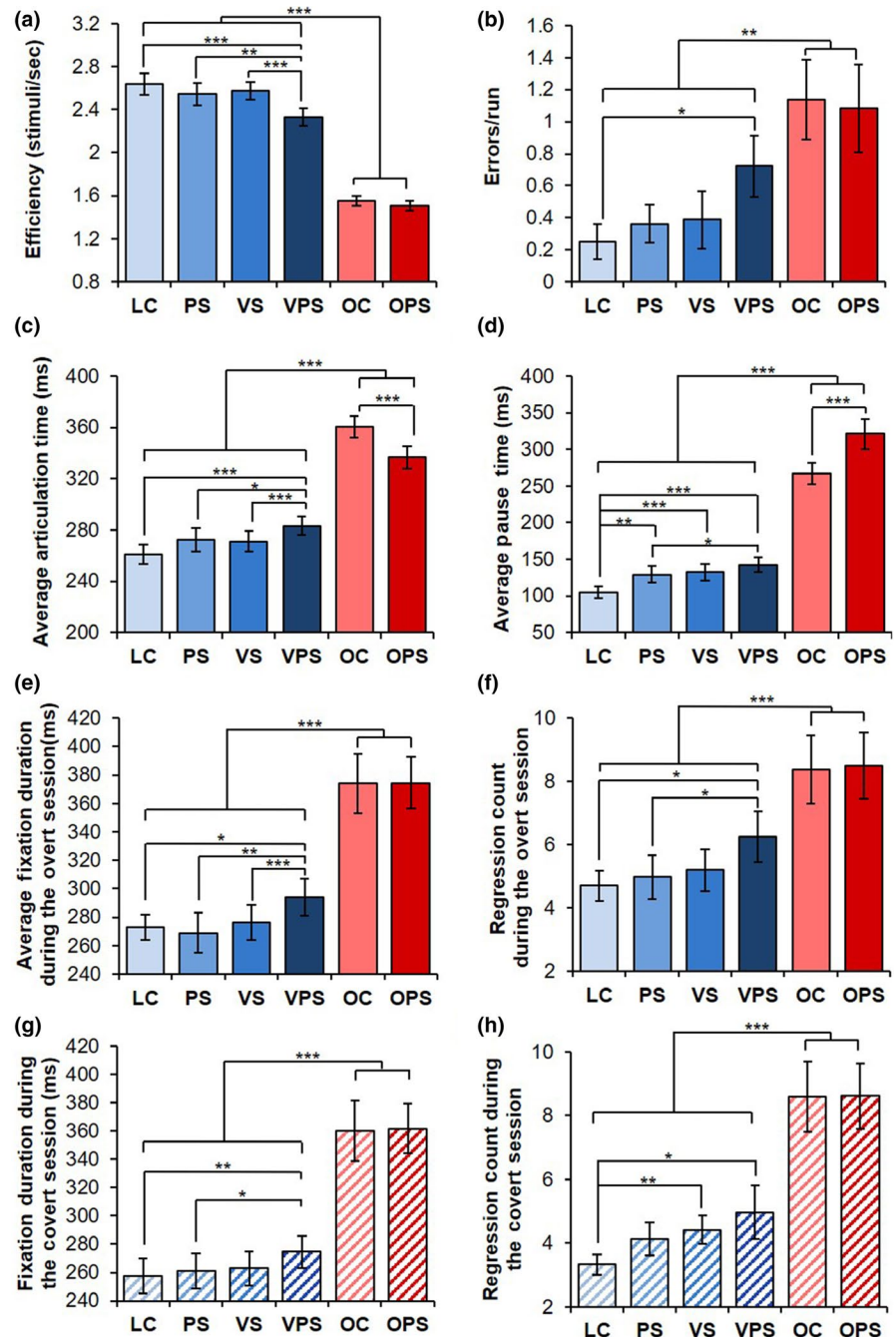
samples t tests showed that there were no significant differences in eye movement measures between the covert and overt sessions or when manipulating stimulus composition of the tasks (all $p's > .40$). These nonsignificant differences are consistent with the hypothesis that the covert and overt sessions were similar to one another with respect to eye tracking behavior.

3.2 | Neural activation during task performance

To examine the neural regions involved in the serial processing and naming of the stimuli, we first compared neural activations during all NS tasks with fixation (*main contrast*) during the overt and covert sessions to establish whether any differences found between the tasks were driven by differences in sensorimotor processes. After establishing an absence of differences between sessions in sensorimotor activation, and due to behavioral studies of NS using tasks which rely on spoken responses, we focus primarily on examining neural activity during the *overt* session. The NS tasks were contrasted with one another to examine the differences in neural activation between alphanumeric and non-alphanumeric NS tasks, and the effects of manipulating stimulus composition. Finally, the levels of activation in the identified regions were compared between the overt and covert sessions

TABLE 2 Descriptive statistics on eye movement measures during the overt and covert sessions

	M		SD	
	Overt	Covert	Overt	Covert
Letter NS tasks				
Fixation duration				
LC	272.98	257.63	37.20	51.78
PS	268.93	261.13	60.05	52.92
VS	276.14	263.10	52.10	51.06
VPS	294.34	274.67	55.21	48.45
Regression count				
LC	4.69	3.28	1.99	1.40
PS	4.97	4.14	2.93	2.18
VS	5.19	4.42	2.83	1.86
VPS	6.25	4.97	3.41	3.51
Saccade count				
LC	60.97	56.47	10.15	8.54
PS	61.22	58.31	8.94	11.87
VS	61.39	57.39	7.94	9.56
VPS	63.08	57.85	9.07	10.59
Object NS tasks				
Fixation duration				
OC	374.06	359.97	89.17	89.57
OPS	374.56	361.62	77.46	73.91
Regression count				
OC	8.36	8.58	4.58	4.70
OPS	8.50	8.61	4.46	4.35
Saccade count				
OC	72.72	57.62	13.53	10.04
OPS	73.56	57.73	12.88	10.31

Abbreviations: NS, naming speed; LC, letters control NS task; PS, phonologically similar NS task; VS, visually similar NS task; VPS, visually and phonologically similar NS task; OC, object control NS task; OPS, phonologically similar object NS task. $N = 18$.

to ensure that these results were not driven by false positives associated with spurious factors such as motion artifacts.

3.2.1 | Sensorimotor activation

An initial RFX GLM contrast of all NS tasks with fixation (*main contrast*) was conducted to confirm that participants recruited the key sensorimotor regions involved during the serial processing and naming of letters and objects during each session (e.g., data shown for the *overt* session in Figure 3 & Table 3). For both sessions, compared to fixation, activation across NS tasks was significantly greater in key oculomotor regions that are involved in saccade control, such as the FEF, SEF, PEF, DLPFC, ACC and the CN (Alahyane, Brien, Coe, Stroman, &

Munoz, 2014; Brown et al., 2007; Connolly et al., 2005, 2002; Ford et al., 2005); key speech areas, such as the inferior frontal gyrus, insula and primary motor cortex (Guenther et al., 2006); and key visual regions that are involved in reading along the ventral visual pathway, such as the cuneus, lingual gyrus and the fusiform gyrus (Indefrey & Levelt, 2004; Price, 2012). To ensure that a specific NS task was not driving these findings, we subsequently contrasted each task with fixation and found similar results. Furthermore, paired samples *t* tests revealed that within these regions, there was no significant difference in BOLD activation between the tasks (Figure 4, all *ps* > .30), indicating that the results are consistent with the hypothesis that these regions were recruited similarly across the tasks. Lastly, there was no significant difference in sensorimotor activation between the overt and covert sessions (all *ps* > .50), except for the insula and the primary motor cortex which are regions involved in the motor aspects of speech production (compare solid vs. striped bars in Figure 4, *p* < .01). Overall, these non-significant differences are consistent with the hypothesis that the covert and overt sessions were similar to one another in neural activation related to sensorimotor processing, except for areas involved in speech production. We next compared activation in the reading network to assess whether there were task and/or session differences.

3.2.2 | Comparison of neural activation between control letter and object naming speed tasks

Having confirmed that there was similar sensorimotor activation across all NS tasks (Figure 4), and all NS tasks activated key regions involved in the reading network (Figure 3), including temporoparietal areas, inferior frontal cortex, and the ventral visual stream, we next contrasted the LC and OC tasks during the overt session with one another to examine the differences in neural activation between alphanumeric and non-alphanumeric stimuli (Figure 5 & Table 3). This contrast revealed that there was significantly greater activation within key regions of the reading network for the LC task (Figure 5 "hot" colors) than the OC task in the left-hemisphere supramarginal gyrus, angular gyrus, middle temporal gyrus and superior temporal gyrus (*p* < .05). For the OC task, there was significantly greater activation (Figure 5 "cold" colors) for the inferior frontal gyrus, bilateral fusiform gyrus and bilateral middle occipital gyrus (*p* < .05).

3.2.3 | Neural activation during letter naming speed tasks

Activation in each of the letter NS tasks in the overt session was compared to activation in the LC task to examine whether
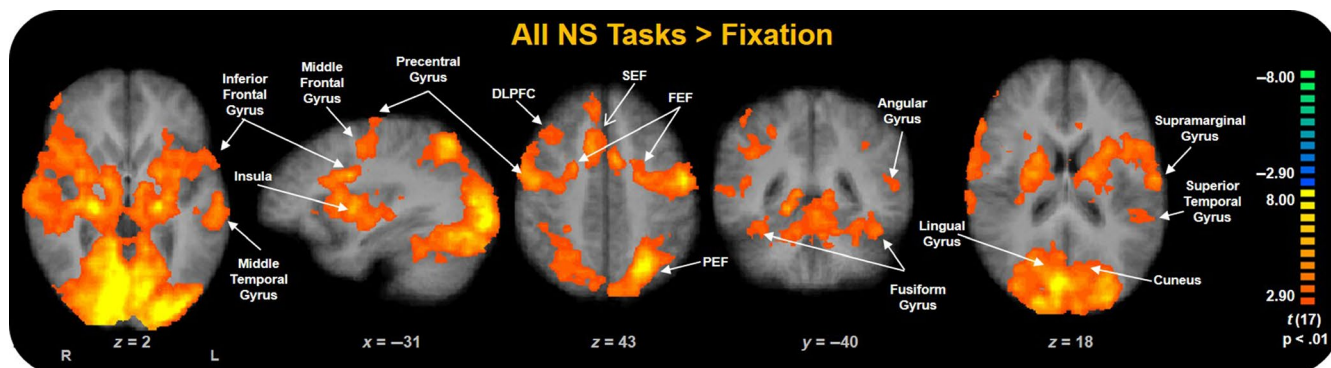
FIGURE 3 Sensorimotor activation during task performance. Contrast map of all NS tasks subtracted from fixation during the overt session, cluster size corrected at $p < .05$ (10 contiguous voxels). Significant BOLD activations were observed in all ROIs ("hot" colors) in key sensorimotor areas that are involved during the serial processing and naming of letters and objects as well as key regions involved in the reading network, and are labeled. Coordinate values of planes in Talairach space are indicated. NS, naming speed; DLPFC, dorsolateral prefrontal cortex; FEF, frontal eye fields; SEF, supplementary eye field; PEF, parietal eye field [Colour figure can be viewed at wileyonlinelibrary.com]

neural processes were differentially associated with each task (PS vs. LC, VS vs. LC, VPS vs. LC; Figure 6, Table 3). These contrasts revealed that the inferior frontal gyrus and fusiform gyrus were significantly more activated for all three manipulation tasks compared to the LC task; the middle temporal gyrus, supramarginal gyrus and angular gyrus were significantly more activated for the VS and VPS tasks than the LC task; and the superior temporal gyrus was significantly more activated for the VPS task than for the LC task ($p < .05$).

To further investigate the neural processes that were differentially associated with each letter NS task, the PS, VS and VPS conditions were contrasted with one another (VS vs. PS, VPS vs. PS, VPS vs. VS; Figure 6, Table 3). These contrasts indicated that the anterior cingulate, posterior cingulate and precuneus were significantly more activated for the VS task than the PS and VPS tasks ($p < .05$), and the inferior frontal gyrus, superior temporal gyrus, supramarginal gyrus, angular gyrus and middle temporal gyrus were significantly more activated for the VPS task than the PS and VS tasks ($p < .05$). Overall, these results indicate that activation increases with task difficulty (i.e., stimulus similarity), and visual similarity led to a greater increase in activation than phonological similarity.

3.2.4 | Neural activation during object naming speed tasks

The OPS and OC tasks in the overt session were contrasted with one another to examine whether there were different processes associated with each task (Figure 7, Table 3). These contrasts revealed that the superior temporal gyrus, middle temporal gyrus, precuneus and posterior cingulate were significantly more activated for the OPS task ($p < .05$), whereas there was significantly greater bilateral activation in the fusiform gyrus and the middle occipital gyrus for the OC task ($p < .05$).

3.3 | Effect of stimulus manipulations on activation in the reading network

The direct task comparisons performed above revealed that key regions of the reading network (inferior frontal gyrus, superior and middle temporal gyri, supramarginal gyrus, angular gyrus, and fusiform gyrus) were differentially activated during the NS tasks. To further investigate the activation differences among the NS tasks and examine how activation within these regions was correlated with behavioral performance during the tasks, we extracted beta weights from each of these regions in the overt session using the *main contrast* and then performed paired samples *t* tests on the averages of the mean beta weights of the four-letter NS tasks and the two object NS tasks (Figure 8). There was significantly greater activation during the letter NS tasks in the superior temporal gyrus and middle temporal gyrus, and significantly lower activation in the right fusiform gyrus, than in the object NS tasks ($p < .05$; Figure 8).

We next examined how activation was affected by the different stimulus manipulations. For the letter NS tasks, there was significantly greater activation for each of the ROIs when the letters were both visually and phonologically similar to one another (all $ps < 0.05$), except for the left fusiform gyrus, in which the conditions did not differ ($p > .05$). Paired samples *t* tests showed that the two object naming tasks only differed in the right fusiform gyrus in which there was greater activation during the OC task than the OPS task ($p < .01$).

3.4 | Relationship between neural activation and behavior

We next examined the relationships between the neural activation and behavioral measures. For the letter NS tasks, greater activation in the angular gyrus and the superior

TABLE 3 Talairach coordinates of peak activations for each of the contrasts during the overt session

Contrast	Brain Areas	Talairach Coordinates			T value	Volume of cluster (voxels)
		x	y	z		
Letter and Object NS Tasks > Fixation (main contrast)	LH middle frontal gyrus	−31	−11	53	3.59	744
	Supplementary eye fields	−3	−4	54	4.86	900
	RH frontal eye fields	21	−2	43	4.00	699
	LH frontal eye fields	−21	−5	43	3.64	513
	RH parietal eye fields	18	−69	43	3.78	972
	LH parietal eye fields	−19	−67	43	5.73	993
	RH dorsolateral prefrontal cortex	36	22	43	3.24	284
	LH inferior frontal gyrus	−52	11	2	3.91	900
	RH insula	31	10	7	4.57	996
	LH insula	−31	10	7	3.92	978
	RH precentral gyrus	48	−9	43	4.45	742
	LH precentral gyrus	−50	−10	43	3.50	544
	RH fusiform gyrus	36	−40	−18	3.81	899
	LH fusiform gyrus	−40	−40	−15	3.59	532
	RH lingual gyrus	10	−60	−5	5.73	1,000
	LH lingual gyrus	−11	−63	−5	5.09	1,000
	RH cuneus	10	−60	18	3.38	637
	LH cuneus	−12	−62	18	7.13	1,000
	LH supramarginal gyrus	−58	−15	18	4.16	762
	LH angular gyrus	−49	−40	12	3.44	445
	LH middle temporal gyrus	−58	−33	2	4.43	644
	LH superior temporal gyrus	−50	−35	18	3.85	597
LC > OC	LH inferior frontal gyrus	−39	13	30	−2.53	359
	LH superior temporal gyrus	−36	−38	17	2.69	708
	LH middle temporal gyrus	−58	−38	−5	2.67	554
	LH supramarginal gyrus	−51	−23	30	2.60	506
	LH angular gyrus	−42	−55	30	2.66	532
	LH fusiform gyrus	−30	−38	−14	−3.04	628
	RH fusiform gyrus	28	−38	−12	−3.24	736
	LH middle occipital gyrus	−31	−90	7	−3.60	990
	RH middle occipital gyrus	26	−95	7	−3.07	495
PS > LC	LH inferior frontal gyrus	−51	11	4	2.36	321
	LH fusiform gyrus	−30	−38	−18	2.04	161
VS > LC	LH inferior frontal gyrus	−50	12	8	2.52	251
	LH fusiform gyrus	−26	−34	−31	2.73	369
	LH middle temporal gyrus	−41	−55	10	2.41	351
	LH supramarginal gyrus	−34	−36	39	2.86	435
	LH angular gyrus	−47	−46	39	2.83	342
VPS > LC	LH inferior frontal gyrus	−52	9	8	2.84	591
	LH fusiform gyrus	−35	−58	−10	2.59	297

(Continues)

TABLE 3 (Continued)

Contrast	Brain Areas	Talairach Coordinates			T value	Volume of cluster (voxels)
		x	y	z		
	LH middle temporal gyrus	−40	−58	8	2.12	528
	LH superior temporal gyrus	−50	5	3	2.59	256
	LH supramarginal gyrus	−60	−23	25	2.54	453
	LH angular gyrus	−32	−61	36	2.22	139
VS > PS	LH precuneus	−4	−66	28	2.65	466
	LH posterior cingulate	−3	−16	37	2.40	175
VPS > PS	LH superior temporal gyrus	−38	−31	22	2.47	347
	LH supramarginal gyrus	−34	−38	42	2.64	693
	LH angular gyrus	−50	−47	42	2.56	365
	LH middle temporal gyrus	−38	−58	13	2.52	284
VPS > VS	LH inferior frontal gyrus	−44	3	28	2.40	158
	LH anterior cingulate	−1	21	27	−2.87	543
OPS > OC	LH superior temporal gyrus	−50	1	−8	2.90	498
	LH middle temporal gyrus	−52	1	−10	2.95	703
	LH middle occipital gyrus	−27	−93	3	−2.91	890
	RH middle occipital gyrus	17	−91	3	−3.10	646
	LH fusiform gyrus	−28	−55	−9	−2.61	641
	RH fusiform gyrus	27	−55	−10	−2.73	664
	LH posterior cingulate	−6	−32	19	2.72	413
	LH precuneus	−6	−55	25	2.85	838

Note: Talairach coordinates and numbers of voxels have been averaged across participants.

Abbreviations: LH, left hemisphere; RH, right hemisphere; LC, letters control NS task; OC, objects control NS task; PS, phonologically similar NS task; VS, visually similar NS task; VPS, visually and phonologically similar NS task; OPS, phonologically similar object NS task.

temporal gyrus was associated with decreased NS efficiency, and longer articulation times and fixation durations, but these patterns were not significant after correcting for multiple correlations (in this case, alpha was divided by six because each behavioral measure was correlated with six neural areas). A similar approach was taken for the object NS measures (see bottom panel of Table 4), showing greater activation in the angular gyrus, middle temporal gyrus and superior temporal gyrus associated with longer fixation durations, but these patterns were also not significant after correcting for multiple correlations (again alpha was divided by six because of the six neural areas correlated with each behavioral measure).

3.5 | Comparison between covert and overt naming speed performance

Due to the possibility that the overt task could potentially lead to false positives in activation maps due to movement (Soltysik & Hyde, 2006), we examined whether beta weight activations in the reading network ROIs were correlated between the overt and covert sessions and whether they were significantly different from one another. There were

significant correlations for all reading network ROIs between the overt and covert sessions among the individual letter and object NS tasks after correcting for multiple comparisons (all $p's < .01$; alpha was divided by six because of the six ROIs; rs ranged from 0.68 to 0.97). Furthermore, paired samples t tests indicated that there were no significant differences in these regions between the two sessions (Figure 8; all $ps > .50$), indicating that the overt session results were not driven by false positives caused by spurious factors such as motion artifacts.

4 | DISCUSSION

Despite previous research identifying the left-hemisphere reading network and showing differences in neural activity between alphanumeric and non-alphanumeric NS tasks (Cummine et al., 2015, 2014; Misra et al., 2004), researchers have yet to examine how this network changes with various stimulus manipulations. To address these important gaps in the literature and to build upon the existing work conducted, we combined fMRI with eye tracking and speech recording in average adult readers to examine
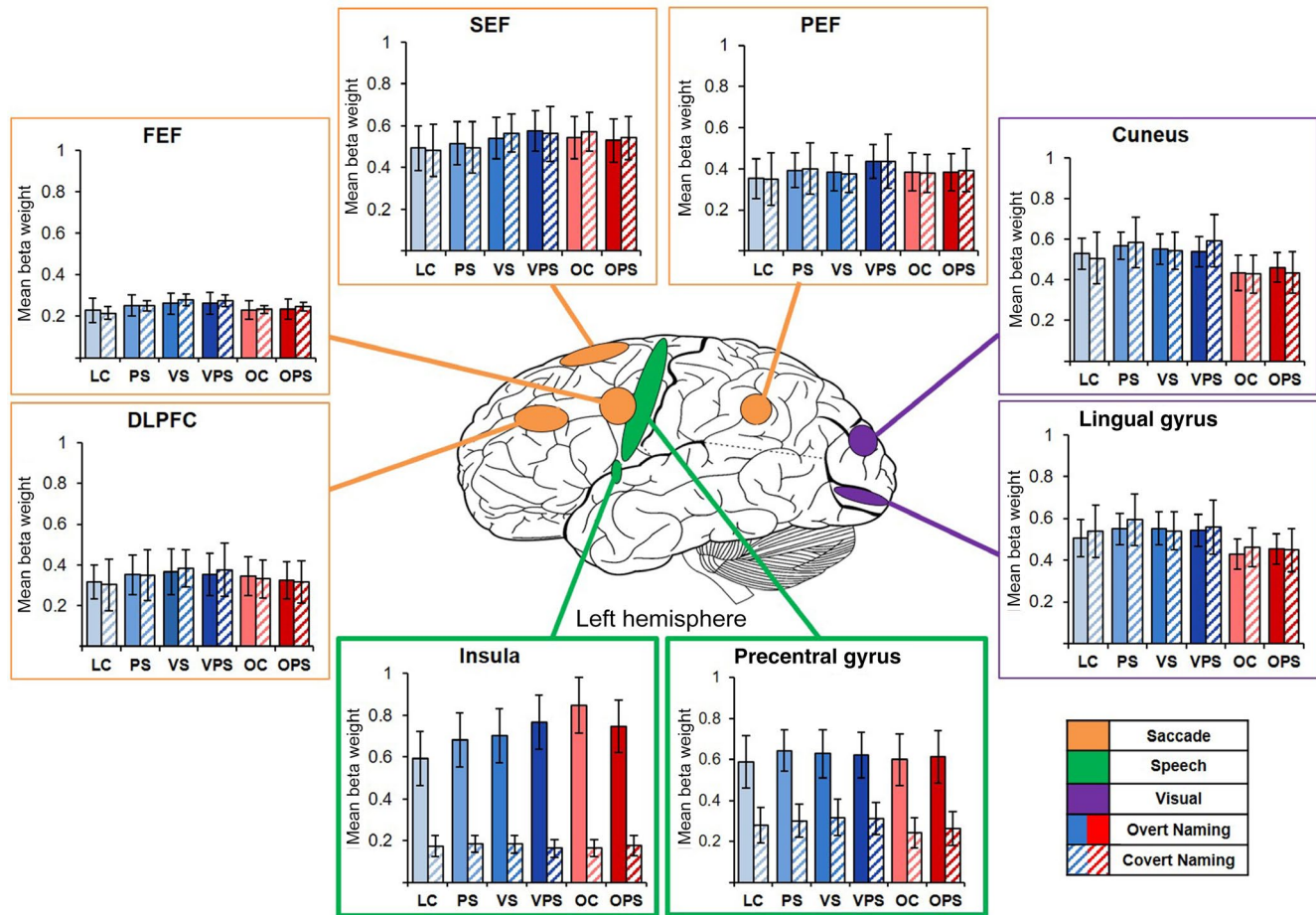
FIGURE 4 Comparisons of sensorimotor activation among the NS tasks. NS, naming speed task; LC, letters control NS task; PS, phonologically similar NS task; VS, visually similar NS task; VPS, visually and phonologically similar NS task; OC, object control NS task; OPS, phonologically similar object NS task; DLPFC, dorsolateral prefrontal cortex; FEF, frontal eye fields; SEF, supplementary eye field; PEF, parietal eye field. Blue bars represent performance on the letter NS tasks, and red bars represent performance on the object NS tasks. Stripped bars represent performance during the covert session. Standard errors are shown [Colour figure can be viewed at wileyonlinelibrary.com]
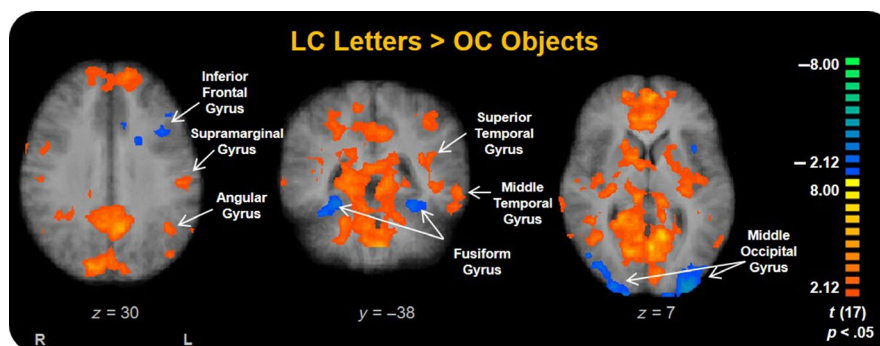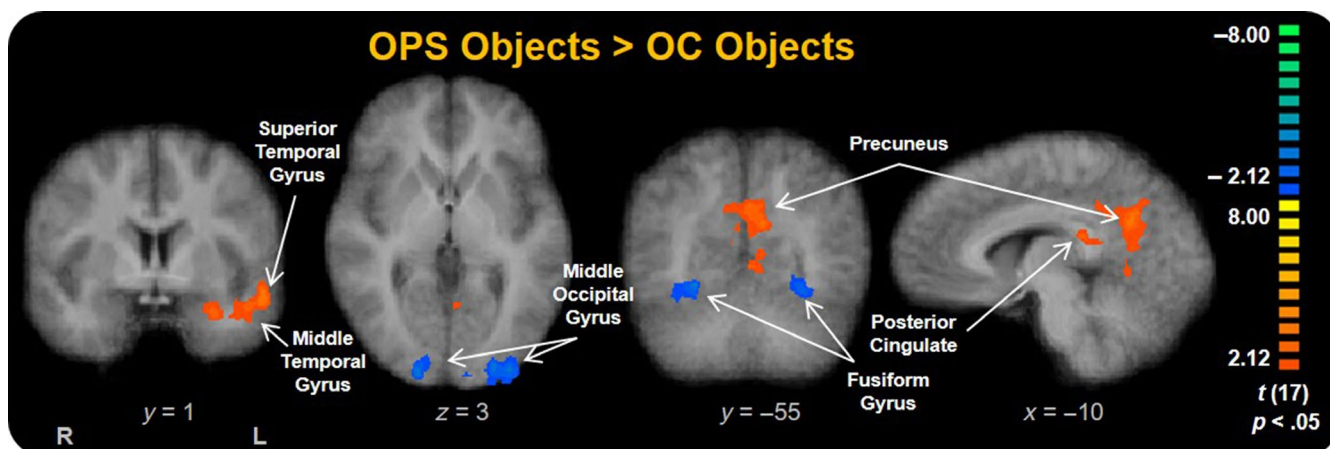

FIGURE 5 Comparison between letter and object control NS tasks. Contrast map of letter control (LC) NS task and object control (OC) NS task during the overt session, cluster size corrected at $p < .05$ (10 contiguous voxels). Significantly greater BOLD activation is shown for the LC task ("hot" colors) and OC task ("cold" colors) as labeled. Coordinate values of planes in Talairach space are indicated [Colour figure can be viewed at wileyonlinelibrary.com]

how manipulating stimulus composition of these NS tasks, to make the stimuli either visually and/or phonologically similar to one another, affected performance. There were no significant differences between the overt and covert sessions in behavioral performance (Figure 2 E and F vs. G and H), sensorimotor activation (except for regions involved in the motor aspects of speech production; Figure 4), or BOLD activation in key regions of the left-hemisphere reading network (Figure 8). This established that the differences found between the tasks in the overt session within
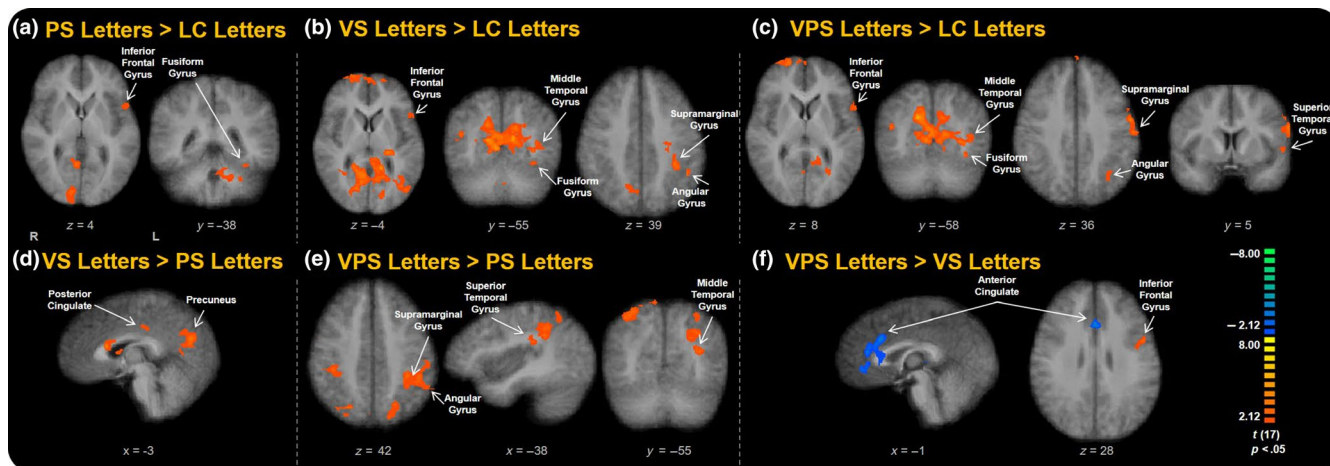
FIGURE 6 Neural activation specific to letter naming. (a) Contrast of PS letters subtracted from LC letters. (b) Contrast of VS letters subtracted from LC letters. (c) Contrast of VPS letters subtracted from LC letters. (d) Contrast of VS letters subtracted from PS letters. (e) Contrast of VPS letters subtracted from PS letters. (f) Contrast of VPS letters subtracted from VS letters. These contrast maps were obtained from the overt session, and each map has a cluster size corrected at $p < .05$ (10 contiguous voxels). ROIs are labeled, with significant BOLD activations shown as "hot" colors. Coordinate values of planes in Talairach space are indicated. NS, naming speed task; LC, letters control NS task; PS, phonologically similar NS task; VS, visually similar NS task; VPS, visually and phonologically similar NS task [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 Neural activation specific to object naming. Contrast map of phonologically similar object (OPS) NS task and object control (OC) NS task during the overt session, cluster size corrected at $p < .05$ (10 contiguous voxels). Significantly greater BOLD activation is shown for the OPS task ("hot" colors) and OC task ("cold" colors) as labeled. Coordinate values of planes in Talairach space are indicated [Colour figure can be viewed at wileyonlinelibrary.com]

the reading network were not due to speech production motion artifacts. Within the reading network, there was overall greater activation for the letter NS tasks than the object NS tasks (Figure 8), and activation in the temporoparietal areas of this network varied by task difficulty. These results help to further unravel the neural and cognitive processes that are involved during reading, and how these processes differ between alphanumeric and non-alphanumeric stimuli and with specific stimulus manipulations.

4.1 | Neural mechanisms of rapid naming

The pattern of neural activation obtained during NS tasks was consistent across key regions involved in the reading network

that are involved in speech production (Figure 3): anterior cingulate cortex (speech monitoring; Chang, Kenney, Loucks, Poletto, & Ludlow, 2009; Christoffels, Formisano, & Schiller, 2007; Guenther & Vladusich, 2012), motor cortex (timing and initiating motor output; He et al., 2013), supplementary motor association cortex (articulation; Alario, Chainay, Lehericy, & Cohen, 2006; Brown et al., 2009), supramarginal gyrus (somatosensory maps and grapheme–phoneme mapping; Stoeckel, Gough, Watkins, & Devlin, 2009) and middle temporal gyrus (semantic access; Graves, Desai, Humphries, Seidenberg, & Binder, 2010; Rapcsak & Beeson, 2004; Whitney, Kirk, O'Sullivan, Ralph, & Jefferies, 2010). Rapid serial naming of the letters and objects also resulted in significant activation of the frontal eye fields, which reflects the voluntary saccadic eye movements needed to perform the
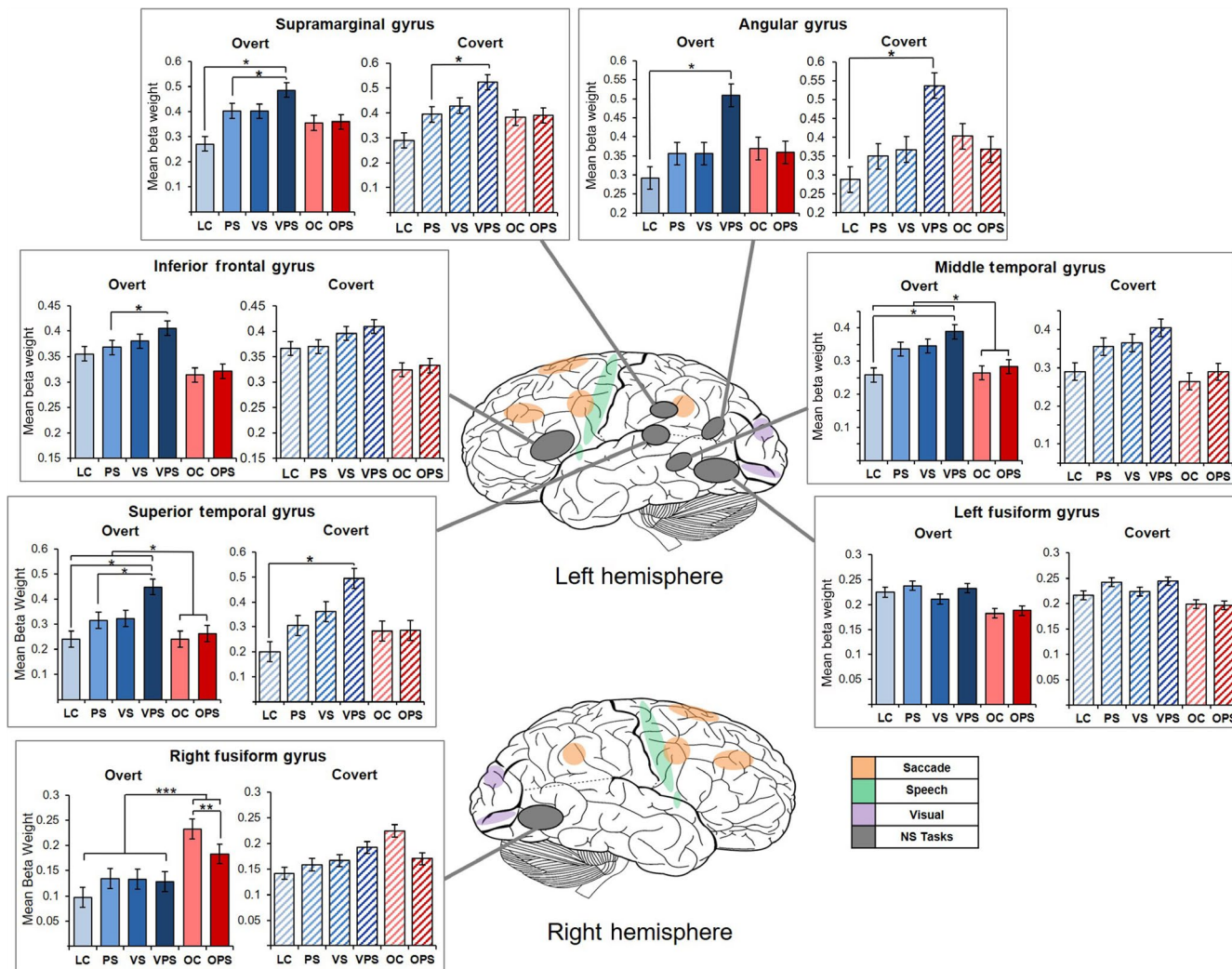
FIGURE 8 Effect of stimulus manipulations on BOLD activation in the reading network. Beta weights were extracted from 125 cubic voxels surrounding the peak activations in regions displaying greater activation during all NS tasks compared to fixation (*main contrast*). NS, naming speed task; LC, letters control NS task; PS, phonologically similar NS task; VS, visually similar NS task; VPS, visually and phonologically similar NS task; OC, object control NS task; OPS, phonologically similar object NS task. Blue bars represent performance on the letter NS tasks, and red bars represent performance on the object NS tasks. Stripped bars represent performance during the covert session. Standard errors are shown; * $p < .05$; **$p < .01$; ***$p < .001$ [Colour figure can be viewed at wileyonlinelibrary.com]

task, as well as the basal ganglia, which reflects the automaticity that is required during these NS tasks (Misra et al., 2004; Poldrack & Gabrieli, 2001). However, even though the NS tasks activated key regions of the reading network, the magnitude of this activation differed between the tasks (Figure 8).

4.2 | Differences in performance between alphanumeric and non-alphanumeric stimuli

Behavioral measures showed that letter naming performance was significantly better than object naming performance. Participants were more efficient, made fewer errors and regressions, and had shorter articulation times, pause times and fixation durations during the letter NS tasks than the object

NS tasks indicating the automaticity that is associated with letter NS tasks (Figure 2). These behavioral differences were further reflected in greater activation within the reading network for the letter NS tasks (Figure 8), suggesting that the reading network is specific to letter stimuli and explains why alphanumeric NS is a better predictor of reading that non-alphanumeric stimuli (Kirby et al., 2010).

There was a significant difference in BOLD activation between letters and objects in the right fusiform gyrus, the middle temporal gyrus and the superior temporal gyrus (Figure 8), with more activation for objects in the right fusiform gyrus and more activation for letters in the left middle and superior temporal gyrus. There was no significant difference in BOLD activation among the letter and the object conditions in the left fusiform gyrus (Figure 8). This suggests that the left fusiform gyrus is not specific to linguistic stimuli but instead processes general

TABLE 4 Correlations between regions of interest and behavior during the overt session

	1.	2.	3.	4.	5.	6.
1. Inferior frontal gyrus	–					
2. Left Fusiform gyrus	0.58	–				
3. Supramarginal gyrus	0.69*	0.77*	–			
4. Angular gyrus	0.57	0.67*	0.81*	–		
5. Middle temporal gyrus	0.54	0.49	0.68*	0.56	–	
6. Superior temporal gyrus	0.57	0.67*	0.79*	0.99*	0.56	–
Letter NS tasks						
NS efficiency	−0.22	−0.28	−0.35	−0.56	−0.06	−0.58
Articulation time	0.32	0.39	0.42	0.58	0.05	0.58
Pause time	−0.02	0.00	0.18	0.38	0.04	0.42
Fixation duration	0.18	0.16	0.21	0.48	−0.14	0.52
Saccade count	0.12	0.17	0.28	0.25	0.30	0.27
Regression count	0.24	0.08	0.27	0.01	−0.09	0.03
Object NS tasks						
NS efficiency	−0.26	0.06	−0.03	−0.16	−0.16	−0.16
Articulation time	0.09	−0.04	−0.07	0.19	0.22	0.18
Pause time	0.15	−0.00	−0.03	0.08	0.07	0.11
Fixation duration	0.31	0.11	−0.10	0.44	0.52	0.47
Saccade count	0.22	−0.07	0.00	−0.08	−0.01	−0.08
Regression count	−0.16	−0.12	0.00	−0.20	−0.08	−0.16

Abbreviations: NS, naming speed. $N = 18$.

*Significant at $p < .05$ (adjusted for multiple correlations).

visual objects, with the right fusiform gyrus being more specific to pictures/objects (Cohen et al., 2002; Dehaene, Clec, Poline, Bihan, & Cohen, 2002; Devlin, Jamison, Gonnerman, & Matthews, 2006; Pernet, Celsis, & Demonet, 2005; Price & Friston, 2005; Xue, Chen, Jin, & Dong, 2006). Current knowledge of the neural circuitry of overt word reading (Indefrey & Levelt, 2004; Jobard, Crivello, & Tzourio-Mazoyer, 2003; Price, 2012) allows us to hypothesize that the tasks began to differ from one another as information moved from the left fusiform gyrus to the left middle temporal gyrus and left superior temporal gyrus, indicating the key role these regions play in the transition from visual to lexical-semantic to phonological processing (Carreiras, Armstrong, Perea, & Frost, 2014; Cattinelli, Borghese, Gallucci, & Paulesu, 2013; Indefrey & Levelt, 2004; Jobard et al., 2003; Taylor, Rastle, & Davis, 2013).

4.3 | Effect of task stimulus manipulations on performance

The letter and object NS tasks differentially activated the left-dominant neural reading network associated with phonological (inferior frontal gyrus, supramarginal gyrus and superior temporal gyrus; Dhanjal, Handunneththi, Patel, & Wise, 2008; Jobard et al., 2003; Joubert et al., 2004),

orthographic (fusiform gyrus and middle temporal gyrus; Bruno, Zumberge, Manis, Lu, & Goldman, 2008; Graves et al., 2010) and orthographic-to-phonological (inferior and superior parietal lobule; Guenther & Vladusich, 2012; Price, 2012) processing, but not articulatory/motor processing related to speech production (precentral gyrus, cerebellum and supplementary motor association cortex; Dhanjal et al., 2008; Guenther & Vladusich, 2012; Guenther et al., 2006; Price, 2010, 2012). This indicates that the speech production processes activated when participants are presented with visual stimuli are consistent, and not influenced by stimulus characteristics (Palmer et al., 2001), even when some stimuli have been made more phonologically similar.

For each of these regions within the reading network, there was greater BOLD activation and poorer naming and eye movement performance when the letters were both visually and phonologically similar to one another compared to the single letter manipulation conditions (Figure 8). This suggests that increasing the similarity between the letters within the matrix required greater attentional processing and speech monitoring to ensure accurate naming of the letters, which was reflected in the greater activation of the inferior parietal cortex, anterior cingulate, posterior cingulate and precuneus (Figure 6; Binder, Desai, Graves, & Conant, 2009; Chang et al., 2009; Christoffels et al., 2007; Guenther & Vladusich, 2012).

The only differences between the two object NS tasks were significantly longer pause times on the OPS task and longer articulation times in the OC task (Figure 2c,d). This indicates that greater visual and semantic processing is required to differentiate among the stimuli and prime the articulation of the phonologically similar words in the OPS task, reflected in the increased activation of the precuneus and posterior cingulate (Figure 7; Binder et al., 2009). This in turn increases the efficiency of articulatory recoding and the execution of speech motor commands.

4.4 | Relationship between neural activation and behavior

Greater activation in the angular gyrus and the superior temporal gyrus of the left hemisphere was associated with decreased NS efficiency and longer articulation times and fixation durations for the letter naming conditions, and longer fixation durations for the object conditions (Table 4), but these relationships were not significant after correcting alpha levels; these relationships are substantial enough to warrant investigation in larger studies. Furthermore, the present findings are consistent with NS component studies that have found variability in NS time becomes associated more strongly with articulation time than pause time as readers become more skilled (e.g., Georgiou, Papadopoulos, & Kaizer, 2014). As naming becomes more automatic, the preparation phase of reading, pause time, becomes shorter and much more likely to overlap with articulation processes; thus, participants' efficiency during a task becomes largely a function of how well they are able to coordinate these processes.

In terms of the eye movement parameters, longer fixation durations are associated with more effortful language processing (Engbert, Nuthmann, Richter, & Kliegl, 2005; Nuthmann & Henderson, 2012) and greater attentional focus (Rayner, 2009). Thus, fixation duration has been found to be related to activity in cortical regions associated with language processing, such as the superior temporal gyrus (Henderson, Choi, Luke, & Desai, 2015), and with oculomotor and attentional control, such as the intraparietal sulcus, frontal eye fields and supplementary eye fields (Poldrack & Gabrieli, 2001). There was a substantial negative relationship between fixation duration and activation in both the angular gyrus and the superior temporal gyrus for both letters and objects, which suggests that higher order language processes play a role in controlling fixation duration during NS task and reading (Table 4; Rayner, 2009; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003), but it should be noted that these relationships were not significant after correcting for multiple correlations. Studies with larger sample sizes will be needed to test these correlational relationships more convincingly.

4.5 | Limitations

Some limitations of the present study are worth mentioning. We acknowledge that due to the gender disparity of this study and participants being from a graduate student community, the sample is not as representative as it should be and identify this as a limitation to this study. However, this gender ratio is currently typical of the graduate departments from which these participants were recruited. Some substantial correlations were not significant after correcting alpha levels, raising the possibility that some true relationships have not been identified (i.e., type II error) due to sample size restrictions. Future studies should include larger sample sizes with balanced gender ratio and with participants having more typical reading ability.

5 | CONCLUSION

The design of this study allowed us to examine the processes that are involved during NS tasks, which are strongly related to reading. There were no differences in behavioral performance (Figure 2), sensorimotor activation (except for regions involved in the motor aspects of speech production; Figure 4) or activation in the reading network (Figure 8) between the overt and covert sessions. These findings validate the use of overt naming in fMRI studies and further expand the possibility of replicating findings of traditional behavioral studies that use overt naming tasks. More substantively, activation during the various NS tasks differed mainly based on the tasks' sensitivity to posterior cortical areas in the reading network involved in the processing and interpretation of orthographic information: The NS tasks differentially activated the temporoparietal regions of the reading network of the left hemisphere. More generally, combining fMRI with eye tracking and speech recording to examine the neural and cognitive accounts of reading during tasks such as NS furthers the understanding of the neural circuitry that is involved, and will allow researchers to examine how these processes change both during reading development and following interventions for individuals with reading difficulties, with the potential to lead to improved instructional practices.

CONFLICT OF INTEREST
The authors declare no competing financial interests.

AUTHOR CONTRIBUTIONS

NZA, JRK, DCB and DPM designed research; NZA performed research; NZA analyzed data; NZA, JRK, YC and DPM wrote the paper.

DATA AVAILABILITY STATEMENT

Data presented in this paper are available upon request.

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REFERENCES

Al Dahhan, N., Georgiou, G. K., Hung, R., Munoz, D., Parrila, R., & Kirby, J. R. (2014). Eye-movements of university students with and without reading difficulties during naming speed tasks. *Annals of Dyslexia*, *64*, 137–150. https://doi.org/10.1007/s11881-013-0090-z

Al Dahhan, N. Z., Kirby, J. R., Brien, D. C., & Munoz, D. P. (2017). Eye movements and articulations during a letter naming speed task: Children with and without dyslexia. *Journal of Learning Disabilities*, *50*, 275–285. https://doi.org/10.1177/0022219415618502

Al Dahhan, N. Z., Kirby, J. R., & Munoz, D. P. (2016). Understanding reading and reading difficulties through naming speed tasks: Bridging the gaps among neuroscience, cognition, and education. *AERA Open*, *2*, 1–15. https://doi.org/10.1177/2332858416675346

Alahyane, N., Brien, D. C., Coe, B. C., Stroman, P. W., & Munoz, D. P. (2014). Developmental improvements in voluntary control of behavior: Effect of preparation in the fronto-parietal network. *NeuroImage*, *98*, 103–117.

Alario, F.-X., Chainay, H., Lehericy, S., & Cohen, L. (2006). The role of the supplementary motor area (SMA) in word production. *Brain Research*, *1076*, 129–143. https://doi.org/10.1016/j.brainres.2005.11.104

Araújo, S., Inácio, F., Francisco, A., Faisca, L., Petersson, K. M., & Reis, A. (2011). Component processes subserving rapid automatized naming in dyslexia and non-dyslexic readers. *Dyslexia*, *17*, 242–255.

Araújo, S., Reis, A., Petersson, K. M., & Faísca, L. (2015). Rapid automatized naming and reading performance: A meta-analysis. *Journal of Educational Psychology*, *107*, 868–883. https://doi.org/10.1037/edu0000006

Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*, *19*, 2767–2796. https://doi.org/10.1093/cercor/bhp055

Borowsky, R., Cummine, J., Owen, W. J., Friesen, C. K., Shih, F., & Sarty, G. E. (2006). FMRI of ventral and dorsal processing streams in basic reading processes: Insular sensitivity to phonology. *Brain Topography*, *18*, 233–239. https://doi.org/10.1007/s10548-006-0001-2

Bowers, P. G. (1995). Tracking symbol naming speed's unique contributions to reading disability over time. *Reading and Writing*, *7*, 186–216.

Bowers, P. G., & Wolf, M. (1993). Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia. *Reading and Writing*, *5*, 69–85.

Bowey, J. A., McGuidan, M., & Ruschena, A. (2005). On the association between serial naming speed for letters and digits and word-reading skill: Towards a developmental account. *Journal of Research in Reading*, *28*, 400–422. https://doi.org/10.1111/j.1467-9817.2005.00278.x

Brown, M. R. G., Vilis, T., & Everling, S. (2007). Frontoparietal activation with preparation for antisaccades. *Journal of Neurophysiology*, *98*, 1751–1762. https://doi.org/10.1152/jn.00460.2007

Brown, S., Laird, A. R., Pfordresher, P. Q., Thelen, S. M., Turkeltaub, P., & Liotti, M. (2009). The somatotopy of speech: Phonation and articulation in the human motor cortex. *Brain and Cognition*, *70*, 31–41. https://doi.org/10.1016/j.bandc.2008.12.006

Bruno, J. L., Zumberge, A., Manis, F. R., Lu, Z.-L., & Goldman, J. G. (2008). Sensitivity to orthographic familiarity in the occipito-temporal region. *NeuroImage*, *39*, 1988–2001. https://doi.org/10.1016/j.neuroimage.2007.10.044

Carreiras, M., Armstrong, B. C., Perea, M., & Frost, R. (2014). The what, when, where, and how of visual word recognition. *Trends in Cognitive Sciences*, *18*, 90–98. https://doi.org/10.1016/j.tics.2013.11.005

Cattinelli, I., Borghese, N. A., Gallucci, M., & Paulesu, E. (2013). Reading the reading brain: A new meta-analysis of functional imaging data on reading. *Journal of Neurolinguistics*, *26*, 214–238. https://doi.org/10.1016/j.jneuroling.2012.08.001

Chang, S.-E., Kenney, M. K., Loucks, T. M. J., Poletto, C. J., & Ludlow, C. L. (2009). Common neural substrates support speech and non-speech vocal tract gestures. *NeuroImage*, *47*, 314–325. https://doi.org/10.1016/j.neuroimage.2009.03.032

Christoffels, I. K., Formisano, E., & Schiller, N. O. (2007). Neural correlates of verbal feedback processing: An fMRI study employing overt speech. *Human Brain Mapping*, *28*, 868–879. https://doi.org/10.1002/hbm.20315

Clarke, P., Hulme, C., & Snowling, M. J. (2005). Individual differences in RAN and reading: A response timing analysis. *Journal of Learning Disabilities*, *28*, 73–86.

Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., & Montavont, A. (2008). Reading normal and degraded words: Contribution of the dorsal and ventral visual pathways. *NeuroImage*, *40*, 353–366. https://doi.org/10.1016/j.neuroimage.2007.11.036

Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex? Functional properties of the visual word form area. *Brain*, *125*, 1054–1069. https://doi.org/10.1093/brain/awf094

Compton, D. L. (2003). The influence of item composition on RAN letter performance in first-grade children. *The Journal of Special Education*, *37*, 81–94. https://doi.org/10.1177/00224669030370020301

Connolly, J. D., Goodale, M. A., Goltz, H. C., & Munoz, D. P. (2005). fMRI activation in the human frontal eye field is correlated with saccadic reaction time. *Journal of Neurophysiology*, *94*, 605–611. https://doi.org/10.1152/jn.00830.2004

Connolly, J. D., Goodale, M. A., Menon, R. S., & Munoz, D. P. (2002). Human fMRI evidence for the neural correlates of preparatory set. *Nature Neuroscience*, *5*, 1345–1352. https://doi.org/10.1038/nn969

Cronin, V., & Carver, P. (1998). Phonological sensitivity, rapid naming, and beginning reading. *Applied Psycholinguistics*, *19*, 447–461. https://doi.org/10.1017/S0142716400010262

Cummine, J., Chouinard, B., Szepesvari, E., & Georgiou, G. K. (2015). An examination of the rapid automatized naming-reading

relationship using functional magnetic resonance imaging. *Neuroscience*, *305*, 49–66. https://doi.org/10.1016/j.neuroscience.2015.07.071

Cummine, J., Cribben, I., Luu, C., Kim, E., Bakhtiari, R., Georgiou, G., & Boliek, C. A. (2016). Understanding the role of speech production in reading: Evidence for a print-to-speech neural network using graphical analysis. *Neuropsychology*, *30*, 385–397. https://doi.org/10.1037/neu0000236

Cummine, J., Gould, L., Zhou, C., Siddiqi, Z., Hrybouski, S., Chouinard, B., & Borowsky, R. (2013). Varying reliance on visual processing streams as a function of task demands in reading aloud. *Brain and Language*, *125*, 203–214.

Cummine, J., Szepesvari, E., Chouinard, B., Hanif, W., & Georgiou, G. K. (2014). A functional investigation of RAN letters, digits, and objects: How similar are they? *Behavioural Brain Research*, *275*, 157–165. https://doi.org/10.1016/j.bbr.2014.08.038

Cutting, L. E., & Denckla, M. B. (2001). The relationship of rapid serial naming and word reading in normally developing readers: An exploratory model. *Reading and Writing*, *14*, 673–705.

Dehaene, S., Le Clec, H. G., Poline, J. B., Le Bihan, D., & Cohen, L. (2002). The visual word form area: A prelexical representation of visual words in the fusiform gyrus. *NeuroReport*, *13*, 321–325. https://doi.org/10.1097/00001756-200203040-00015

Denckla, M. B., & Rudel, R. G. (1976). Rapid 'automatized' naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, *14*, 471–479. https://doi.org/10.1016/0028-3932(76)90075-0

Devlin, J. T., Jamison, H. L., Gonnerman, L. M., & Matthews, P. M. (2006). The role of the posterior fusiform gyrus in reading. *Journal of Cognitive Neuroscience*, *18*, 911–922. https://doi.org/10.1162/jocn.2006.18.6.911

Dhanjal, N., Handunneththi, L., Patel, M. C., & Wise, R. J. S. (2008). Perceptual systems controlling speech production. *Journal of Neuroscience*, *28*, 9969–9975. https://doi.org/10.1523/JNEUROSCI.2607-08.2008

Di Filippo, G., Brizzolara, D., Chilosi, A., De Luca, M., Judica, A., Pecini, C., … Zoccolotti, P. (2005). Rapid naming, not cancellation speed or articulation rate, predicts reading in an orthographically regular language (Italian). *Child Neuropsychology*, *11*, 349–361. https://doi.org/10.1080/09297040490916947

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review*, *112*, 777–813. https://doi.org/10.1037/0033-295X.112.4.777

Ford, K. A., Goltz, H. C., Brown, M. R. G., & Everling, S. (2005). Neural processes associated with antisaccade task performance investigated with event-related fMRI. *Journal of Neurophysiology*, *94*, 429–440. https://doi.org/10.1152/jn.00471.2004

Georgiou, G. K., Papadopoulos, T. C., & Kaizer, E. L. (2014). Different RAN components relate to reading at different points in time. *Reading and Writing*, *27*, 1–16. https://doi.org/10.1007/s11145-014-9496-1

Georgiou, G. K., Parrila, R., & Kirby, J. (2006). Rapid naming speed components and early reading acquisition. *Scientific Studies of Reading*, *10*, 199–220. https://doi.org/10.1207/s1532799xssr1002_4

Georgiou, G. K., Parrila, R., & Kirby, J. R. (2009). RAN components and reading development from grade 3 to grade 5: What underlies their relationship. *Scientific Studies of Reading*, *13*, 508–534.

Georgiou, G., Parrila, R., Kirby, J. R., & Stephenson, K. (2008). Rapid naming components and their relationship with phonological awareness, orthographic knowledge, speed of processing, and different reading outcomes. *Scientific Studies of Reading*, *12*, 325–350.

Georgiou, G., & Stewart, B. (2013). Is rapid automatized naming automatic? *Preschool & Primary Education*, *1*, 67–81. https://doi.org/10.12681/ppej.46

Gordon, P. C., & Hoedemaker, R. S. (2016). Effective scheduling of looking and talking during rapid automatized naming. *Journal of Experimental Psychology: Human Perception and Performance*, *42*, 742–760.

Graves, W. W., Desai, R., Humphries, C., Seidenberg, M. S., & Binder, J. R. (2010). Neural systems for reading aloud: A multiparametric approach. *Cerebral Cortex*, *20*, 1799–1815. https://doi.org/10.1093/cercor/bhp245

Guenther, F. H., Ghosh, S. S., & Tourville, J. A. (2006). Neural modeling and imaging of the cortical interactions underlying syllable production. *Brain and Language*, *96*, 280–301. https://doi.org/10.1016/j.bandl.2005.06.001

Guenther, F. H., & Vladusich, T. (2012). A neural theory of speech acquisition and production. *Journal of Neurolinguistics*, *25*, 4087–4422. https://doi.org/10.1016/j.jneuroling.2009.08.006

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. *Journal of Neuroscience*, *33*, 12835–12843. https://doi.org/10.1523/JNEUROSCI.0449-13.2013

Henderson, J. M., Choi, W., Luke, S. G., & Desai, R. H. (2015). Neural correlates of fixation duration in natural reading: Evidence from fixation-related fMRI. *NeuroImage*, *119*, 390–397. https://doi.org/10.1016/j.neuroimage.2015.06.072

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition*, *92*, 67–99.

Indefrey, P., & Levelt, W. J. M. (2004). The spatial and temporal signatures of word production components. *Cognition*, *92*, 101–144. https://doi.org/10.1016/j.cognition.2002.06.001

Jobard, G., Crivello, F., & Tzourio-Mazoyer, N. (2003). Evaluation of the dual route theory of reading: A metaanalysis of 35 neuroimaging studies. *NeuroImage*, *20*, 693–712.

Jones, M. W., Obregon, M., Kelly, M. L., & Branigan, H. P. (2008). Elucidating the component processes involved in dyslexic and non-dyslexic reading fluency: An eye-tracking study. *Cognition*, *109*, 389–407.

Joubert, S., Beauregard, M., Walter, N., Bourgouin, P., Beaudoin, G., Leroux, J.-M., … Lecours, A. R. (2004). Neural correlates of lexical and sublexical processes in reading. *Brain Language*, *89*, 9–20. https://doi.org/10.1016/S0093-934X(03)00403-6

Kirby, J. R., Georgiou, G. K., Martinussen, R., Parrila, R., Bowers, P., & Landerl, K. (2010). Naming speed and reading: From prediction to instruction. *Reading Research Quarterly*, *45*, 341–362. https://doi.org/10.1598/RRQ.45.3.4

Kwong, K. K., Belliveau, J. W., Chesler, D. A., Goldberg, I. E., Weisskoff, R. M., Poncelet, B. P., … Turner, R. (1992). Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. *Proceedings of the National Academy of Sciences of the United States of America*, *89*, 5675–5679. https://doi.org/10.1073/pnas.89.12.5675

Lervåg, A., & Hulme, C. (2009). Rapid automatized naming (RAN) taps a mechanism that places constraints on the development of early reading fluency. *Psychological Science*, *20*, 1040–1048.

Li, J. J., Cutting, L. E., Ryan, M., Zilioli, M., Denckla, M. B., & Mahone, E. M. (2009). Response variability in rapid automatized naming predicts reading comprehension. *Journal of Clinical and Experimental Neuropsychology*, *31*, 877–888. https://doi.org/10.1080/13803 390802646973

Mazzocco, M. M., & Grimm, K. J. (2013). Growth in rapid automatized naming from grades K to 8 in children with math or reading disabilities. *Journal of Learning Disabilities*, *46*, 517–533. https://doi.org/10.1177/0022219413477475

Misra, M., Katzir, T., Wolf, M., & Poldrack, R. A. (2004). Neural systems for Rapid Automatized Naming in skilled readers: Unraveling the RAN-reading relationship. *Scientific Studies of Reading*, *8*, 241–256. https://doi.org/10.1207/s1532799xssr0803_4

Narhi, V., Ahonen, T., Aro, M., Leppasaari, T., Korhonen, T., Tolvanen, A., & Lyytinen, H. (2005). Rapid serial naming: Relations between different stimuli and neuropsychological factors. *Brain Language*, *92*, 45–57. https://doi.org/10.1016/j.bandl.2004.05.004

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. *Journal of Experimental Child Psychology*, *78*, 359–373.

Norton, E. S., & Wolf, M. (2012). Rapid automatized naming (RAN) and reading fluency: Implications for understanding and treatment of reading disabilities. *Annual Review of Psychology*, *63*, 427–452.

Nuthmann, A., & Henderson, J. M. (2012). Using CRISP to model global characteristics of fixation durations in scene viewing and reading with a common mechanism. *Visual Cognition*, *20*, 457–494. https://doi.org/10.1080/13506285.2012.670142

Ogawa, S., Lee, T. M., Kay, A. R., & Tank, D. W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings of the National Academy of Sciences of the United States of America*, *87*(24), 9868–9872. https://doi.org/10.1073/pnas.87.24.9868

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Olitsky, S. E., & Nelson, L. B. (2003). Reading disorders in children. *The Pediatric Clinics of North America*, *50*, 213–224. https://doi.org/10.1016/S0031-3955(02)00104-9

Palmer, E. D., Rosen, H. J., Ojemann, J. G., Buckner, R. L., Kelley, W. M., & Petersen, S. E. (2001). An event-related fMRI study of overt and covert word stem completion. *NeuroImage*, *14*, 182–193. https://doi.org/10.1006/nimg.2001.0779

Pernet, C., Celsis, P., & Demonet, J.-F. (2005). Selective response to letter categorization within the left fusiform gyrus. *NeuroImage*, *28*, 738–744. https://doi.org/10.1016/j.neuroimage.2005.06.046

Poldrack, R. A., & Gabrieli, J. D. (2001). Characterizing the neural mechanisms of skill learning and repetition priming: Evidence from mirror reading. *Brain*, *124*, 67–82. https://doi.org/10.1093/brain/124.1.67

Price, C. J. (2010). The anatomy of language: A review of 100 fMRI studies published in 2009. *Annals of the New York Academy of Sciences*, *1191*, 62–88. https://doi.org/10.1111/j.1749-6632.2010.05444.x

Price, C. J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage*, *62*, 816–847. https://doi.org/10.1016/j.neuroimage.2012.04.062

Price, C. J., & Friston, K. J. (2005). Functional ontologies for cognition: The systematic definition of structure and function. *Cognitive Neuropsychology*, *22*, 262–275. https://doi.org/10.1080/02643 290442000095

Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Lee, J. R., … Shaywitz, B. A. (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation and Developmental Disabilities Research Reviews*, *6*, 207–213. https://doi.org/10.1002/1098-2779(2000)6:3<207:AID-MRDD8>3.0.CO;2-P

Rapcsak, S. Z., & Beeson, P. M. (2004). The role of left posterior inferior temporal cortex in spelling. *Neurology*, *62*, 2221–2229. https://doi.org/10.1212/01.WNL.0000130169.60752.C5

Rayner, K. (1997). Understanding eye movements in reading. *Scientific Studies of Reading*, *1*, 317–339. https://doi.org/10.1207/s1532799xssr0104_2

Rayner, K. (2009). The 35th Sir Frederick Bartlett Lecture: Eye movements and attention in reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, *62*, 1457–1506. https://doi.org/10.1080/17470210902816461

Reichle, E. D., Pollatsek, A., Fisher, D. I., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, *105*, 125–157. https://doi.org/10.1037/0033-295X.105.1.125

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences*, *26*, 445–476. https://doi.org/10.1017/S0140525X03000104

Sato, M., Tremblay, P., & Gracco, V. L. (2009). A mediating role of the premotor cortex in phoneme segmentation. *Brain & Language*, *111*, 1–7.

Saur, D., Kreher, B. W., Schnell, S., Kummerer, D., Kellmeyer, P., Vry, M.-S., … Weiller, C. (2008). Ventral and dorsal pathways for language. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 18035–18040. https://doi.org/10.1073/pnas.0805234105

Savage, R., & Frederickson, N. (2005). Evidence of a highly specific relationship between rapid automatic naming and text-reading speed. *Brain Language*, *93*, 152–159.

Schrank, F. A., McGrew, K. S., Mather, N., & Woodcock, R. W. (2014). *Woodcock-Johnson IV*. Rolling Meadows, IL: Riverside Publishing.

Simmonds, A. J., Wise, R. J., Collins, C., Redjep, O., Sharp, D. J., Iverson, P., & Leech, R. (2014). Parallel systems in the control of speech. *Human Brain Mapping*, *35*, 1930–1943.

Skuldarkski, P., Constable, R. T., & Gore, J. C. (1999). ROC analysis of statistical methods used in functional MRI: Individual subjects. *NeuroImage*, *9*, 311–329. https://doi.org/10.1006/nimg.1999.0402

Soltysik, D. A., & Hyde, J. S. (2006). Strategies for block-design fMRI experiments during task-related motion of structures of the oral cavity. *NeuroImage*, *29*, 1260–1271. https://doi.org/10.1016/j.neuroimage.2005.08.063

Starr, M. S., & Rayner, K. (2001). Eye movements during reading: Some current controversies. *TRENDS in Cognitive Sciences*, *5*, 156–163. https://doi.org/10.1016/S1364-6613(00)01619-3

Stoeckel, C., Gough, P. M., Watkins, K. E., & Devlin, J. T. (2009). Supramarginal gyrus involvement in visual word recognition. *Cortex*, *45*, 1091–1096. https://doi.org/10.1016/j.cortex.2008.12.004

Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain*. Stuttgart: Thieme.

Taylor, J. S., Rastle, K., & Davis, M. H. (2013). Can cognitive models explain brain activation during word and pseudoword reading? A meta-analysis of 36 neuroimaging studies. *Psychological Bulletin*, *139*, 766–791. https://doi.org/10.1037/a0030266

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *Journal of Learning Disabilities*, *27*, 276–286.

Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Burgess, S., & Hecht, S. (1997). Contributions of phonological awareness and rapid automatic naming ability to the growth of word-reading skills in second to fifth-grade children. *Scientific Studies of Reading*, *1*, 161–185.

van den Bos, K. P., Zijlstra, B. J. H., & Spelberg, B. J. H. (2002). Life-span data on continuous-naming speeds of numbers, letters, colors, and pictured objects, and word-reading speed. *Scientific Studies of Reading*, *6*, 25–49. https://doi.org/10.1207/S1532799XSSR0601_02

Wagner, R. K., Torgesen, J. K., Rashotte, C. A., & Pearson, N. A. (2013). *Comprehensive test of phonological processing*, 2nd ed. Austin, TX: PRO-ED.

Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence*. San Antonio, TX: Harcourt Assessment.

Whitney, C., Kirk, M., O'Sullivan, J., Ralph, M. A. L., & Jefferies, E. (2010). The neural organization of semantic control: TMS evidence for a distributed network in left inferior frontal and posterior middle temporal gyrus. *Cerebral Cortex*, *21*, 1066–1075. https://doi.org/10.1093/cercor/bhq180

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology*, *91*, 415–438. https://doi.org/10.1037/0022-0663.91.3.415

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming- speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities*, *33*, 387–407.

Woodcock, R. (1998). *Woodcock reading mastery tests – revised*. Circle Pines, MN: American Guidance Services.

Xue, G., Chen, C., Jin, Z., & Dong, Q. (2006). Cerebral asymmetry in the fusiform areas predicted the efficiency of learning a new writing system. *Journal of Cognitive Neuroscience*, *18*, 923–931. https://doi.org/10.1162/jocn.2006.18.6.923