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The eyes speak when the mouth cannot: Using eye movements to interpret omissions in primary progressive aphasia

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ABSTRACT

Though it may seem simple, object naming is a complex multistage process that can be impaired by lesions at various sites of the language network. Individuals with neurodegenerative disorders of language, known as primary progressive aphasias (PPA), have difficulty with naming objects, and instead frequently say "I don't know" or fail to give a vocal response at all, known as an omission. Whereas other types of naming errors (paraphasias) give clues as to which aspects of the language network have been compromised, the mechanisms underlying omissions remain largely unknown. In this study, we used a novel eye tracking approach to probe the cognitive mechanisms of omissions in the logopenic and semantic variants of PPA (PPA-L and PPA-S). For each participant, we identified pictures of common objects (e.g., animals, tools) that they could name aloud correctly, as well as pictures that elicited an omission. In a separate word-to-picture matching task, those pictures appeared as targets embedded among an array with 15 foils. Participants were given a verbal cue and tasked with pointing to the target, while eye movements were monitored. On trials with correctly-named targets, controls and both PPA groups ceased visual search soon after foveating the target. On omission trials, however, the PPA-S group failed to stop searching, and went on to view many foils "post-target". As further indication of impaired word knowledge, gaze of the PPA-S group was subject to excessive "taxonomic capture", such that they spent less time viewing the target and more time viewing related foils on omission trials. In contrast, viewing behavior of the PPA-L group was similar to controls on both correctly-named and omission trials. These results indicate that the mechanisms of omission in PPA differ by variant. In PPA-S, anterior temporal lobe degeneration causes taxonomic blurring, such that words from the same category can no longer be reliably distinguished. In PPA-L, word knowledge remains relatively intact, and omissions instead appear to be caused by downstream factors (e.g., lexical access, phonological encoding). These findings demonstrate that when words fail, eye movements can be particularly informative.

1. Introduction

Humans can rapidly name common objects with subjective ease, but the overt act of naming is actually the product of multiple cognitive mechanisms that unfold in concert, including object recognition, word knowledge, lexical access, phonological encoding, and articulation (Dell et al., 1997; Levelt, 1989). This diverse set of processes provides ample opportunity for naming to go awry, and it frequently does. Naming errors are common across the lifespan, but take on a whole new scale in degenerative disorders of language, known as primary progressive

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aphasias (PPA). Inability to name objects, a. k.a. anomia, is arguably the most prevalent symptom in PPA (Mesulam et al., 2009). Although anomia is common in PPA and other types of aphasia, it can manifest quite differently between individuals, depending on what sort of speech error is produced. In aphasiology these speech errors are known as paraphasias, and much effort is given to studying their composition and underlying mechanisms (Budd et al., 2010; Kohn and Goodglass, 1985).

PPA provides an ideal experiment of nature for the study of anomia, as there are three commonly recognized phenotypic variants (Gorno--Tempini et al., 2011), each producing differing patterns of paraphasias. Atrophy in the agrammatic variant (PPA-G) is most concentrated in the left frontal lobe including Broca's area (Rogalski et al., 2011). Anomia can be mild especially in the early stages of PPA-G; their signature impairment lies with sentence as opposed to single-word production (Mesulam et al., 2014; Mesulam et al., 2012). They generate "phonemic paraphasias" more frequently than the other variants, producing a noun that is recognizably close to the object's name but with phoneme distortions (Migliaccio et al., 2016; M. J. Nelson et al., 2020). We have explored the mechanisms of phonemic paraphasias elsewhere (M. J. Nelson et al., 2020), and our focus in the current study will be on speech errors in the remaining semantic (PPA-S) and logopenic variants (PPA-L).

PPA-S is diagnosed based on word knowledge impairments, such that individuals are not only anomic but also unable to match objects with their corresponding nouns, or to provide a definition for those nouns (a. k.a. a "two-way" naming impairment [Mesulam, 2001; Mesulam et al., 2014], or a deficit in single-word comprehension). These verbal deficits are linked to atrophy in the left anterior temporal lobe, an area now thought to fulfill much of the functionality originally ascribed to Wernicke's area (Mesulam et al., 2015). Degradation of word knowledge commonly manifests as "taxonomic blurring"; individuals with PPA-S are increasingly unable to distinguish between nouns from the same taxonomic category (e.g., "cat" and "dog") in a variety of experimental paradigms (R. S. Hurley et al., 2012; Mesulam et al., 2013; Seckin et al., 2016b). In the context of naming, taxonomic blurring can be observed by a preponderance of "semantic paraphasias", often producing another noun from the same category rather than the target noun (Jefferies and Lambon Ralph, 2006; Migliaccio et al., 2016; Snowden et al., 2018; van Scherpenberg et al., 2019).

PPA-L is diagnosed based on anomia along with impaired repetition of sentences (Gorno-Tempini et al., 2011). Naming deficits in PPA-L are "one-way" rather than two-way, as individuals can still match and define nouns that they cannot produce aloud, suggesting that word knowledge remains relatively intact (Gorno-Tempini et al., 2008; Mesulam et al., 2014). This suggests an anomia whose cognitive mechanisms are downstream from word knowledge, in stages such as lexical access or phonological encoding (Gorno-Tempini et al., 2008; Mack et al., 2013; Vonk et al., 2019), but more work is needed to evaluate these possibilities. Individuals with PPA-L may generate fewer semantic and phonological paraphasias compared to their PPA-S and PPA-L counterparts, respectively (Migliaccio et al., 2016). They often simply say "I don't know" or give no response at all, known as an omission (Budd et al., 2010).

The goal of the current study is to investigate the cognitive mechanisms of omissions in PPA-S and PPA-L. As with overt errors of "commission", there are both theoretical and clinical reasons for exploring the mechanisms of omissions in PPA. Compared to semantic and phonemic paraphasias, which readily yield themselves to interpretation, omissions are enigmatic. As noted by Dell et al. (2004), omissions "… have rarely been studied, and for good reason: without an overt attempt to produce the target, it is difficult to come to any conclusions about the mental processes that are occurring". Often treated as a missing data point rather than a paraphasia of interest, omissions are rarely discussed if they are reported at all. As such omissions remain open to interpretation, and are currently fertile ground for investigation, with the potential to reveal new information about brain-language relationships.

When reported, errors of omission are just as common as errors of commission, and are actually among the most frequent types of naming errors in PPA-S and PPA-L (Bruffaerts et al., 2020; Budd et al., 2010; Jefferies and Lambon Ralph, 2006; Migliaccio et al., 2016; Snowden et al., 2018; Woollams et al., 2008). As such, omissions make for a practical target in therapeutic "word retraining" interventions (Hoffman et al., 2015). For example, Savage et al. (2021) found that a group with PPA-S more than halved their rates of omissions after retraining. One could imagine, however, that these interventions would be even more effective if the underlying cognitive and anatomic mechanisms of omissions were better understood. That could facilitate, for example, treatments to be tailored to the individual, addressing the most likely mechanism associated with their phenotype (Chen et al., 2019).

Given the inherent difficulties in studying omissions, creative approaches are needed to uncover their mechanisms. One approach involves examination of the relationships between omissions and their more readily interpretable counterparts (commissions). For example, omissions and semantic paraphasias both appear to be influenced by taxonomy, suggestive of a common lexicosemantic mechanism. Omissions are more frequent in response to items that are from sparse taxonomic categories with few items, while semantic paraphasias are more frequent for items from large categories (Bormann et al., 2008). Likewise, omissions are more likely in response to items that are less typical of their category, while semantic paraphasias are more likely for highly typical items (Woollams et al., 2008). Furthermore, as anomia and word knowledge impairments become more severe in PPA-S, semantic paraphasias become less frequent and omissions become more frequent (Jefferies and Lambon Ralph, 2006; Woollams et al., 2008). This may reflect the progressive nature of deterioration in PPA-S, such that word representations are subject to taxonomic blurring before being rendered more fully inoperable.

In the current study we employed a novel approach, eye tracking, to further characterize omissions in PPA. Eye tracking enabled us to circumvent the lack of a vocal response during omissions, by instead focusing on ocular responses to the items that trigger omissions. We administered a paradigm validated in previous studies of PPA, in which a noun cue is followed by an array of 16 pictures including the target, category competitors, and unrelated items (M. J. Nelson et al., 2020; Seckin et al., 2016a; Seckin et al., 2016b). This "word-to-picture eye tracking task" yields several metrics that are sensitive to word knowledge impairments.

Whereas controls and "non-semantic" variants of PPA (PPA-G and PPA-L) almost always cease visual search immediately upon foveating the target, participants with PPA-S often continue their visual search, resulting in "post-target" fixations on additional items (Seckinet al., 2016a; Seckin et al., 2016b). This provides clear indication of corruption in word recognition, as there is no reason to continue searching once the target has been viewed. A case study by our group demonstrates the relationship between post-target fixations and anomia in PPA (Seckinet al., 2016b). The participant showed more post-target fixations on trials where the target was misnamed (in a separate confrontation naming procedure), compared to trials where the target was named correctly. Post-target fixations were most numerous on two-way trials where the participant also failed to point to the target, but were also elevated on one-way trials in which he did. The latter demonstrates the superior sensitivity of eye tracking over traditional testing methods, in which correct pointing is taken as evidence of intact knowledge. Confidence ratings after each trial were inversely correlated with post-target fixations, again demonstrating their relationship to word knowledge impairments.

The word-to-picture eye tracking task is also sensitive to the signature symptom of word knowledge impairments in PPA-S: taxonomic blurring. In a group study, participants with PPA-S spent proportionately less time viewing the target, and more time viewing category competitors, compared to controls (Seckinet al., 2016b). This "taxonomic capture" of gaze was strongly anti-correlated with confidence ratings, and was heightened even on trials where they correctly pointed to the target. In contrast, taxonomic capture in non-semantic variants (including PPA-L) was within the typical range shown by controls.

Given the clear phenotypic and neuroanatomic differences between variants, we hypothesized that the mechanisms of omission would differ between PPA-S and PPA-L. More specifically, we hypothesized that omissions in PPA-S would be driven by loss of word knowledge, while omissions in PPA-L would involve downstream mechanisms in stages such as lexical access or phonological encoding. The key distinction between these theoretical mechanisms is whether knowledge of nouns remains relatively intact, or is degraded enough to hinder visual search for the corresponding object.

For PPA-S, we predicted that post-target fixations would be elevated on trials where the target elicited an omission, compared to trials where the target was successfully named (in a separate confrontation naming procedure). We restricted analyses to trials in which the participant ultimately pointed to the correct item, so this finding would demonstrate significant corruption of word knowledge even for items that would be classified as "recognized" according to traditional pencil and paper testing. We also made the orthogonal prediction that taxonomic capture would be heightened on omission trials, which would further support the central role of taxonomic blurring in the symptomatology of PPA-S. Alternatively, it may be that blurring is replaced by phenomena such as omissions in the course of disease, as noun representations are progressively rendered inoperable (Jefferies and Lambon Ralph, 2006; Woollams et al., 2008). If so, omissions could be associated with elevated post-target fixations while taxonomic capture is actually lessened.

We hypothesized that omissions in PPA-L would be based on mechanisms such as lexical access or phonological encoding, but our eye tracking task largely eliminates the demands on these downstream stages of confrontation naming. On each trial participants were provided with a noun cue (simultaneously written and spoken) several seconds before the onset of the picture array, so we expected lexical access and phonological encoding of the noun to be complete prior to visual search for the corresponding object. We therefore predicted that PPA-L participants would show relatively normal behavior on the eye tracking paradigm, with post-target fixations and taxonomic capture comparable to levels shown by controls, and critically that this would be the case even on omission trials. Alternatively, there could be subtle word knowledge impairments in PPA-L that are undetected by traditional clinical assessments, but instead reveal themselves to sensitive technique such as eye tracking.

2. Methods

2.1. Participants

The current sample includes 21 participants with PPA and 26 neurotypical controls. All participants were right-handed native English speakers. The diagnosis of PPA was made using established guidelines, necessitating a progressive language impairment that remained the most salient clinical symptom for at least the first 2 years of the disease (Gorno-Tempini et al., 2011; Mesulam et al., 2009; Mesulam et al., 2012). PPA participants were sorted into logopenic variant (PPA-L; $n = 12$) and semantic variant (PPA-S; $n = 9$) based on the guidelines described in Gorno-Tempini et al. (2011). The agrammatic variant of PPA (PPA-G) was excluded, as our a priori hypotheses were instead focused on the PPA-S and PPA-L variants.

Control participants were matched to both PPA groups in age, years of education and gender. The study was approved by the Institutional Review Board at Northwestern University. The study was undertaken with the understanding and written consent of each participant.

2.2. Standardized language testing

The Aphasia Quotient (AQ) from the Western Aphasia Battery-Revised (WAB-R) was used as a global measure of aphasia severity (Kertesz, 2007). Object naming was assessed with the Boston Naming Test (BNT) (Kaplan et al., 2001). Single-word comprehension was measured via a 36-item subset of the Peabody Picture Vocabulary Test (PPVT) (Dunn and Dunn, 2007), previously validated by our group for use in PPA (Mesulam et al., 2009; Mesulam et al., 2012). To assess repetition, participants were asked to repeat the 6 most difficult phrases and sentences in the repetition subset of the WAB-R, and percentage of words successfully repeated was calculated (WAB-R Repetition).

2.3. Shapes task

We administered a novel "shapes task" designed to serve as a control condition for the word-to-picture eye tracking test (Fig. 1a), allowing us to assess for visuoperceptual, spatial, or working memory impairments that could contaminate performance in the main experiment. Rather than using words and complex objects, the stimuli in this task were all basic geometric shapes (e.g., triangle, octagon, cube). Each shape was a simple black and white line drawing taking up 3.4° visual angle, at an average viewing distance of 22 inches from a 20.5 × 11.5 inch touchscreen monitor. On each trial, a shape cue was shown in the center of the screen for 2.5 s, followed by a fixation cross for 0.5 s, followed by an array of 16 shapes distributed in an iso-acuity ellipse, mirroring conditions present in the main experiment (Fig. 1). Participants were tasked with finding the target shape in the array that matched the preceding cue (identity matching), which was embedded among 15 foils. Once found, participants reached out and touched the target to end the trial. The target appeared pseudo-randomly at each possible location across the 16 trials of the experiment.

The shapes task was a later edition to our experimental battery, and results were obtained on 18/26 control participants (69%), 8/12 participants with PPA-L (67%), and 6/9 participants with PPA-S (67%).

2.4. Word-to-picture eye tracking task

On each trial, participants were given a noun cue presented simultaneously as an auditory word and visually as lowercase text (Fig. 1b), facilitating comprehension in the event that a participant has a modality-specific sensory deficit (Mesulam et al., 2019). The text remained on the screen for 2.5 s, followed by a fixation cross for 0.5 s, after which a search array of 16 standardized grayscale drawings of objects appeared. Participants were instructed to touch the drawing corresponding to the preceding noun cue. After appearing, the search array remained on the screen until the participant made a touch response. Eye movements were monitored during array presentation, and the location and timing of touch responses were recorded. Participants were given no instructions about how they should move their eyes during the task, though they were made aware that their eye movements were being recorded.

The task consisted of 48 trials, with a different target item on each trial. Equal numbers of target items were chosen from 4 taxonomic categories (animals, clothes, fruits & vegetables, and manipulable objects). Each array consisted of 1 target item, 7 related foils from the same taxonomic category, and 8 foils distributed among the remaining 3 unrelated taxonomic categories. The locations of targets, related foils and unrelated foils were balanced across the sixteen array positions.

The targets and foils on each trial were closely matched for psycholinguistic characteristics and visual characteristics of the images we used, as described previously (Seckinet al., 2016a; Seckin et al., 2016b). The object probes were composed of shaded gray scale drawings (Rossion and Pourtois, 2004) from the Snodgrass and Vanderwart (1980) image set, scaled to a visual angle of 3.4°. Pictures in the array were equidistantly spaced along an iso-acuity ellipse with a horizontal axis

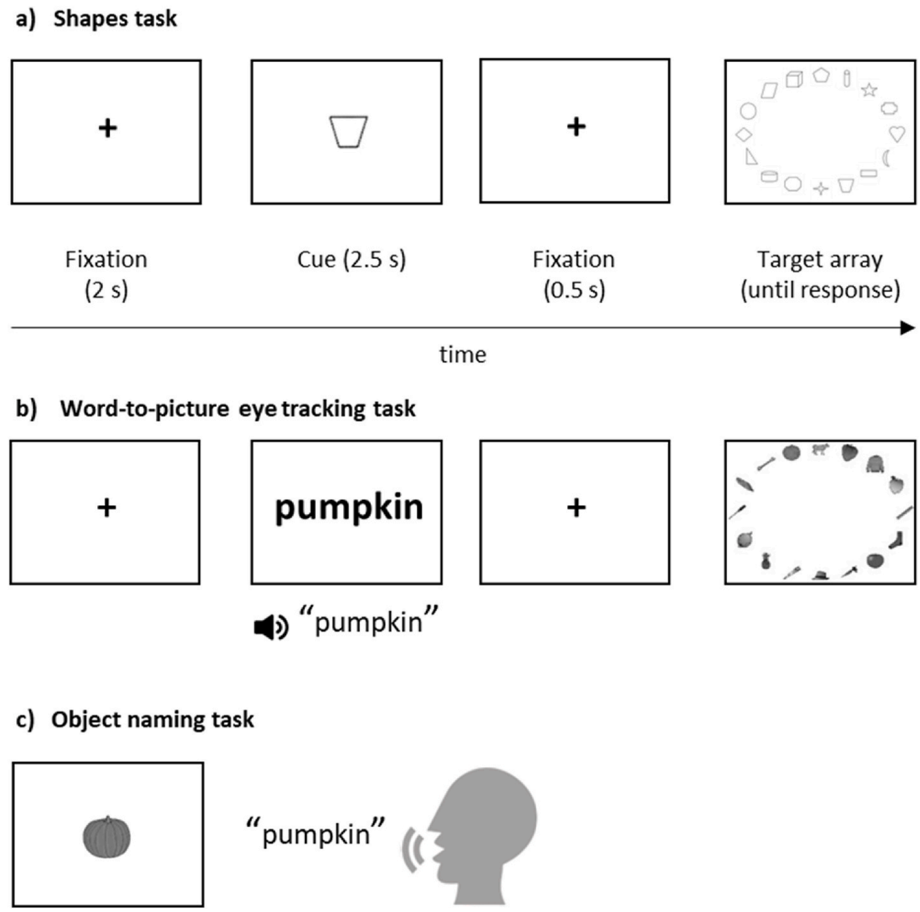

Fig. 1. Experimental design. The shapes task (a) provided a control condition for potential visuoperceptual, spatial, or working memory impairments that could contaminate search performance in the main experiment: the word-to-picture eye tracking task (b). The object naming task (c) revealed which items were nameable versus those that elicited omissions.

31.4° and a vertical axis of 24.2°. This aspect ratio equates parafoveal acuity across positions when centrally-fixating (Iordanescu et al., 2011). Objects were thus located from 12.1 to 15.7° from the center of the screen, depending on their location along the ellipse. At this degree of eccentricity typical adults are generally able to detect whether or not an object is present (Thorpe et al., 2001), but are unable to discern fine-grained featural differences between objects (Nelson and Loftus, 1980). Participants were therefore unlikely to complete the task solely with covert attention, necessitating overt eye movements.

Eye movements were recorded with an Eyelink 1000 eye tracking system (SR Research, Mississauga, ON, Canada). For most participants the Eyelink 1000 Tower Mount was used. For a minority of participants (4 control participants, 1 PPA-L, and 2 PPA-S), the Desktop Mount was used. The effects described here did not differ between this group and the remaining participants, therefore we combined the groups for analyses. Eye positions were calibrated prior to the recording sessions using nine-point calibration procedures, with five-point calibration procedures used for some participants. Participants rested against a chin and forehead rest to reduce head movements. Participants were seated with the center of their eyes approximately 22 inches from the screen. Before performing the main task, participants practiced the task for 1 to 3 trials without recording eye movements, using different items from different taxonomic categories than those used in the main task. Participants with glasses were asked if they could see the practice stimuli accurately and comfortably without glasses. Those that could perform the task without glasses did so in order to improve eye movement recording quality, while those that could not performed the task with their glasses. The Presentation experimental software package (Neurobehavioral Systems, Inc., Berkeley, CA, USA) was used to present the stimuli.

Edf files containing eyetracking data were imported to MATLAB (Mathworks, Natick, MA, USA) using the Edf2Mat toolbox, and further processing and analyses were conducted in MATLAB. The fixation locations for each entire experiment were plotted in two-dimensional screen space and visually inspected post-hoc to ensure data quality. Fixations at the center of the screen (with an eccentricity less than 6° of visual angle) or visibly off of the screen were excluded from analyses.

Eye movement analyses were restricted to trials with accurate pointing responses only. Two metrics were generated for analysis. *Post-target viewing* was tabulated as the number of foils the participant went on to view after foveating the target item. Given the presence of 15 foils in the array, this metric could thus range from 0 to 15, with higher numbers indicating a more exhaustive visual search after failing to stop on the target. The second metric, *taxonomic capture*, was calculated as the percentage of time spent viewing related foils over time spent viewing the target object. Higher values on this index thus indicate greater levels of capture.

2.5. *Object naming task*

The object naming task was performed for the target items in the word-to-picture eye tracking task (Fig. 1c). Participants were shown the same grayscale drawings at the same size that appeared in the array in the word-to-picture matching task and asked to name the item aloud as quickly as possible. The audio stream of the participants' vocal responses was recorded. Items were presented in a different randomized order than the word-to-picture matching task within frequency blocks, while again presenting the high frequency items before the low frequency items. Advancing to the next item in naming was controlled by the experimenter. Participants were given 20 s or more to produce a response if needed. The naming task was conducted without recording eye movements and with the participants' head free but at the same distance from the monitor as during the word-to-picture matching task. The naming task was administered immediately after the word-to-picture eye tracking task. E-Prime (Psychology Software Tools, Inc., Sharpsburg, PA, USA) was used to present stimuli and record audio responses.

Participant naming responses were recorded and scored offline. Responses were sorted into 3 categories of interest: items that were correctly named, items that elicited omissions, and items that elicited commissions. Omissions were identified when the participant said "I don't know", gave a similar phrase (e.g., "can't get it"), or gave no response at all. Given the emphasis of the current study on omissions, all other types of speech errors (e.g., semantic paraphasias, phonemic paraphasias) were generically categorized as commissions. Word-to-picture trials in which the target was misnamed by commission were excluded from analysis.

2.6. Statistical analyses

We employed nonparametric statistics as they are robust to smaller sample sizes and non-normally distributed variables. The study design included three participant groups, so differences between any of the three groups were first probed via one-way Kruskal-Wallis (χ) tests. When significant, these were followed up with pair-wise group comparisons (control vs PPA-L, control vs PPA-S, and PPA-L vs PPAS) using Mann-Whitney (U) tests. As a categorical variable, gender composition of the groups was compared using Fischer's exact test. Within-groups pairwise comparisons were conducted using Wilcoxon signed-rank (W) tests. Error bars in all figures show the standard error of the mean.

3. Results

3.1. Demographic and language profiles

The control, PPA-L and PPA-S groups did not significantly differ in age (Kruskal-Wallace $\chi(2) = 1.4$; $p = .36$), gender (Fisher's exact test: $p = .57$), or years of education ($\chi(2) = 0.51$; $p = .65$) (Table 1). The PPA-L and PPA-S groups did not significantly differ in number of years since diagnosis (Mann Whitney $U = 37.5$, $p = .43$), indicating they were well-matched in terms of stage of disease. On the WAB-R AQ, PPA-L and PPA-S did not significantly differ ($U = 120$, $p = .42$), indicating similar rates of global aphasic impairment. There were significant differences between groups on the BNT ($\chi(2) = 22.4$; $p < .001$), PPVT ($\chi(2) = 145.3$; $p < .001$), and WAB-R Repetition Tests ($\chi(2) = 43.16$; $p < .001$). The PPA-L group showed lower BNT ($U = 325$, $p < .001$) and PPVT ($U = 300$, $p < .001$) scores than controls, and in turn the PPA-S group showed lower BNT ($U = 170$, $p < .001$) and PPVT ($U = 182$, $p < .001$) scores than PPA-L. The PPA-S group showed lower repetition scores compared to controls ($U = 433$, $p < .001$), while repetition scores were lowest in PPA-L ($U = 92$, $p = .004$). These differences are consistent with the diagnostic criteria of the PPA-L and PPA-S variants (Gorno-Tempini et al., 2011).

Table 1
Demographic and language characteristics.

	Control	PPA-L	PPA-S
Sample size	26	12	9
Age	64.2 (1.3)	67.4 (2.5)	62.7 (1.4)
% Female	36 (.1)	25 (.1)	44.4 (.2)
Years of education	16.1 (.5)	15.5 (.7)	16.6 (.8)
Years since diagnosis	–	5.3 (.7)	4.5 (.6)
WAB-R Aphasia Quotient	–	77.6 (3.4)	81.4 (4.5)
Boston Naming Test	97.2 (.7)	46 (7.5)[a]	19.1 (5.1)[a,b]
Peabody Picture Vocabulary Test	98.4 (.4)	87.5 (2.5)[a]	56.3 (6.4)[a,b]
WAB-R Repetition	99 (0)	56 (7)[a,c]	89 (3)[a]

Mean values (standard error) are shown. Language scores are expressed as percent correct. [a]: significantly lower than controls, [b]: lower than PPA-L, [c]: lower than PPA-S, $p < .05$.

3.2. Touch responses on the shapes and word-to-picture tasks

There were no significant differences in accuracy on the shapes task ($\chi(2) = 0.59$; $p = .64$), with all groups showing highly accurate performance (>96% correct; Fig. 2). It is thus unlikely that non-linguistic factors such as spatial neglect, low-to-intermediate visuoperceptual impairments (e.g., "visual form agnosia" (Benson and Greenberg, 1969)), or pervasive working memory impairments would prevent either of the PPA groups from completing the word-to-picture eye tracking test (which had very similar task parameters; Fig. 1).

There were, however, significant differences in accuracy on the word-to-picture eye tracking task ($\chi(2) = 26.1$, $p < .001$). The PPA-L group was less accurate than the control group ($U = 610$, $p < .001$), and the PPA-S group was less accurate than the PPA-L group ($U = 580$, $p < .001$).

Trials with inaccurate responses were excluded from further analysis.

3.3. Vocal responses in the object naming task

There were significant differences between groups on the object naming task (Fig. 3.), in both number of items named correctly ($\chi(2) = 35.5$; $p < .001$) and number of items that elicited omissions ($\chi(2) = 41.5$; $p < .001$). Controls successfully named a greater percentage of the 48 experimental objects than PPA-L ($U = 660$, $p < .001$), who in turn named a greater percentage than PPA-S ($U = 163.5$, $p = .03$). Conversely, PPA-S showed more omissions than PPA-L ($U = 96.5$, $p = .01$), and PPA-L showed more omissions than controls ($U = 351.5$, $p < .001$). Omissions were the dominant form of paraphasia in both PPA groups; the PPA-L group generated more than twice as many omissions compared to all other forms of paraphasias combined (commissions), and the PPA-S group generated more than four times as many omissions as commissions.

These naming results were used to classify each trial in the word-to-picture task, according to whether the target was correctly-named, resulted in an omission, or resulted in a commission. Data from the correctly-named and omission trials were compared in eye movement analyses (next section). Controls generated too few omissions for analyses to be conducted separately on those trials, so they were only used as a comparison group on correctly-named trials. Data from commission trials were excluded from further analysis.

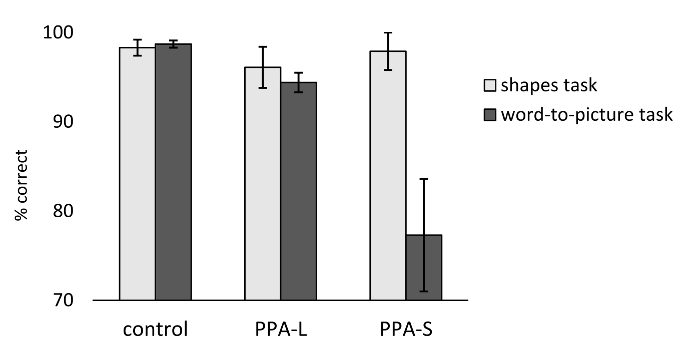

Fig. 2. Accuracy of touchscreen responses. Means are shown with standard error bars. All groups were highly accurate on the shapes control test, but both PPA groups were less accurate than controls on the word-to-picture eye tracking test ($p < .001$).

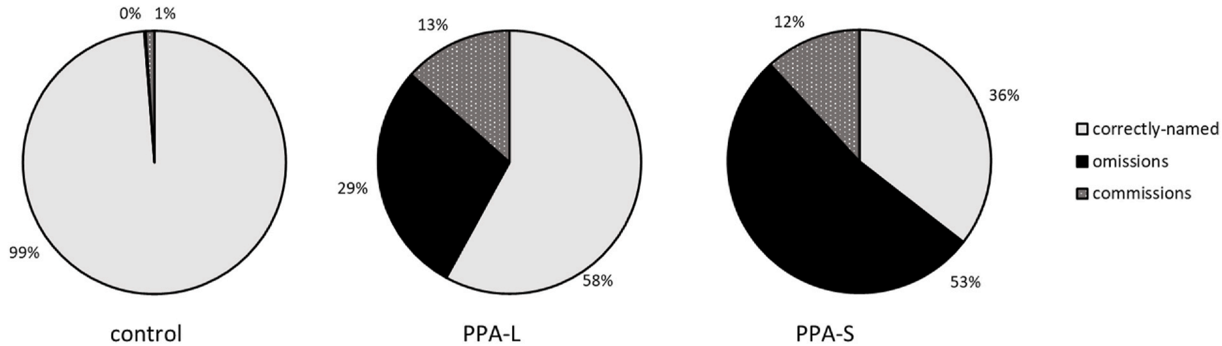

Fig. 3. Vocal responses from the object naming task. For each group, the percentage of the 48 experimental pictures that were correctly-named are shown, along with the percentage eliciting an omission, and the percentage eliciting an error of commission (e.g., semantic paraphasia, phonemic paraphasia).

3.4. Post-target viewing in the word-to-picture task

The number of foils viewed after the target had already been foveated ("post-target") are shown in Fig. 4. Results were examined separately on trials where the target had been correctly-named versus those that elicited omissions (although the control group generated too few omissions to be included in the latter). On correctly-named trials, there were no differences between groups in the number of items viewed post-target ($\chi(2) = 4.1$; $p = .13$). On omission trials, the PPA-S group viewed significantly more foils post-target than the PPA-L group ($U = 89$, $p = .003$). Within-subjects comparisons for the PPA-L group found no differences in post-target viewing on correctly-named versus omission trials (Wilcoxon signed-rank W (11) $= 33$; $p = .68$), while the PPA-S viewed more foils post-target on omission trials (W (8) $= 0$; $p = .004$).

3.4.1. Taxonomic capture in the word-to-picture task

Percent viewing times on each class of object.

Values indicate the time viewing each class of object during the word-to-picture eye tracking task, expressed as a percentage of viewing time on all objects. A taxonomic capture index was constructed based on the raw viewing times, by dividing viewing time on related foils over viewing time on the target.

We defined and operationalized taxonomic capture as the propensity to view related foils from the same category rather than the target item. The percentage of time each group spent viewing the target, related foils, and unrelated foils is shown in Supplementary Table 1. The raw viewing times were used to calculate a taxonomic capture index, by dividing viewing time on related foils over viewing time on the target. These capture values are shown in Fig. 5. There were no differences between groups on correctly-named trials ($\chi(2) = 3.1$, $p = .13$). On omission trials, the PPA-S group showed higher capture values than the PPA-L group ($U = 87.0$, $p = .002$). Within-subjects comparisons showed that the PPA-L group did not differ in capture values across trial types (W (11) $= 31$; $p = .57$), but the PPA-S group had greater capture on omission compared to correctly-named trials (W (8) $= 0$; $p = .004$).

4. Discussion

4.1. Summary of findings

The goal of this study was to examine the cognitive mechanisms of omissions in PPA-L and PPA-S. When attempting to name common objects aloud, the PPA-L group instead generated omissions 29% of the time, and the more severely anomic PPA-S group generated omissions 53% of the time. In PPA-L, omissions were twice as common compared to than all other forms of paraphasia combined (commissions), and the PPA-S group showed four times as many omissions compared to commissions. Commissions often provide clues as to which aspects of the language network are dysfunctional, but with omissions there is no such guidance. We found that in these circumstances, when participants cannot produce even part of the object's name, eye movements are informative.

Vocal responses during the object naming task were used to identify two sets of pictures for each participant: those that were correctly named aloud, and those that provoked an omission. These items appeared as targets in the word-to-picture eye tracking task, in an array including 15

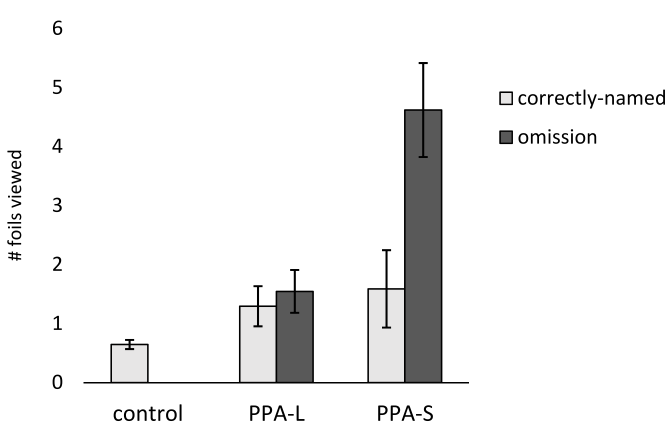

Fig. 4. Post-target viewing in the word-to-picture task. Vocal responses during the object naming task were used to sort trials in the word-to-picture task, into those where the target was correctly-named versus those where the target elicited an omission. On correctly-named trials, all groups ceased visual search shortly after foveating the target. On omission trials, PPA-S participants continued a lengthy visual search even after viewing the target, reflected by higher numbers of foils being viewed post-target.

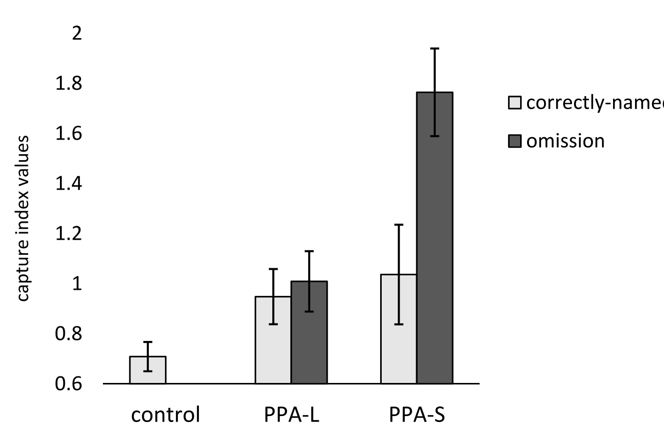

Fig. 5. Taxonomic capture in the word-to-picture task. An index of taxonomic capture was calculated as the percentage of time spent viewing related foils over time spent viewing the target object. Higher values on this index thus indicate greater levels of capture.

other foils. On both types of trials (correctly-named and omission), the control and PPA-L groups ceased visual search upon foveating the target. The PPA-S group failed to halt visual search on omission trials, instead going on to view an average of 4.6 foils "post-target". On omission trials, the PPA-S group also spent less time viewing the target, and more time viewing related foils from the same category (e.g., other animals), displaying excessive "taxonomic capture" of gaze. In contrast, the PPA-L group showed capture levels similar to those of controls, on both correctly-named and omission trials.

Overall, these results indicate that the mechanisms of omission in PPA differ according to variant. In PPA-S, omissions are associated with failures of word knowledge, and appear to be related to the phenomenon of taxonomic blurring, where words from the same category can no longer be reliably distinguished. In PPA-L, omissions were associated with fairly normal word-to-picture matching and visual search, suggesting a mechanism further downstream, in theoretical stages of naming such as lexical access or phonological encoding.

4.2. Relationships between accuracy and eye movements

Accuracy in the word-to-picture task was assessed by whether the participant ultimately selected the picture target that matched the preceding verbal cue, or mistakenly chose a foil (via computer touchscreen). The control and PPA-L groups were highly accurate, but the PPA-S group was less so, particularly on omission trials. It is potentially problematic to examine eye movements on trials with inaccurate touch responses, as one cannot be sure why behavior failed. The most straightforward interpretation is that the participant could not recognize the relationship between noun and object (i.e. a failure of word knowledge), but errors could also theoretically be caused by lapses in attention when the cue was being delivered, failure to maintain the cue in working memory, problems with directing spatial attention (e.g., visual neglect), visuoperceptual problems in viewing objects, or failures of object knowledge (e.g., associative agnosia).

We administered a control task that helped to eliminate some of these alternative interpretations. The shapes task was extremely similar to the word-to-picture task, but the cues and array items were all simple geometric shapes (e.g., octagon, cube). All groups were highly accurate in this task, helping to rule out flagrant conditions such as visual neglect or global working memory impairment.

We further circumvented these potential issues with inaccurate trials by focusing all eye movement analyses on trials with correct touch responses. The current findings of abnormal eye movements in PPA-S are thus all the more striking, considering that they are based on successful matching events. Word-to-picture matching tasks are currently the gold standard for assessing word knowledge (a.k.a. "single-word comprehension"). The vast majority of standardized assessments (e.g., PPVT, WAB-R Auditory Word Recognition) require selection of a target from among four pictures, and correct matching is interpreted as intact knowledge for that item. In the current study, participants with PPA-S had to clear a higher bar, selecting from among 16 rather than four items. Even when they did so successfully, eye movements revealed corruption of word knowledge (on omission trials), demonstrating the superior sensitivity of eye tracking techniques to partial failures of recognition. In the future, eye tracking could conceivably contribute to clinical diagnosis of PPA, with potential applications in early detection screening, variant assignment (subtyping), or as an outcome measure in therapeutic interventions.

4.3. Interpreting omission-related eye movements in PPA-S

Participants were instructed to locate each target in the word-to-picture task as quickly as possible, and each trial ended with the participant's touch response. There was no incentive to continue visual search after the target has been seen. Post-target viewing is therefore a maladaptive and atypical behavior, and one we have never observed controls engage in. It demonstrates that the participant has failed to fully recognize the one-to-one correspondence between the target and the noun cue. Post-target viewing is more likely in PPA for one-way misnamed items, reaches an apogee for two-way misnamed items, and is anti-correlated with confidence ratings (Seckinet al., 2016a; Seckin et al., 2016b). It appears to be a sensitive and reliable indicator of word knowledge impairments.

In the current study, we found that omissions in PPA-S were associated with elevated post-target viewing. The control group viewed on average less than one foil post-target on each trial, and the PPA-L group viewed just over one item on average. The PPA-S group showed similar rates of post-target viewing on correctly-named trials, but on omission trials they viewed an average of over 5 foils post-target, representing over a third of the items in the array. This suggests that omissions in PPA-S are grounded in word knowledge impairments.

One might wonder why participants with PPA-S would fail to discontinue the visual search after foveating the target, especially in circumstances where they ultimately end up returning to the target for a successful match. Post-target viewing and related phenomena such as low confidence ratings could be understood as reflections of a matching process that has become probabilistic rather than definitive. After controls read the verbal cue, they engage in visual search for one and only one object, and cease visual search as soon as it is foveated. In PPA-S, taxonomic blurring causes nouns to be confused with other members of the same category, altering the search process. Scan path recordings show that these individuals often survey the array in serial fashion, and then return their gaze to a smaller subset of pictures from the same category as the target (Seckinet al., 2016b). We have likened this strategy to the formation of a "police lineup"; a small set of candidates are identified which could conceivably match the cue. The goodness of fit for each candidate is then considered, and the best fitting item is then chosen in an educated guess. These educated guesses are correct much of the time, when the target remains more strongly associated with the cue than other foils are. Other times the guess is wrong, as reflected by inaccurate touch responses on 23% of trials in PPA-S.

In support of the view that taxonomic blurring contributes to omissions, the PPA-S group showed not only increased post-target fixations but also increased taxonomic capture on omission trials. They spent less time viewing the target, and more time viewing related foils, compared to correctly-named trials. In contrast, the PPA-L group showed similar rates of capture to controls on both correctly-named and omission trials. These findings speak to the centrality of taxonomic blurring in the symptomatology of PPA-S.

4.4. Interpreting intact viewing behavior in PPA-L

In general, eye movements of the PPA-L group were similar to those of the control group. They engaged in few post-target fixations, and showed typical levels of taxonomic capture. Critically, this was true even on omission trials. This supports our hypothesis that omissions in PPA-L are based in stages of language production which are downstream from word knowledge, and closer to vocal output. Although we have excluded word knowledge impairments as the source of omissions, serial and cascading models of language include a number of downstream stages which could be a theoretical source of misnaming, including ones which are meaning-based, sound-based, and motoric in nature (Dell et al., 1997; Levelt, 1989). Although motor speech impairments are a source of anomia in some individuals with PPA (Hurley et al., 2009), they are infrequent in the PPA-L variant (more often occurring in PPA-G (Gorno-Tempini et al., 2011);), so we will instead briefly comment on the remaining meaning and sound-based stages of naming.

A distinction has been made between failures of lexical access versus failures of lexical storage, and the former can occur even when word knowledge is relatively intact (Jefferies et al., 2007; Warrington and Cipolotti, 1996). A pure access deficit could go undetected in our word-to-picture task: unlike confrontation naming, the verbal label for the object is provided in advance in the form of a written and auditory cue on each trial, eliminating the need for word retrieval. The possibility of access deficits as a source of omissions in PPA-L could be evaluated through the design of future experiments with greater retrieval demands, and/or via a process of elimination (excluding prior and subsequent stages of word production).

After the meaning of words has been retrieved, production models specify that units of sound (phonemes) are plugged in and arranged, in a stage referred to as phonological encoding (Levelt, 1989). The results from several studies examining verbal repetition and working memory span in PPA-L have identified phonological processing deficits (Foxe et al., 2016; Leyton et al., 2014), leading to a hypothesis that phonological loop dysfunction is the core signature of the syndrome (Gorno-Tempini et al., 2008; Rohrer et al., 2010). As such, phonological stages of word production represent a plausible source of omissions in PPA-L worth investigating.

Although the current results do not allow us to fully isolate the source of omissions in PPA-L, they do provide proof of concept that there are multiple routes to omission in PPA, and these routes differ by variant. In characterizing these routes, there is the potential to inform therapeutic word relearning interventions, which could be custom-tailored to address the most likely source of misnaming given each individual's phenotype.

4.5. Limitations

The word-to-picture task required participants to maintain the verbal cue for several seconds while searching through the object array, which raises concerns about working memory impairments as a potential confound. Most models of working memory specify separate modules for verbal and nonverbal material (Baddeley, 2012). The PPA groups were highly accurate in the shapes control task, indicating spared maintenance of nonverbal material, but this leaves open the possibility of a selective deficit for maintenance of verbal material. This is particularly plausible in the case of PPA-L, given the hypothesis that phonological loop (a.k.a. verbal working memory) dysfunction is the core impairment of that syndrome (Gorno-Tempini et al., 2008; Rohrer et al., 2010). We were fortunate in that the PPA-L sample was equally accurate on the shapes and word-to-picture task, and, furthermore, we constrained analyses to trials with accurate match responses. Although we can be fairly sure the current results were uncontaminated, future studies could eliminate verbal maintenance issues by leaving the written cue on the screen for the duration of each trial (e.g., in the center of the array). Return of gaze to the written cue could then be evaluated as a metric of maintenance failures.

Object recognition impairments represent another potential set of confounds that can affect performance in PPA. The shapes task helped us to rule out low-level perceptual impairments in object recognition such as visual form agnosia (Benson and Greenberg, 1969), but higher-level impairments in the conceptual processing of objects remains a concern. In particular, we have demonstrated that when anterior temporal atrophy in PPA-S spreads to both hemispheres, they are likely to develop an associative agnosia (Hurley et al., 2018)). Again, we have mitigated this possibility by focusing on trials with correct matching responses. Future studies could isolate and measure object recognition with a task design that includes entirely nonverbal trials with pictures as cues, targets, and foils (Hurley et al., 2021). Eye movements could then be compared to those from entirely verbal trials that include only word stimuli. Such a design could help to determine to what extent phenomena observed in the current study (e.g., post-target search, excessive taxonomic capture) are selective for verbal material.

4.6. Conclusions

Omissions are perhaps the most frequent type of misnaming in PPA, and are difficult to interpret. The results of this study indicate that the underlying mechanisms of omission differ across PPA variants. Eye movements from individuals with PPA-S suggest that loss of word meaning, associated with taxonomic blurring, is the underlying source of most of their omission errors. In contrast, eye movements of individuals with PPA-L showed no indication of word recognition failures, so omissions in that group seem to represent failures in lexical access or phonological encoding. Researchers and clinicians evaluating language disorders may consider employing eye movements as a particularly informative supplement to traditional assessments.

Author contributions

RSH, MS, MM, MJN, Designed research; MJN, SM, MS, Performed research; MJN, RSH, Analyzed data; RSH, MJN, Wrote the paper; SM, MS, EJR, MM, Edited and contributed to the writing; MM, EJR, Funded and directed the project.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2023.108530.

References

Baddeley, A., 2012. Working memory: theories, models, and controversies. Annu. Rev. Psychol. 63, 1–29.
Benson, D.F., Greenberg, J.P., 1969. Visual form agnosia. A specific defect in visual discrimination. Arch. Neurol. 20, 82–89.
Bormann, T., Kulke, F., Wallesch, C.-W., Blanken, G., 2008. Omissions and semantic errors in aphasic naming: is there a link? Brain Lang. 104, 24–32.
Bruffaerts, R., Schaeverbeke, J., De Weer, A.S., Nelissen, N., Dries, E., Van Bouwel, K., Sieben, A., Bergmans, B., Swinnen, C., Pijnenburg, Y., Sunaert, S., Vandenbulcke, M., Vandenberghe, R., 2020. Multivariate analysis reveals anatomical correlates of naming errors in primary progressive aphasia. Neurobiol. Aging 88, 71–82.
Budd, M.A., Kortte, K., Cloutman, L., Newhart, M., Gottesman, R.F., Davis, C., Heidler-Gary, J., Seay, M.W., Hillis, A.E., 2010. The nature of naming errors in primary progressive aphasia versus acute post-stroke aphasia. Neuropsychology 24, 581–589.
Chen, Q., Middleton, E., Mirman, D., 2019. Words fail: lesion-symptom mapping of errors of omission in post-stroke aphasia. J. Neuropsychol. 13, 183–197.
Dell, G.S., Lawler, E.N., Harris, H.D., Gordon, J.K., 2004. Models of errors of omission in aphasic naming. Cogn. Neuropsychol. 21, 125–145.
Dell, G.S., Schwartz, M.F., Martin, N., Saffran, E.M., Gagnon, D.A., 1997. Lexical access in aphasic and nonaphasic speakers. Psychol. Rev. 104, 801–838.
Dunn, L.M., Dunn, D.M., 2007. Peabody Picture Vocabulary Test, fourth ed. Pearson Assessments, Minneapolis, Minnesota.

Foxe, D., Leyton, C.E., Hodges, J.R., Burrell, J.R., Irish, M., Piguet, O., 2016. The neural correlates of auditory and visuospatial span in logopenic progressive aphasia and Alzheimer's disease. Cortex 83, 39–50.
Gorno-Tempini, M.L., Brambati, S.M., Ginex, V., Ogar, J., Dronkers, N.F., Marcone, A., Perani, D., Garibotto, V., Cappa, S.F., Miller, B.L., 2008. The logopenic/phonological variant of primary progressive aphasia. Neurology 71, 1227–1234.
Gorno-Tempini, M.L., Hillis, A.E., Weintraub, S., Kertesz, A., Mendez, M., Cappa, S.F., Ogar, J.M., Rohrer, J.D., Black, S., Boeve, B.F., Manes, F., Dronkers, N.F., Vandenberghe, R., Rascovsky, K., Patterson, K., Miller, B.L., Knopman, D.S., Hodges, J.R., Mesulam, M.M., Grossman, M., 2011. Classification of primary progressive aphasia and its variants. Neurology 76, 1006–1014.
Hoffman, P., Clarke, N., Jones, R.W., Noonan, K.A., 2015. Vocabulary relearning in semantic dementia: positive and negative consequences of increasing variability in the learning experience. Neuropsychologia 76, 240–253.
Hurley, R.S., Mesulam, M.M., Sridhar, J., Rogalski, E.J., Thompson, C.K., 2018. A nonverbal route to conceptual knowledge involving the right anterior temporal lobe. Neuropsychologia 117, 92–101.
Hurley, R.S., Paller, K.A., Rogalski, E.J., Mesulam, M.M., 2012. Neural mechanisms of object naming and word comprehension in primary progressive aphasia. J. Neurosci. 32, 4848–4855.
Hurley, R.S., Paller, K.A., Wieneke, C.A., Weintraub, S., Thompson, C.K., Federmeier, K. D., Mesulam, M.M., 2009. Electrophysiology of object naming in primary progressive aphasia. J. Neurosci. 29, 15762–15769.
Hurley, R.S., Sander, J., Nemeth, K., Lapin, B.R., Huang, W., Seckin, M., 2021. Differential eye movements in verbal and nonverbal search. Frontiers in Communication 6.
Iordanescu, L., Grabowecky, M., Suzuki, S., 2011. Object-based auditory facilitation of visual search for pictures and words with frequent and rare targets. Acta Psychol. 137, 252–259.
Jefferies, E., Baker, S.S., Doran, M., Ralph, M.A., 2007. Refractory effects in stroke aphasia: a consequence of poor semantic control. Neuropsychologia 45, 1065–1079.
Jefferies, E., Lambon Ralph, M.A., 2006. Semantic impairment in stroke aphasia versus semantic dementia: a case-series comparison. Brain 129, 2132–2147.
Kaplan, E., Goodglass, H., Weintraub, S., 2001. Boston Naming Test, second ed. Pro-, Austin, Texas.
Kertesz, A., 2007. The Western Aphasia Battery - Revised. The Psychological Corporation, San Antonio, Tx.
Kohn, S.E., Goodglass, H., 1985. Picture-naming in aphasia. Brain Lang. 24, 266–283.
Levelt, W.J.M., 1989. Speaking: from Intention to Articulation. The MIT Press, Cambridge, MA.
Leyton, C.E., Savage, S., Irish, M., Schubert, S., Piguet, O., Ballard, K.J., Hodges, J.R., 2014. Verbal repetition in primary progressive aphasia and Alzheimer's disease. J Alzheimers Dis 41, 575–585.
Mack, J.E., Cho-Reyes, S., Kloet, J.D., Weintraub, S., Mesulam, M.M., Thompson, C.K., 2013. Phonological facilitation of object naming in agrammatic and logopenic primary progressive aphasia (PPA). Cogn. Neuropsychol. 30, 172–193.
Mesulam, M., Wieneke, C., Rogalski, E., Cobia, D., Thompson, C., Weintraub, S., 2009. Quantitative template for subtyping primary progressive aphasia. Arch. Neurol. 66, 1545–1551.
Mesulam, M.M., 2001. Primary progressive aphasia. Ann. Neurol. 49, 425–432.
Mesulam, M.M., Nelson, M.J., Hyun, J., Rader, B., Hurley, R.S., Rademakers, R., Baker, M.C., Bigio, E.H., Weintraub, S., 2019. Preferential disruption of auditory word representations in primary progressive aphasia with the neuropathology of FTLD-TDP type A. Cognit. Behav. Neurol. 32, 46–53.
Mesulam, M.M., Rogalski, E.J., Wieneke, C., Hurley, R.S., Geula, C., Bigio, E.H., Thompson, C.K., Weintraub, S., 2014. Primary progressive aphasia and the evolving neurology of the language network. Nat. Rev. Neurol. 10, 554–569.
Mesulam, M.M., Thompson, C.K., Weintraub, S., Rogalski, E.J., 2015. The Wernicke conundrum and the anatomy of language comprehension in primary progressive aphasia. Brain 138, 2423–2437.
Mesulam, M.M., Wieneke, C., Hurley, R., Rademaker, A., Thompson, C.K., Weintraub, S., Rogalski, E.J., 2013. Words and objects at the tip of the left temporal lobe in primary progressive aphasia. Brain 136, 601–618.
Mesulam, M.M., Wieneke, C., Thompson, C., Rogalski, E., Weintraub, S., 2012. Quantitative classification of primary progressive aphasia at early and mild impairment stages. Brain 135, 1537–1553.
Migliaccio, R., Boutet, C., Valabregue, R., Ferrieux, S., Nogues, M., Lehéricy, S., Dormont, D., Levy, R., Dubois, B., Teichmann, M., 2016. The brain network of naming: a lesson from primary progressive aphasia. PLoS One 11, e0148707.
Nelson, W.W., Loftus, G.R., 1980. The functional visual field during picture viewing. J Exp Psychol Hum Learn 6, 391–399.
Nelson, M.J., Moeller, S., Basu, A., Christopher, L., Rogalski, E.J., Greicius, M., Weintraub, S., Bonakdarpour, B., Hurley, R.S., Mesulam, M.-M., 2020. Taxonomic interference associated with phonemic paraphasias in agrammatic primary progressive aphasia. Cerebr. Cortex 30, 2529–2541.
Rogalski, E., Cobia, D., Harrison, T.M., Wieneke, C., Weintraub, S., Mesulam, M.M., 2011. Progression of language decline and cortical atrophy in subtypes of primary progressive aphasia. Neurology 76, 1804–1810.
Rohrer, J.D., Ridgway, G.R., Crutch, S.J., Hailstone, J., Goll, J.C., Clarkson, M.J., Mead, S., Beck, J., Mummery, C., Ourselin, S., Warrington, E.K., Rossor, M.N., Warren, J.D., 2010. Progressive logopenic/phonological aphasia: erosion of the language network. Neuroimage 49, 984–993.
Rossion, B., Pourtois, G., 2004. Revisiting Snodgrass and Vanderwart's object pictorial set: the role of surface detail in basic-level object recognition. Perception 33, 217–236.
Savage, S.A., Lampe, L.F., Nickels, L., 2021. No negative impact of word retraining on vocabulary use or clarity of communication in semantic dementia. Neuropsychol. Rehabil. 1–33.
Seckin, M., Mesulam, M.M., Rademaker, A.W., Voss, J.L., Weintraub, S., Rogalski, E.J., Hurley, R.S., 2016a. Eye movements as probes of lexico-semantic processing in a patient with primary progressive aphasia. Neurocase 22, 65–75.
Seckin, M., Mesulam, M.M., Voss, J.L., Huang, W., Rogalski, E.J., Hurley, R.S., 2016b. Am I looking at a cat or a dog? Gaze in the semantic variant of primary progressive aphasia is subject to excessive taxonomic capture. J. Neurolinguistics 37, 68–81.
Snodgrass, J.G., Vanderwart, M., 1980. A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. J Exp Psychol Hum Learn 6, 174–215.
Snowden, J.S., Harris, J.M., Thompson, J.C., Kobylecki, C., Jones, M., Richardson, A.M., Neary, D., 2018. Semantic dementia and the left and right temporal lobes. Cortex 107, 188–203.
Thorpe, S.J., Gegenfurtner, K.R., Fabre-Thorpe, M., Bulthoff, H.H., 2001. Detection of animals in natural images using far peripheral vision. Eur. J. Neurosci. 14, 869–876.
van Scherpenberg, C., Fieder, N., Savage, S., Nickels, L., 2019. The relationship between response consistency in picture naming and storage impairment in people with semantic variant primary progressive aphasia. Neuropsychology 33, 13–34.
Vonk, J.M.J., Jonkers, R., Hubbard, H.I., Gorno-Tempini, M.L., Brickman, A.M., Obler, L. K., 2019. Semantic and lexical features of words dissimilarly affected by non-fluent, logopenic, and semantic primary progressive aphasia. J. Int. Neuropsychol. Soc. 25, 1011–1022.
Warrington, E.K., Cipolotti, L., 1996. Word comprehension - the distinction between refractory and storage impairments. Brain 119, 611–625.
Woollams, A.M., Cooper-Pye, E., Hodges, J.R., Patterson, K., 2008. Anomia: a doubly typical signature of semantic dementia. Neuropsychologia 46, 2503–2514.