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Words fail: Lesion-symptom mapping of errors of omission in post-stroke aphasia

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Impaired object naming is a core deficit in post-stroke aphasia, which can manifest as errors of commission – producing an incorrect word or a non-word – or as errors of omission – failing to attempt to name the object. Detailed behavioural, computational, and neurological investigations of errors of commission have played a key role in the development of neurocognitive models of word production. In contrast, the neurocognitive basis of omission errors is radically underspecified despite being a prevalent phenomenon in aphasia and other populations. The prevalence of omission errors makes their neurocognitive basis important for characterizing an individual's deficits and, ideally, for personalizing treatment and evaluating treatment outcomes. This study leveraged established relationships between lesion location and errors of commission to investigate omission errors in picture naming. Omission error rates from the Philadelphia Naming Test for 123 individuals with post-stroke aphasia were analysed using support vector regression lesion-symptom mapping. Omission errors were most strongly associated with left frontal and mid-anterior temporal lobe lesions. Computational model analysis further showed that omission errors were positively associated with impaired semantically driven lexical retrieval rather than phonological retrieval. These results suggest that errors of omission in aphasia predominantly arise from lexical–semantic deficits in word retrieval and selection from a competitor set.

Difficulty naming familiar objects is the quintessential symptom of post-stroke aphasia. Such difficulties often manifest as errors of commission, which include the production of a word that is semantically or phonologically related to the correct response, or production of a non-word. Detailed analysis of object naming errors has provided important insights into the cognitive and neural organization of the processes that underpin word production (e.g., Schwartz, 2014).

In the literature on word production, theoretical frameworks differ in their characterization of the timing, number, and nature of the stages of processing, the role of extra-linguistic factors on processing, and the flow of activation through the system. However, theories generally agree that producing a word from meaning (e.g., such as when naming a familiar object) begins with visual–semantic processes that activate the semantic features of the object (e.g., cat) and semantically related concepts (e.g., dog).

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Activation from these semantic features is propagated forward to activate a set of candidate words, from which a word is selected. Word selection is followed by retrieval of that word's phonological form (cf. Caramazza, 1997), ending with articulatory planning and execution. Lexical–semantic deficits (prior to the phonological stages of this process) cause production of a semantically related word instead of the target – semantic errors such as PIG → 'cow' (e.g., Dell, Schwartz, Nozari, Faseyitan, & Coslett, 2013; Levelt, Roelofs, & Meyer, 1999; Ueno, Saito, Rogers, & Lambon Ralph, 2011). Deficits at the post-word selection stages of this process, which correspond to phonological production deficits, cause misselection or misordering of sounds that results in the production of phonologically related words or non-words – phonological errors such as SHELL → 'sell' or 'chell' (e.g., Dell *et al.*, 2013; Roelofs, 2014).

In addition to behavioural and computational investigations that have revealed the cognitive basis of these common commission error types, lesion-symptom mapping studies have revealed their neural correlates. Semantic errors in picture naming are strongly associated with damage to the anterior temporal lobe (Butler, Brambati, Miller, & Gorno-Tempini, 2009; Campo *et al.*, 2016; Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Lambon Ralph, McClelland, Patterson, Galton, & Hodges, 2001; Mesulam *et al.*, 2009, 2013; Mirman, Zhang, Wang, Coslett, & Schwartz, 2015; Schwartz *et al.*, 2009; Walker *et al.*, 2011), presumably because this region is an important hub for semantic cognition (Lambon Ralph, Jefferies, Patterson, & Rogers, 2017). In contrast, phonological errors in word production are associated with damage to posterior superior temporal and inferior parieto-frontal regions (Buchsbaum *et al.*, 2011; Fridriksson *et al.*, 2016; Mirman, Chen, *et al.*, 2015; Mirman, Zhang, *et al.*, 2015; Schwartz, Faseyitan, Kim, & Coslett, 2012).

Errors of omission – failure to attempt to name the object – comprise a significant proportion of naming failures across the various clinical sub-types of aphasia, and in dementia as well. Unfortunately, the lack of an overt naming attempt makes it challenging to draw conclusions about their underlying origins. As a result, compared to the classic errors of commission, errors of omission are much less well studied and less well understood (though see Halai, Woollams, & Lambon Ralph, 2018). In addition to shedding new light on the dynamics of the word production system, a better understanding of omission errors in picture naming may have clinical implications. The prevalence of omissions in aphasia and dementia makes their neurocognitive basis important for characterizing an individual's deficits, which can inform the personalization of treatment and evaluation of treatment outcomes.

As described above, research from multiple independent laboratories has converged to a very clear picture of the distinct neural bases of semantic versus phonological-based naming errors, aligning with the prevailing view of separable processing origins for the two types. Leveraging these established facts about commission errors and examining the neuroanatomical basis of omission errors in aphasia may provide new insights into naming impairment. Models of naming identify four possible functional causes of omission errors (Dell, Lawler, Harris, & Gordon, 2004), each of which makes a different prediction regarding the lesion site(s) that should be most strongly associated with omission errors.

1. A deficit in core semantic knowledge or in the connections between semantic knowledge and lexical representations undermines activation or retrieval of a lexical item

Core semantic deficits are associated with anterior temporal lobe (ATL) damage (Bozeat, Lambon Ralph, Patterson, Garrard, & Hodges, 2000; Lambon Ralph *et al.*, 2017;

Mummery *et al.*, 2000; Nestor, Fryer, & Hodges, 2006), and unilateral left ATL damage is specifically associated with semantic deficits in picture naming (Damasio *et al.*, 2004; Lambon Ralph *et al.*, 2001; Mesulam *et al.*, 2009; Schwartz *et al.*, 2009; Walker *et al.*, 2011). Omission errors could arise because no lexical representation receives sufficient semantic input to become activated. This could occur either because core semantic knowledge has been degraded or because the connections between (relatively intact) semantic knowledge and lexical representations have been degraded. Although these are somewhat distinct mechanisms, both core semantic deficits and degraded semantic–lexical connections are associated with ATL damage; therefore, in either of these two cases, omission errors should be associated with ATL damage.

2. An executive function deficit undermines selection among competing lexical alternatives

Competitive selection deficits are associated with inferior frontal gyrus (IFG) damage (Mirman & Graziano, 2013; Piai, Riès, & Swick, 2016; Riès, Dronkers, & Knight, 2016; Schnur, Schwartz, Brecher, & Hodgson, 2006; Schnur *et al.*, 2009). The critical element across different computational mechanisms of competitive selection is that the selected word must be substantially more activated than other, competing, words (for a discussion of selection deficits in aphasia see Mirman & Britt, 2014). Failure to resolve competition would occur when multiple words are approximately equally active, regardless of whether that activation level is low or high. If omission errors result from failure to resolve competition for lexical selection, they should be primarily associated with IFG damage.

3. A lexical–phonological, phonological, or motor speech deficit either prevents any production or produces a phonological or articulatory error that is suppressed by a speech monitoring process

These three sources of errors are combined here because they are all associated with damage to a system known as the dorsal speech stream, which is comprised of posterior superior temporal and inferior parieto-frontal regions (Buchsbaum *et al.*, 2011; Fridriksson *et al.*, 2016; Hickok, 2012; Mirman, Chen, *et al.*, 2015; Mirman, Zhang, *et al.*, 2015; Schwartz *et al.*, 2012). One classical explanation of omission errors is that they constitute instances of failed retrieval of a holistic word form representation (i.e., lexeme in Levelt *et al.*, 1999). In this case, omission errors should localize to the posterior aspect of this dorsal stream: left posterior superior temporal cortex (Graves, Grabowski, Mehta, & Gordon, 2007; Graves, Grabowski, Mehta, & Gupta, 2008; Indefrey, 2011; Indefrey & Levelt, 2004; Wilson, Isenberg, & Hickok, 2009). In contrast, omissions may be covert phonological errors arising from problems in the retrieval, assembly, or articulation of constituent phonemes after target word form retrieval, which are suppressed by a speech monitoring process. If so, omissions will localize to inferior parieto-frontal regions of the dorsal stream (Mirman, Chen, *et al.*, 2015; Mirman, Zhang, *et al.*, 2015; Schwartz *et al.*, 2012). An association with damage to the precentral gyrus and insula would implicate an articulatory basis for such covert phonological errors (Baldo, Wilkins, Ogar, Willock, & Dronkers, 2011; Basilakos, Rorden, Bonilha, Moser, & Fridriksson, 2015; Itabashi *et al.*, 2016). Importantly, although this dorsal pathway reaches the frontal lobe, damage associated with phonological and articulatory errors is posterior to IFG damage that is associated with lexical selection deficits, making it possible to

distinguish these two hypotheses. If omission errors are (suppressed) motor speech or phonological errors, then they should also be associated with damage to the dorsal speech production system.

4. Omission errors are generated by deficits outside the systems that produce other naming errors

For example, omission errors could arise from impaired visual object recognition (i.e., agnosia). To be distinct from the semantic deficit hypothesis (see #1 above), these would have to be apperceptive agnosic deficits generally associated with occipital or posterior inferior temporal damage. Such deficits are rare in post-stroke aphasia, perhaps because those regions are rarely affected by middle cerebral artery strokes, which are the primary cause of post-stroke aphasia. More generally, the 'independence model' (Ruml, Caramazza, Shelton, & Chialant, 2000) hypothesis that omission errors are caused by other deficits highlights the importance of a broader analysis to avoid missing contributions outside of the a priori regions enumerated above.

Because errors of commission have been the subject of such extensive study using behavioural, computational, and lesion-symptom methods, the space of possible hypotheses regarding errors of omission in post-stroke aphasia is strongly constrained. Each of the hypotheses in this limited set is based on a specific cognitive deficit that has a well-established lesion location correlate. In this study, we used multivariate lesion-symptom mapping to adjudicate among these conflicting hypotheses to provide new insights into the cognitive basis of omission errors in post-stroke aphasia. To facilitate direct evaluation of these hypotheses, we also conducted lesion-symptom mapping analyses of semantic and phonological commission errors in object naming and of performance on the Camel and Cactus Test, a non-verbal test of semantic cognition. Overlap between the lesion correlates of omission errors and these three landmarks will localize omissions within the neural system that supports picture naming. Finally, we used a computational model of picture naming (the interactive two-step model) to evaluate whether degradation of lexical–semantic or lexical–phonological connections contributes to omissions error rates.

Method

The data were drawn from a large-scale study of language processing following left hemisphere stroke. Analyses of other language deficits in earlier sub-sets of the participants have been reported in several previous articles (Mirman & Graziano, 2013; Mirman, Chen, *et al.*, 2015; Mirman, Zhang, *et al.*, 2015; Schwartz *et al.*, 2009, 2011, 2012; Thothathiri, Kimberg, & Schwartz, 2012; Walker *et al.*, 2011), which also provide more detailed descriptions of the participants and imaging methods. The study was carried out in accordance with protocols approved by the Institutional Review Boards at the Einstein Healthcare Network and University of Pennsylvania School of Medicine.

This study examined omission errors produced on the Philadelphia Naming Test (PNT) (Roach, Schwartz, Martin, Grewal, & Brecher, 1996), which is comprised of 175 black and white line drawings of familiar objects from a broad range of semantic categories. Omission errors were defined as failure to produce a complete naming attempt, including silence or only a word fragment, personally relevant circumlocutions (e.g., 'I know what that is'), and vague descriptions (e.g., 'It's a thing'). Semantically relevant descriptions (i.e., multiword responses that characterize the object or explain its function or purpose)

are similar to semantic errors, both cognitively and neuroanatomically (Schwartz *et al.*, 2011). Including semantic descriptions as omission errors would have risked re-discovering that semantic errors are associated with ATL damage, so these were excluded to avoid biasing the results towards a semantic account.

The participants were 123 individuals with aphasia secondary to left hemisphere stroke (not bilateral or solely sub-cortical). All had English as their first language, were right-handed prior to stroke, and were able to produce at least one correct response on the PNT. Participants were tested outside the acute phase, at least 1 month post-onset, with almost all tested in the chronic phase (120/123 were at least 3 months post-onset). The participant sample consisted of 52 females and 71 males, with mean age 57.6 (range = 26–79) and mean 14.3 years of education (range = 6–21). The sample included a wide range of aphasia sub-types (51 anomic, 34 Broca's, 23 conduction, 11 Wernicke's, two transcortical motor, one transcortical sensory, and one global) and aphasia severity based on the Western Aphasia Battery (Kertesz, 1982) aphasia quotient (Mean = 72.1, *SD* = 19.0, range = 25.2–97.9). Average PNT picture naming accuracy was 61.6% correct with scores from the full range of performance (1.1–97.7% correct).

Lesion location was assessed based on MRI (n = 68) or CT (n = 55) brain scans, following the same procedures as previous studies of this data set (or sub-sets of these data). For the MRI scans, lesions were manually segmented on each participant's T1-weighted structural image, and then, the structural scans and lesion maps were registered to the Montreal Neurological Institute (MNI) space Colin27 template by an automated process (Avants, Schoenemann, & Gee, 2006). For the CT scans, the lesion was drawn directly onto the Colin27 template after rotating it (pitch only) to match the approximate slice plane of the participant's scan. Lesion coverage included the lateral portion of the left hemisphere exclusive of the occipital lobe and the medial and posterior inferior temporal lobe (Figure 1). Only voxels where at least 10 participants had lesions were included in the analysis (a total of 389,502 voxels) to provide a stable comparison of lesioned vs. non-lesioned performance. Both the coding of the naming data and the lesion drawing were performed by individuals who were blind to the hypotheses tested here.

Lesion-symptom mapping analyses were performed using support vector regression (SVR-LSM; Zhang, Kimberg, Coslett, Schwartz, & Wang, 2014). SVR-LSM leverages a multivariate machine learning algorithm to discover lesion–behaviour relationships. Compared to standard mass-univariate voxel-based lesion-symptom mapping methods (e.g., Wilson, 2017), SVR-LSM is better able to capture independent contributions of multiple brain regions to performance and is less sensitive to differences in statistical power that arise from differences in the proportion of participants with lesions in each voxel. These advantages are particularly important for this study because omissions could arise from multiple independent causes and at least one of the hypothesized regions of

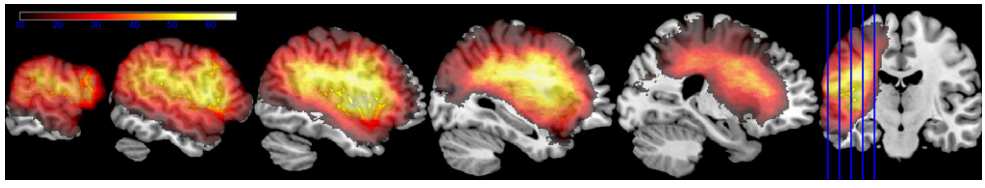

Figure 1. Lesion overlap for the 123 participants (left hemisphere stroke) on the MNI space Colin27 template. The colour scale ranges from 10 lesions (minimum for inclusion in analyses) to 66 (maximum observed overlap).

interest (the ATL) lies near the outer edge of the lesion coverage. As a standard pre-processing step for SVR-LSM, each participant's lesion vector was normalized by dividing each voxel's binary lesion status value by the square root of the total lesion volume. This also serves as an effective control for the impact of lesion volume, referred to as 'direct total lesion volume control' (Zhang *et al.*, 2014). SVR parameters (cost = 1.0, gamma = 3.5) for the primary analysis were selected based on a grid search with fivefold cross-validation to maximize prediction accuracy (as suggested by Zhang *et al.*). Follow-up analyses used the same parameters for consistency. SVR-LSM produces a voxel-wise map of raw regression β values. Statistical significance for the β values was calculated using a permutation test (2,000 permutations) and corrected at false discovery rate (FDR) (Genovese, Lazar, & Nichols, 2002; Zhang *et al.*, 2014) $q < .05$. The final results include only voxels that passed the FDR-corrected threshold, were in the top 5% of raw β values, and comprised clusters larger than 50 voxels.

To facilitate direct comparisons between different error types, we conducted additional SVR-LSM analyses of two key types of errors of commission in picture naming that have been analysed in previous lesion-symptom studies: (1) semantic errors, which include semantically related single-word errors and semantically appropriate multiword descriptions (Dell *et al.*, 2013; Schwartz *et al.*, 2009; Walker *et al.*, 2011), and reflect semantic or semantic-to-lexical mapping deficits (i.e., Hypothesis #1 above); (2) phonological errors, which include non-word errors (neologisms) and phonologically related word errors (Halai *et al.*, 2018; Schwartz *et al.*, 2012), which reflect phonological retrieval or planning deficits (i.e., Hypothesis #3 above). We also analysed performance on the Camel and Cactus Test (CCT; Bozeat *et al.*, 2000), a non-verbal test of semantic cognition in which participants are required to choose which one of four pictured objects goes best with a probe object (e.g., for the CAMEL probe, the choices are CACTUS, TREE, SUNFLOWER, AND ROSES). The CCT provides a measure of semantic knowledge without requiring word production, and because many of the trials require focusing on specific semantic properties to identify the relationship between the probe and the correct response, it is also thought to be a measure of semantic control (Lambon Ralph *et al.*, 2017). These three analyses serve as landmarks to help localize omission errors within the neural system that supports picture naming.

Results

Across all participants, the mean omission error rate was 10.3% (range = 0–84%). SVR-LSM of omission errors identified a total of 19,219 significant voxels (Figure 2A). These voxels comprised two main clusters: a frontal cluster that included middle frontal gyrus and inferior frontal gyrus (especially pars triangularis), with some extension into precentral gyrus, and a temporal cluster that included the mid-anterior portion of the middle temporal gyrus and temporal pole. These results are consistent with both an executive basis and a semantic basis for omission errors. The remaining supra-threshold voxels were scattered throughout the middle cerebral artery territory without substantial clusters in the dorsal language route. At FDR $q < .05$, up to 5% of supra-threshold voxels can be expected to be false positives (Bennett, Wolford, & Miller, 2009), so these small clusters are within the margin of false positives that can be expected. This pattern of results provided no support for a phonological basis for omission errors.

Figure 2B shows SVR-LSM results along with results from SVR-LSM of semantic errors, phonological errors, and performance on the Camel and Cactus Test. Table 1

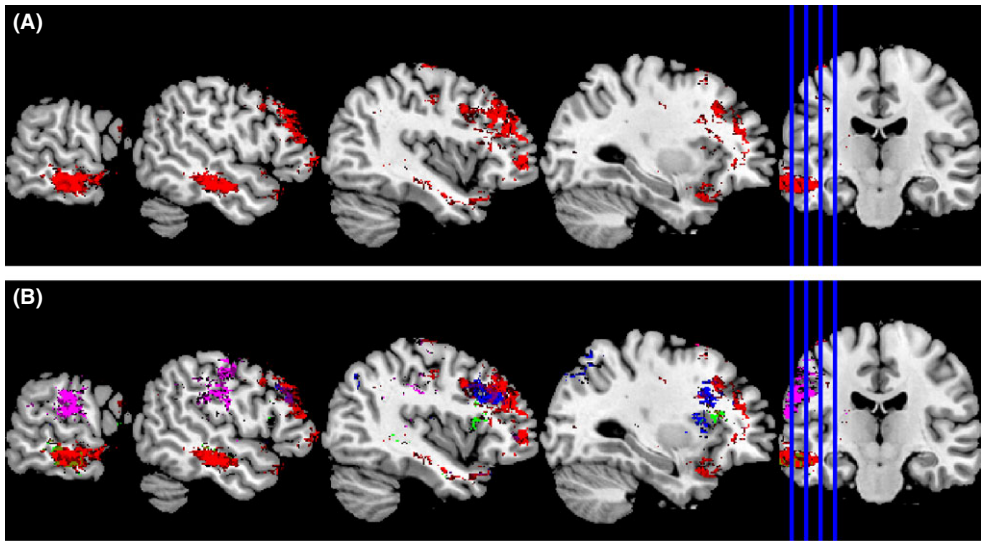

Figure 2. (A) Results of SVR-LSM analysis of omission error proportions. Voxels shown in red had permutation-based $p < .003$ (FDR $q < .05$). (B) Results of SVR-LSM analysis of omission error proportions (red), Camel and Cactus Test score (blue), semantic error proportion (including semantic descriptions; green), and phonological error proportion (non-word and formal errors; violet). Only voxels that survived FDR correction ($q < .05$) are shown. The omission error results overlap with the semantic error results in the temporal lobe and with the CCT results in the frontal lobe, but not with the phonological error results.

quantitatively describes the overlap (and lack thereof) by listing the number of supra-threshold voxels for each of these analyses by anatomical region (defined by AAL atlas). These comparisons confirmed that the lesion correlates of omissions overlap with lesion correlates of performance on the Camel and Cactus Test (in the frontal lobe) and with the lesion correlates of semantic errors (in the mid-anterior temporal lobe), but not with the lesion correlates of phonological errors. In sum, these results indicate that frontal and mid-anterior temporal lesions are the primary neural correlates of omission errors in picture naming in post-stroke aphasia and suggest that they have two primary causes: impaired selection among competing lexical alternatives and impaired semantically driven word retrieval. In the next section, we report computational model analyses that were conducted to further evaluate the claim that omission errors are caused by deficits in semantically driven lexical retrieval rather than deficits in phonological retrieval and planning.

Model-based analysis

The broad conceptual model of naming described in the Introduction has been implemented in an explicit computational model known as the 'interactive two-step model' (Dell, Martin, & Schwartz, 2007; Dell *et al.*, 2013; Schwartz, Dell, Martin, Gahl, & Sobel, 2006). This model makes a clear distinction between semantic and phonological aspects of word production and accounts for variability in patterns of naming errors across a large, unselected sample of people with aphasia in terms of just two parameters: an 's-weight' that determines the ability of semantic knowledge of the picture to drive lexical

Table 1. Voxels surviving FDR correction for each SVR-LSM analysis in regions of interest (ROI) defined by the AAL atlas

ROI	Omission errors	CCT	Semantic errors	Phonological errors
FDR threshold	0.003	0.001	0.0005	0.001
Frontal_Mid_L	6,249	1,324	–	–
Frontal_Inf_Tri_L	3,248	1,702	224	–
Temporal_Mid_L	5,871	–	754	–
Temporal_Pole_Sup_L	949	–	–	–
Temporal_Inf_L	827	–	242	–
Frontal_Mid_Orb_L	489	40	–	–
Frontal_Inf_Oper_L	367	442	–	–
Post-central_L	292	–	–	3,692
Frontal_Inf_Orb_L	291	1	–	–
Insula_L	242	542	203	–
Temporal_Pole_Mid_L	238	–	–	–
Temporal_Sup_L	69	–	–	267
Putamen_L	38	146	–	–
Caudate_L	24	–	–	–
Thalamus_L	16	3	–	–
Frontal_Sup_L	8	–	–	–
Hippocampus_L	1	–	–	–
Angular_L	–	74	–	–
Parietal_Inf_L	–	151	–	175
Parietal_Sup_L	–	295	–	–
Occipital_Mid_L	–	46	–	–
Rolandic_Oper_L	–	–	–	24
Supra-Marginal_L	–	–	–	1,233

retrieval and a 'p-weight' that determines the ability of lexical activation to drive phonological retrieval for production. Given a participant's distribution of correct responses, semantic errors, phonological errors, mixed errors, non-word errors, and unrelated responses, the model provides a description of that participant's naming system in terms of an s-weight and a p-weight.[1] Note that omission errors are not included in the estimation of s-weights and p-weights, so these model parameters provide a quantitative way to test whether omission errors are related to deficits at semantically driven lexical retrieval (quantified by the s-weight) or phonological planning and execution (quantified by the p-weight). In addition, because s-weight and p-weight parameter estimates are based on the distribution across multiple error types, they provide a more comprehensive estimate of deficits in different aspects of word production than a direct correlation between, for example, semantic and omission errors.

As this analysis is not constrained by availability of structural lesion data, a larger set of PNT data was downloaded (on 20 June 2017) from the Moss Aphasia Psycholinguistics Project Database (Mirman *et al.*, 2010) (www.mappd.org). This data set consisted of PNT data from 273 participants with aphasia. Some of the participants had s-weight and p-weight parameters that were higher than the default value for neurologically healthy

[1] *A detailed description of the model and parameter-fitting procedure is provided elsewhere (Schwartz* et al., *2006), and an online model-fitting tool is available at http://langprod.cogsci.illinois.edu/cgi-bin/webfit.cgi.*

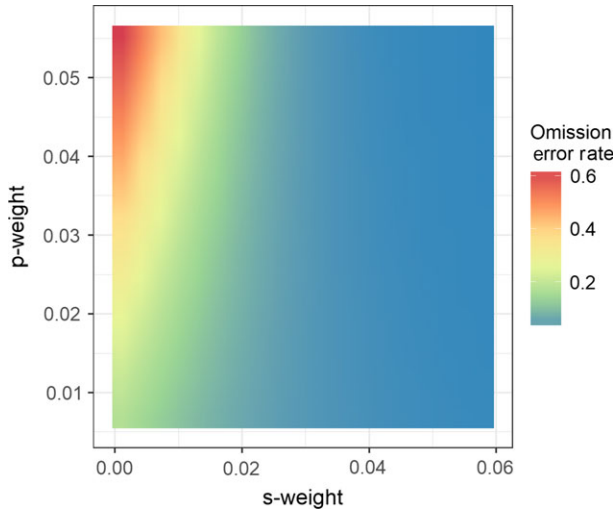

Figure 3. Relationship between omission error proportions and s-weights and p-weights. Hotter colours indicate higher proportion of omission errors estimated by logistic regression of data for 241 participants from the Moss Aphasia Psycholinguistics Project Database.

adults (0.6). Because these hypernormal weight estimates may reflect poor model fit to an individual participant's data, the analysis was restricted to participants with s-weight and p-weight estimates below the control level (N = 241). For participants who completed the PNT multiple times, only the first administration was used. Logistic regression was used to analyse rate of omission errors as a function of s-weights, p-weights, and their interaction. The results revealed that both kinds of weights were significant predictors of omission error rate, but in opposite directions: higher p-weights were associated with more omission errors (Estimate = 45.9, SE = 4.74, $p < .001$), whereas higher s-weights were associated with *fewer* omission errors (Estimate = −57.4, SE = 5.52, $p < .0001$). The interaction was also statistically significant (Estimate = −1410, SE = 247.5, $p < .0001$). Figure 3 depicts this relationship between omission error proportions and s- and p-weights. The highest rates of omission errors were observed for individuals with low s-weights (impaired semantic-to-lexical mapping) and high p-weights (relatively spared lexical-to-phonological mapping).

The association between omission errors and lower s-weights converges with the SVR-LSM result in suggesting that failure of semantic knowledge to drive lexical access is a key contributor to omission errors. The association between omission errors and higher p-weights may reflect that phonological feedback to the lexical level can exacerbate the lexical selection challenge, especially when low s-weights have created a cohort of weakly active lexical candidates. For example, if the target is CAT and low s-weights have weakly activated CAT and DOG, phonological feedback may additionally activate COG, thus adding yet another lexical competitor and making lexical selection more difficult. A related phenomenon was observed in a recent study of homophone picture naming (e.g., deer), which found that homophone counterparts compete and exert a detrimental effect at the lexical–semantic level but cooperate and exert a facilitative effect at the phonological level (Middleton, Chen, & Verkuilen, 2015). These strikingly opposite effects were reflected in semantic and omission errors at the lexical–semantic level and in phonological errors at the phonological level.

Discussion

Although omission errors in picture naming are common in aphasia, the cognitive and neural bases of these errors are poorly understood. Models of word production define three distinct possible causes of omission errors and their neural correlates: (1) if omission errors are due to lexical–semantic deficits, then they should have the same neural correlates as semantic errors – ATL damage; (2) if omission errors are due to deficits in lexical selection, then they should have the same neural correlates as other lexical selection deficits – inferior frontal damage; and (3) if omission errors are due to phonological deficits, then they should have the same neural correlates as phonological (word and non-word) errors – posterior superior temporal and inferior parieto-frontal damage. The present SVR-LSM analyses localized the neuroanatomical correlates of omission errors to the left frontal and anterior temporal regions, consistent with the lexical–semantic and lexical selection deficit hypotheses and not consistent with the phonological deficit hypothesis. The computational model analysis further suggested that omission errors are associated with degraded connections between semantic and lexical representations and not degraded connections between lexical and phonological representations. Together, these results provide computational and neural evidence that omission errors in picture naming in aphasia are primarily due to lexical–semantic deficits in word retrieval and selection.

Computational models of picture naming generally agree that word retrieval begins with visual–semantic processes that activate the semantic features of the picture (e.g., cat) and semantically-related concepts (e.g., dog). Activation from these semantic features is propagated forward through intermediate levels to phonological and articulatory planning and execution. Along the way, the target word will be selected from among the semantically related cohort.

Converging evidence from functional neuroimaging and neuropsychological studies has identified bilateral ATL as a critical 'hub' for semantic cognition (Lambon Ralph *et al.*, 2017; Mummery *et al.*, 2000; Nestor *et al.*, 2006; Patterson, Nestor, & Rogers, 2007), with the left ATL being particularly important for verbal semantic processing, including picture naming (Butler *et al.*, 2009; Campo *et al.*, 2016; Lambon Ralph *et al.*, 2001; Mesulam *et al.*, 2013; Mirman, Zhang, *et al.*, 2015). Damage to the left ATL may weaken either the activation of the semantic features (Lambon Ralph *et al.*, 2001; Ueno *et al.*, 2011) or the mapping (connections) from semantic features to words (Dell *et al.*, 2004, 2013; Schwartz *et al.*, 2006). The present SVR-LSM results suggest that omission errors in picture naming arise, in part, when activation of semantic knowledge is insufficient to guide retrieval of the correct lexical representation. Whether resulting from degraded semantic activation or degraded connections, weak semantic input to lexical representations, combined with normal activation noise, can produce two different behavioural outcomes: (1) a semantically related word is selected, resulting in a semantic error, or (2) no word becomes activated strongly enough (e.g., relative to some absolute or relative threshold) to be selected, resulting in no naming attempt being produced – an omission error (a similar finding is reported by Halai *et al.*, 2018). Which of these two outcomes is observed depends on the absolute activation of the different candidates: if a non-target word reaches sufficiently high activation, then the response will be a semantic error; if no candidate word reaches sufficiently high activation, then no response will be produced.

The present results strongly associate omission errors with lexical–semantic deficits rather than phonological deficits, but they do not distinguish between core semantic ('storage') deficits and deficits in semantically driven lexical retrieval ('access'). It has

been proposed that semantic deficits in semantic dementia (also known as the semantic variant of primary progressive aphasia) reflect degradation of the semantic store, whereas semantic deficits in post-stroke aphasia reflect impaired access to relatively intact semantic knowledge, although there is currently no adequate cognitive or computational account for this difference (for a review see Mirman & Britt, 2014). Despite these behavioural differences and differences in the aetiology of brain damage, the neural correlates of semantic errors in picture naming are remarkably consistent – in both the semantic dementia and the post-stroke aphasia groups, semantic errors are associated with ATL damage. As a result, the present finding that omission errors are also associated with ATL damage suggests a lexical–semantic deficit cause, although it does not distinguish between impaired semantic representations (core semantic deficit) and impaired connections between intact semantic representations and lexical representations (lexical access deficit).

Neuroimaging and neuropsychological studies suggest that inferior frontal regions are critical to efficient lexical selection (Mirman & Graziano, 2013; Piai *et al.*, 2016; Riès *et al.*, 2016; Schnur *et al.*, 2006, 2009). The present SVR-LSM results suggest that difficulty resolving lexical competition contributes to failure to produce a picture naming response. Lexical selection requires that one lexical representation becomes substantially more active than the others, so it can be selected. If no single lexical item is able to achieve activation sufficiently greater than the others – possibly because high noise or impaired inhibition (competition) leaves multiple candidates approximately equally activated – then no lexical item will be selected, resulting in no response being produced.

The present study specifically examined omission errors in picture naming in aphasia secondary to left hemisphere stroke. Phenomenologically similar kinds of omission errors, such as 'tip-of-the-tongue' states in neurologically intact speakers, may have other causes. This study only considered structural lesion information from individuals with left hemisphere stroke, so it does not address the role of the right hemisphere or of spared perilesional left hemisphere regions. The present study included a relatively large and diverse sample of participants with left hemisphere stroke. It also used a multivariate lesion-symptom mapping method (SVR-LSM) that is particularly well suited to detecting contributions of distinct brain regions, as in the present results. Thus, the results provide strong evidence that omission errors in picture naming are primarily associated with damage to left frontal and mid-anterior temporal regions and suggest that they arise from combined deficits of lexical selection and semantic cognition. Omission errors are inherently difficult to study due to the lack of an overt response. The present results shed new light on this aspect of the quintessential deficit in post-stroke aphasia.

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