Title: Motivated semantic control: Exploring the effects of extrinsic reward and self-reference on semantic retrieval in semantic aphasia

Short title: *Motivated Semantic Control*

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Abstract:

Recent insights show increased motivation can benefit executive control, but this effect has not been explored in relation to semantic cognition. Patients with deficits of controlled semantic retrieval in the context of semantic aphasia (SA) after stroke may benefit from this approach since their deficits tend to be accompanied by deficits of cognitive control. We assessed the effect of both extrinsic and intrinsic motivation in healthy controls and semantic aphasia patients. Experiment 1 manipulated extrinsic reward using high or low levels of points for correct responses during a semantic association task. Experiment 2 manipulated the intrinsic value of items using self-reference; allocating pictures of items to the participant ('self') or researcher ('other') in a shopping game before people retrieved their

semantic associations. These experiments revealed that patients, but not controls, showed better performance when given an extrinsic reward, consistent with the view that increased external motivation may help to ameliorate patients' semantic control deficits. However, while self-reference was associated with better episodic memory, there was no effect on semantic retrieval. We conclude that semantic control deficits can be reduced when extrinsic rewards are anticipated; this enhanced motivational state is expected to support proactive control, for example, through the maintenance of task representations. It may be possible to harness this modulatory impact of reward to combat the control demands of semantic tasks in SA patients.

Keywords:

Stroke, Semantic, Aphasia, Motivation, Reward, Self-reference

Data availability statement:

Data sharing via a public repository is not possible for the current study, due to insufficient consent. Researchers who wish to access the data should contact the Research Ethics Committee of the York Neuroimaging Centre, or the corresponding author.

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Competing interests statement:

The authors have no competing interests to disclose.

1. Introduction

Our ability to understand the world relies on flexible access to conceptual information within a semantic store (Jefferies, 2013). Evidence supports the existence of dissociable systems underlying the storage and controlled retrieval of semantic representations (Lambon Ralph et al., 2017). Semantic dementia patients with relatively focal atrophy focussed on the ventrolateral anterior temporal lobes (ATL) show degraded semantic knowledge, while patients with semantic aphasia (SA) experience deregulated semantic retrieval, or semantic control deficits, following left prefrontal and/or temporoparietal stroke (Jefferies & Lambon Ralph, 2006). Semantic control is an executive process which supports the ability to retrieve non-dominant aspects of knowledge whilst overcoming competition from distractors (Hoffman et al., 2018; Jefferies, 2013). Impaired semantic control in SA gives rise to deficits in both verbal communication and organisation of nonverbal actions (Jefferies et al., 2019), consistent with the definition of SA as impaired manipulation of verbal and non-verbal symbolic information outlined by Head (1926). In line with the damage to left ventrolateral prefrontal cortex and/or left temporoparietal regions in SA, studies of healthy participants employing neuroimaging (Jackson, 2021) and transcranial magnetic stimulation (Hallam et al., 2016) have implicated both left inferior frontal gyrus (LIFG) and posterior middle temporal gyrus (pMTG) in semantic control.

In SA, access to semantic knowledge is not universally compromised, but depends on task demands. Semantic retrieval is impaired for subordinate meanings, and when inhibition of task-irrelevant distractors is required (Jefferies, 2013). This results in reduced flexibility when retrieving semantic information in ambiguous contexts (Noonan et al., 2010). Impaired semantic control in SA is also evident when retrieving thematic associations between concepts: identifying weak as opposed to strong associations requires semantic control

processes that can focus retrieval on non-dominant conceptual information (Thompson et al., 2017). Research has explored manipulations which ameliorate semantic control deficits in SA, such as cueing. Successive phonemic cues (e.g. c.. ca.. cam.. for CAMEL) can facilitate accurate picture naming (Jefferies et al., 2008), while contextual sentences can facilitate the retrieval of non-dominant interpretations of ambiguous homonyms (Noonan et al., 2010). Lanzoni et al. (2019) demonstrated similar effectiveness of contextually-relevant emotional and location cues. Cues reduce control demands by narrowing down the number of retrievable options and biasing ongoing retrieval towards task-relevant information.

An alternative approach to facilitating semantic retrieval in SA involves recruiting processes beyond semantic cognition. Investigations with healthy adults have demonstrated that extrinsic rewards, such as monetary incentives or awarded points, can improve performance in multiple domains, including the control of visual attention (Padmala & Pessoa, 2011), task-switching (Capa et al., 2013), contextual control (Kouneiher et al., 2009), creative problem solving (Cristofori et al., 2018), interference control (Zhao et al., 2018), and conflict adaptation (Dreisbach & Fischer, 2012). Behavioural benefits of extrinsic reward include increased task accuracy, reduced reaction times, and reduced switch-costs (Yee & Braver, 2018). Extrinsic incentives are considered a key element of ‘gamification’ (Mekler et al., 2017), which uses typical elements of digital games to increase engagement with training activities, including in post-stroke rehabilitation (Romani et al., 2019). However, to our knowledge, extrinsic rewards have not been used previously in conjunction with semantic tasks or in patients with SA.

Tasks with high control demands are effortful as they draw on limited resources, such as selective attention and working memory (Yee & Braver, 2018). The cost of mental exertion is typically weighed up against the potential benefits of the action (Botvinick & Braver, 2015). As such, tasks perceived as high effort and low in reward may be less

appealing than more trivial low effort and high reward actions. Introducing task-based incentives can offset perceived costs (Goschke & Bolte, 2014). Such incentives can increase preparatory control, and therefore one's ability to sustainably engage with a task (Notebaert & Braem, 2015). This can benefit either cognitive stability or flexibility, depending on recent reward history (Fröber et al., 2019). The neural processing of extrinsic reward has been consistently linked to a network of regions including the ventromedial prefrontal cortex, caudate, putamen and striatum (Lin et al., 2012). Cumulative reward value appears to be tracked and represented in these regions (Juechems et al., 2017). Effects of reward on cognition have been attributed to dopaminergic transmission between these regions and the multiple demand network (MDN), which supports challenging tasks across domains (Camilleri et al., 2018; Parro et al., 2018). If regions associated with reward processing are intact, it may be possible to harness this modulatory impact of reward to combat semantic control deficits in patients with SA.

While extrinsic reward refers to incentives provided externally, intrinsic reward refers to inherent enjoyment of or interest in a task (Mori et al., 2018). Intrinsic motivation is relatively difficult to manipulate experimentally, but can be modulated indirectly, through factors such as self-reference. Tamir and Mitchell (2012) demonstrated that self-referential information is intrinsically motivating; participants reliably choose to forgo monetary incentives in order to disclose information about the self, in conjunction with increased activation in brain regions associated with reward processing. The neural substrates underlying both intrinsic motivation and self-reference show considerable overlap with reward circuitry (Di Domenico & Ryan, 2017; Enzi et al., 2009). Cognition shows biases in favour of self-referenced items, within perception (Sui et al., 2012), attention (Sui & Humphreys, 2015b), working memory (Röer et al., 2013), and recognition memory (Hou et al., 2019). Moreover, Sui and Humphreys (2015a) demonstrated that extrinsic reward and

self-reference confer separable but equivalent benefits in associative learning. Self-reference benefits to episodic memory persist in patients with episodic memory deficits (Sui & Humphreys, 2013) and SA (Stampacchia et al., 2019). However, there are no previous investigations of the effect of self-reference on semantic retrieval, to our knowledge.

The current study aimed to investigate the influence of both extrinsic reward and intrinsic motivation induced through self-reference on the retrieval of strong and weak thematic associations in SA. Experiment 1 assessed the effect of cued extrinsic reward, in the form of high or low levels of token points given for correct responses. Experiment 2 assessed the effect of self-reference by allocating pictured 'shopping items' either to the participant ('self' condition) or the researcher ('other' condition), prior to semantic judgements about these items. If modulatory effects of motivation can benefit semantic control, high extrinsic reward and/or self-reference might ameliorate patients' semantic deficits. Motivation may support the maintenance of task goals when semantic control is deficient; consequently, any performance gains would likely be greater for weak associations, which place higher demands on semantic control. A better understanding of the effects of motivation on semantic retrieval of strong and weak associations may have implications for the use of extrinsic rewards and self-reference in gamified approaches to aphasia rehabilitation.

2. Method

2.1. Participants

The sample consisted of 16 SA patients (nine females), and 15 controls (12 females). All participated in Experiment 1, while a subset participated in Experiment 2 (demographic information is presented separately in *3.1.1.* and *4.1.1.*, respectively). Patients were recruited

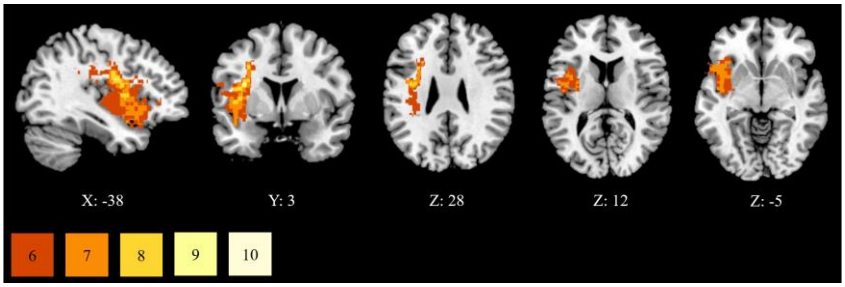
from communication support groups across Yorkshire. All had aphasia following left hemisphere stroke and were at least 18 months post-stroke. Patients were selected to show impairments in both verbal and non-verbal semantic cognition, consistent with previous definitions of SA (Jefferies & Lambon Ralph, 2006). The criteria used are explained in the *Background Neuropsychology* section of the supplementary materials. Controls were healthy adults matched to the patients on age and years in education and reported no history of psychiatric or neurological disorders. Informed consent was obtained for all participants.

2.2. Lesion analyses

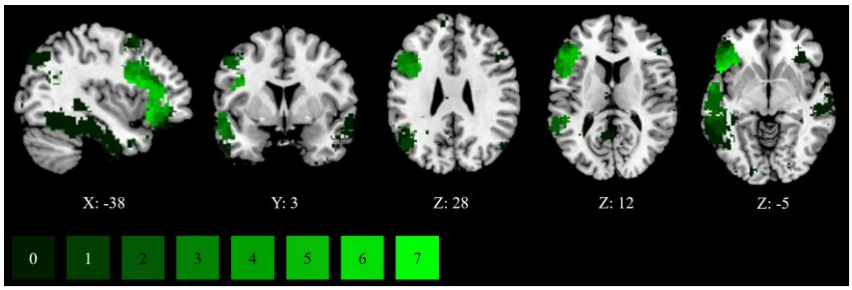
Ten patients (P1 – P10) had MRI scans at York Neuroimaging Centre. These patients all participated in Experiment 1, while four (P3 – P6) participated in Experiment 2. Structural scans underwent brain extraction in ANTs using a template from the OASIS Brain Project (https://www.oasis-brains.org/; Marcus et al., 2010). Registration to MNI space was also performed using ANTs. Each patient's lesion location was manually traced in MRIcron. Figure 1 provides a lesion overlap map for these patients. Eight cases showed damage to LIFG. Several patients showed damage to other regions including the pMTG, superior temporal gyrus, and supramarginal gyrus. Clinical acute-stage scans were available for two further patients and revealed damage to LIFG (MRI for P16) and a left frontal parietal lesion (CT for P12). Lesion information was not available for the remaining four patients due to contraindications for scanning and/or closure of scanning facilities during the COVID-19 pandemic.

To assess the impact of patients' lesions on functional networks of interest, we extracted maps from Neurosynth using term-based meta-analyses (Yarkoni et al., 2011) for the terms 'Semantic', 'Demands', and 'Reward' (see Figure 1), then confined to the left hemisphere. This allowed us to observe the extent to which patients present with damage to regions associated with semantic processing, domain-general task demands, and reward

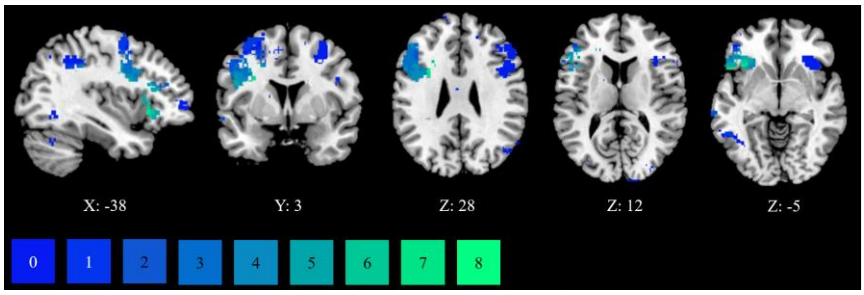
processing. We calculated the average percentage of each of these maps that were damaged across the ten patients in the lesion overlap map. As seen in Figure 1, patients showed the most damage to ‘Demands’ regions, followed by ‘Semantic’ regions. ‘Reward’ regions were relatively spared, suggesting it might be possible to harness modulatory impacts of extrinsic or intrinsic reward to support semantic control in these patients.



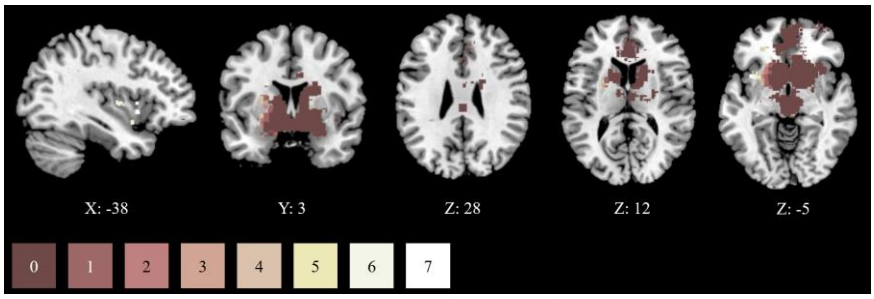
(a) – Lesion Overlap Map



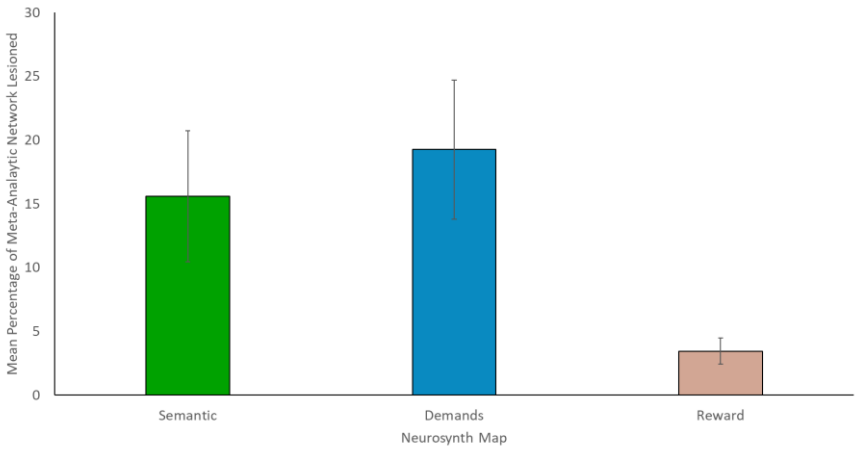
(b) – 'Semantic' Neurosynth map



(c) – 'Demands' Neurosynth map



(d) – 'Reward' Neurosynth map



(e) – Mean percentage of Neurosynth maps lesioned

Figure 1. Patient lesion analyses, including (a) a lesion overlap map for ten semantic aphasia patients in the current study, created using manual segmentation in MRICron. This map shows lesion overlap in 6 or more patients, with the colour of the lesioned area corresponding to the number of affected cases (bottom left). We assessed the extent of overlap between patient lesions and term-based meta-analytic maps from Neurosynth for the terms (b) 'semantic' (1031 studies), (c) 'demands' (596 studies), and (d) 'reward' (922 studies). Neurosynth maps are coloured according to impact by lesion across the sample, with brighter areas reflecting those more often implicated in lesions. Each map was formatted in MRICron. We present (e) the mean percentage of each map lesioned across patients, with standard error of the mean error bars.

2.3.Background neuropsychological testing

Patients completed background tests of language, memory, executive function, and semantic cognition. Patients' individual scores and detailed interpretation of the sample's performance on these measures is provided in the Supplementary Materials (Supplementary Table 1: background neuropsychology and Supplementary Table 2: semantic tests). Patients presented with variable levels of impairment in speech fluency and word repetition, since they were solely selected on the basis of their multimodal semantic deficits. Most patients presented with impaired verbal working memory. Visuospatial processing was largely preserved. Eleven patients showed impairment on at least one test of executive function.

All patients were impaired on at least one verbal and one non-verbal semantic task, in line with our inclusion criteria. All patients performed close to ceiling level on word-picture matching, reflecting the low demands of this task. On word and picture versions of the camel and cactus test (CCT) of semantic association, half of the sample showed impairment.

Patients presented with considerable variation in picture naming, although performance was improved by successive phonemic cues in all patients who were able to name at least one picture, consistent with the view that SA patients retain knowledge of items that they fail to name. Patients also presented with the anticipated impairment in tests manipulating semantic control demands, including difficulty retrieving subordinate conceptual information, benefits from contextual cues and deleterious effects of miscues on synonym judgement, and difficulty rejecting strong thematic distractors. Statistical analyses of these effects are provided in Supplementary Materials *Background Neuropsychology* section and replicate the results of previous studies (e.g., Stampacchia et al., 2018).

Principal components analysis of the semantic tasks using oblique rotation revealed two components with Eigenvalues greater than 1 (see Table 1). The first component reflected performance on tasks with high semantic control demands: these factor scores were used as a semantic control composite for each participant, with lower scores reflecting greater impairment. Spearman's rank correlation coefficients showed this semantic factor was positively correlated with performance on the Brixton Spatial Anticipation Test: $r_s(14) = .837$, $p < .001$. It did not relate to performance on any other manipulation of executive function ($p \geq .200$). The second semantic factor loaded on tasks involving object identification.

Table 1

Pattern matrix for principal components analysis of semantic aphasia patients' performance on semantic tests with oblique rotation.

Task	Component 1 (Eigenvalue = 4.03)	Component 2 (Eigenvalue = 1.52)
CCT words	**.876**	.083
CCT pictures	**.896**	-.078
Picture naming	.089	**.877**
Word-picture matching	-.062	**.916**
Ambiguity task	**.900**	.057
Synonym judgement task	**.903**	-.154
Object use task	**.801**	.156

Note: Strong loadings for each component are in bold. CCT = Camel and Cactus Test

3. Experiment 1: The effect of cued extrinsic reward on semantic retrieval

3.1. Method

3.1.1. Participants

This sample included 16 patients (nine females) with a mean age of 64.4 years (SD = 12.3), a mean age of leaving education of 17.5 years (SD = 2.9), and a mean of 11.3 years (SD = 6.6) since their most recent stroke. These patients were compared with 15 controls (12 females) with a mean age of 70.7 (SD = 9.7), and a mean age of leaving education of 18.8

years (SD = 3.9). Patients and controls were matched for age [U = 74.0, p = .069], and age of leaving education [U = 102.0, p = .469].

3.1.2. Design

This experiment used a repeated measured design, with all participants making strong and weak thematic associations under the conditions of high and low reward. A three alternative forced choice format was used: participants were asked to select a target word, presented alongside two foils, based on the strongest thematic association to a probe word. The experiment was conducted over two sessions, each consisting of four high reward and four low reward blocks. Each block contained eight trials split equally across strong and weak associations. High and low reward blocks were alternated. There were 64 trials per session, and 128 trials in total. There was no difference across sessions for accuracy or response time: $p \geq .190$.

3.1.3. Stimulus properties

Descriptive statistics for Experiment 1 stimulus properties are reported in Supplementary Table 3. Target and probe words were taken from the Edinburgh Associative Thesaurus, a publicly available dataset of associative strength between words (Kiss et al., 1973). Probes and targets in strong association trials were more related than those in weak association trials: $t(67.6) = 42.1$, $p < .001$. There were no differences in association strength across blocks [$t < 1$], or sessions [$t < 1$].

We examined frequency, imageability and length of the target and probe words. Subtlex-UK (Van Heuven et al., 2014) was used to obtain word frequency. Sources for imageability ratings included the MRC Psycholinguistic Database (Coltheart, 1981), N-Watch (Davis, 2005), The Glasgow Norms (Scott et al., 2019), Bird et al. (2001a; 2001b), Cortese and Fugett (2004a; 2004b), and Davey et al. (2015). Frequency and imageability

scores were on 7-point Likert scales, and were averaged when multiple sources were available. Overall, 17% of frequency scores could not be retrieved. Missing scores were largely for compound words such as ‘snooker ball’ or ‘space suit’. Imageability ratings were obtained for all but one word. For both target and probe words, three separate 2x2 ANOVAs were run with frequency, imageability and length as dependent variables, examining effects of reward (high/low) and association strength (strong/weak). These ANOVAs are reported in Supplementary Table 5. All psycholinguistic properties were matched across reward condition and association strength [$p \geq .071$].

3.1.4. Procedure

Stimuli were presented on a laptop using PsychoPy3 (Peirce et al., 2019). Each block was preceded by a graphic, informing the participant that correct answers were each worth either 1 point (low reward) or 1,000 points (high reward). Due to impaired reading ability, the researcher read all words aloud to the patients. Patients indicated their response by pointing to the screen, with the researcher pressing the corresponding key. Control participants read the words themselves, and keyed in their own responses. Responses were followed by feedback, informing the participant that they had won either 1 or 1,000 points, or that they were incorrect and had not won any points. If a response was not given within ten seconds, participants were informed that they had not won any points. The prospect of gaining points was abstract and not linked to monetary gain. Each block was followed by self-report ratings of task enjoyment, response confidence, and task focus, each on a 7-point Likert scale. Figure 2 provides a summary of the procedure for Experiment 1.

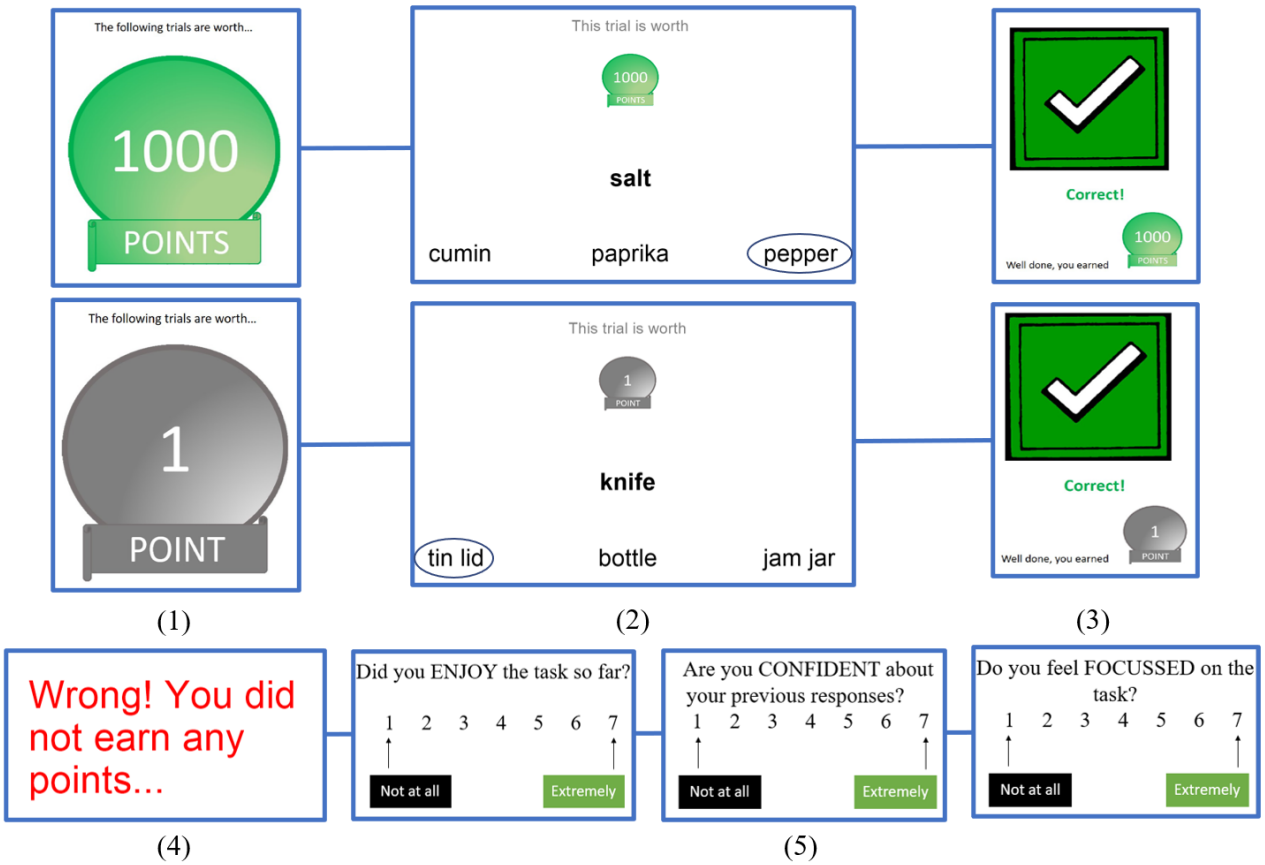


Figure 2: Experiment 1 procedure. (1) Each block was preceded by a high reward or low reward graphic. (2) Participants made thematic associations, either with strong or weak associations. Participants were provided with feedback as to whether their response was (3) correct or (4) incorrect. (5) Following each block, participants completed ratings of enjoyment, confidence, and focus.

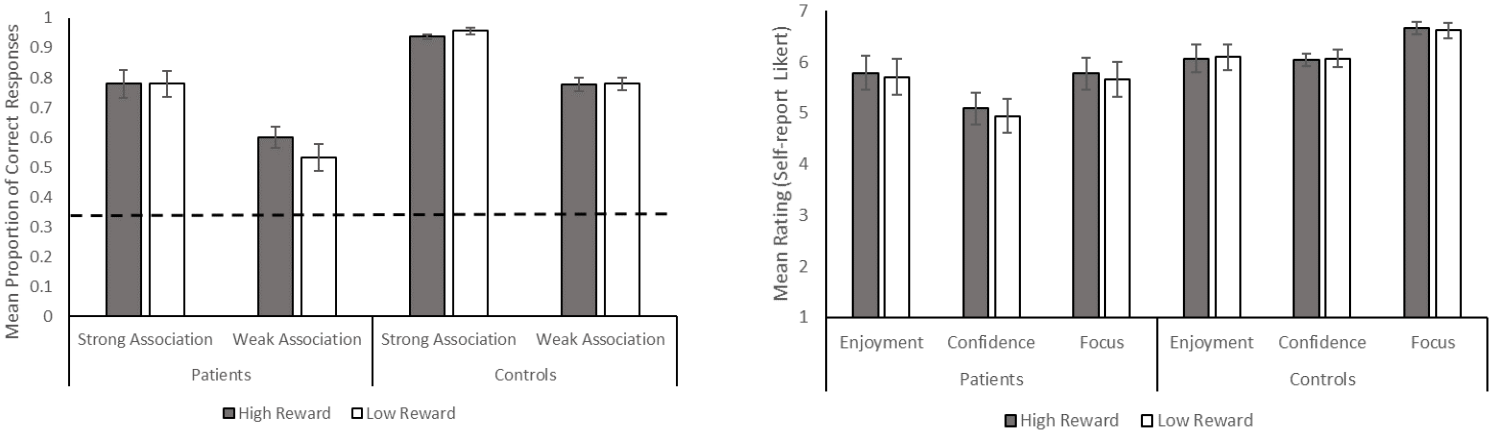
3.1.5. Data analysis

Accuracy (proportion of correct responses) was our key dependent measure. As we were specifically interested in effects of reward on patients' accuracy for weak associations, we first ran a repeated measures ANOVA for the patients alone, observing the effects of reward (high/low) and association strength (strong/weak) as within-subject independent variables. Accuracy was then entered into an omnibus mixed ANOVA, adding group (patients/controls) as a between-subjects independent variable. Post-hoc contrasts for

significant interactions are reported with Bonferroni-correction applied. Mixed ANOVAs were conducted for ratings of enjoyment, confidence, and focus, examining effects of reward and group. Analysis and interpretation of participants' response time can be seen in Supplementary Table 6.

3.2. Results

Figure 3 shows participants' mean accuracy and self-report ratings across reward condition, group, and association strength. Supplementary Table 7 provides metrics for all Experiment 1 variables by group.



(a) (b)

Figure 3: Experiment 1 bar graphs for (a) mean proportion of correct response (dotted line reflects chance performance, .33), and (b) self-report ratings across reward conditions, participant groups, and association strength, with standard error of the mean error bars.

3.2.1. Effects of reward on semantic retrieval in ANOVA patients

The patient group ANOVA revealed significant main effects of strength [$F(1, 15) = 147.7$, $p < .001$, $\eta_p^2 = .91$] and reward [$F(1, 15) = 5.4$, $p = .034$, $\eta_p^2 = .27$], and a significant reward by strength interaction [$F(1, 15) = 7.0$, $p = .019$, $\eta_p^2 = .32$]. Patients had higher accuracy on high than low reward trials, and on strong than weak association trials. Post-hoc contrasts for the interaction demonstrated that patients were more accurate for weak associations in the high than low reward condition [$t(15) = 3.3$, corrected $p = .010$]. There was no effect of reward on accuracy for strong associations [$t < 1$][1]. Patients' semantic control composite scores positively correlated with their overall accuracy [$r_s(14) = .70$, $p = .003$], reflecting higher accuracy in less impaired patients. There was no association between the semantic control composite and the effect of reward [strong: $r_s(14) = .16$, $p = .563$, weak: $r_s(14) = -.08$, $p = .780$].

3.2.2. Omnibus ANOVA comparing effects across patients and controls

ANOVA results are shown in Table 2. Controls were more accurate than patients overall. Accuracy was higher for strong than weak association trials. There was a reward by group interaction, with a larger difference in accuracy between high and low reward trials for patients [$t(15) = 2.3$, corrected $p = .068$] than controls [$t < 1$][2], although neither contrast survived correction for multiple comparisons. There was a reward by strength interaction, with a greater difference in accuracy between the high and low reward conditions for weak [$t(30) = 2.1$, corrected $p = .096$] than for strong association trials [$t < 1$][3], although again neither contrast survived correction. The three-way reward by strength by group interaction was not significant.

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[1] The assumption of normality was not always met but non-parametric tests elicited the same outcomes. Weak associations: $Z = -2.9$, corrected $p = .008$; strong associations: $Z = -.2$, corrected $p > 1$.
[2] [Patients: $Z = -2.1$, corrected $p = .070$, controls: $Z = -.4$, corrected $p > 1$].
[3] [Weak association: $Z = -2.4$, corrected $p = .034$, strong association: $Z = -.7$, corrected $p = .976$].

Ratings of enjoyment and confidence were not influenced by reward. Controls reported significantly higher confidence and focus than patients. A main effect of reward was found for focus, with higher ratings in the high than low reward condition. As all ratings were taken at the block level, it was not possible to investigate effects of association strength. There were too few participants in the current sample to assess the relationship between these ratings and accuracy.

Table 2

Omnibus ANOVA results for all Experiment 1 (extrinsic reward) dependent variables.

Dependent variable	Main effect/interaction	Results
Accuracy	Group	**$F(1, 29) = 18.9$, $p < .001$, $\eta_p^2 = .40$***
	Reward	$F(1, 29) = 1.3$, $p = .263$, $\eta_p^2 = .04$
	Reward by group	**$F(1, 29) = 4.8$, $p = .037$, $\eta_p^2 = .14$***
	Strength	**$F(1, 29) = 215.3$, $p < .001$, $\eta_p^2 = .88$***
	Strength by group	$F(1, 29) = 2.9$, $p = .100$, $\eta_p^2 = .09$
	Reward by strength	**$F(1, 29) = 5.6$, $p = .025$, $\eta_p^2 = .06$***
	Reward by strength by group	$F(1, 29) = 2.0$, $p = .169$, $\eta_p^2 = .06$
Enjoyment	Group	$F(1, 29) = .6$, $p = .438$, $\eta_p^2 = .02$
	Reward	$F(1, 29) = .2$, $p = .690$, $\eta_p^2 < .01$
	Reward by group	$F(1, 29) = .6$, $p = .441$, $\eta_p^2 = .02$
Confidence	Group	**$F(1, 29) = 7.7$, $p = .010$, $\eta_p^2 = .21$***
	Reward	$F(1, 29) = 1.4$, $p = .244$, $\eta_p^2 = .05$
	Reward by group	$F(1, 29) = 2.7$, $p = .112$, $\eta_p^2 = .09$
Focus	Group	**$F(1, 29) = 6.6$, $p = .016$, $\eta_p^2 = .19$***
	Reward	**$F(1, 29) = 5.8$, $p = .023$, $\eta_p^2 = .17$***
	Reward by group	$F(1, 29) = .8$, $p = .379$, $\eta_p^2 = .03$

*Note: ***** reflects a significant result.*

3.3. Experiment 1 summary

Experiment 1 studied effects of cued extrinsic reward on semantic aphasia patients' and controls' ability to retrieve thematic associations. An ANOVA for the patient group demonstrated that high reward improved accuracy on thematic judgements on weak but not strong associations, suggesting that high extrinsic reward can aid the retrieval of semantic associations when semantic control is deficient. Results from the omnibus ANOVA suggest that benefits of extrinsic reward were greater for the patients than for controls, and for weak than strong associations. Self-reported focus was also higher in the high than low reward condition.

4. Experiment 2: The effect of self-reference on semantic retrieval

4.1. Method

4.1.1. Participants

Experiment 2 included a subset of Experiment 1 participants. This included ten SA patients (six females) with a mean age of 62.4 years (SD = 10.1), a mean age of leaving education of 18.3 years (SD = 3.4), and a mean of 10.1 years (SD = 5.4) since their most recent stroke. Eleven control participants (eight females) were included in this sample with a mean age of 69.9 (SD = 10.3), and a mean age of leaving education of 18.9 (SD = 3.6). There was no significant difference between patients and controls for age [$U = 29.0$, $p = .067$], or age leaving education [$U = 52.0$, $p = .831$].

4.1.2. Design

This experiment used a repeated-measures design, with participants making strong and weak thematic associations across ‘self’ and ‘other’ conditions. A three alternative forced choice format was used. Probe pictures were used, as these were viewed as being fitting in the context of the shopping game used to reinforce self-referential encoding (explained in *4.1.4.*). Pictures were selected for 28 pairs of semantically related objects, within categories such as instruments and insects (e.g., HARP-LUTE, ANT-WASP). For each pair, one picture was allocated to the participant (‘self’) and one to the researcher (‘other’), counterbalanced across participants. Self and other trials were presented in a random order. The experiment was conducted over two sessions, each containing 56 trials. During the first session, participants completed strong and weak associations for one item in each pair. During the second session, participants completed the same associations for the remaining probes. Foils were thematically related to the target and were also kept consistent across both objects in each pair (see Figure 4 for examples). Session order was counterbalanced. There was no difference across sessions for accuracy or response time: $p \geq .259$.

4.1.3. Stimulus properties

Descriptive statistics for Experiment 2 stimulus properties are reported in Supplementary Table 4. Association strength between the probe pictures and target words was validated using ratings from an independent sample of healthy adults, on a 7-point Likert scale. Ratings were collected over three surveys, with sample size ranging between 30 and 42 participants. For both probes within each pair, equivalent strong and weak associations were generated. For example, pictures of a HARP and a LUTE were equally strongly and weakly associated with the target words STRINGS and VINYL, respectively. Associations between probes and targets were rated as stronger on strong than on weak association trials: $p < .001$.

Association strength within strong and weak association categories was matched across self-reference conditions and sessions: $p \geq .793$.

Frequency, imageability, and length were examined for the target words (using the same sources detailed in *3.1.3.*). Ratings of frequency and imageability could not be retrieved for 14% and 7% of target words, respectively. As in Experiment 1 this was largely the case for compound words. One-way ANOVAs were run for each factor, looking for effects of association strength. These ANOVAs are reported in Supplementary Table 5. No effects of association strength were found [$p \geq .195$]. Due to counterbalancing, it was not necessary to compare psycholinguistic ratings across self-reference conditions or sessions.

4.1.4. Procedure

At the start of both sessions, participants completed the allocation phase 'shopping game', intended to reinforce self-referential encoding. Both the participant and researcher had a 'shopping list' in front of them, respectively labelled "My shopping list" and "*researcher's name*'s shopping list", including pictures and names of each object allocated to them. The researcher and participant took turns finding the items on their lists and placing them into their respective baskets. Participants searched through a pile of laminated pictures, found the next item on their list, and placed it into their basket. Throughout this process the researcher provided verbal prompts to reinforce the self- and other-allocations (e.g., *"The next item on my list is a bagel, so I'll put that in my basket. Your next item is a ciabatta, find that one and put it into your basket."*).

The testing phase was performed on a laptop using PsychoPy3 (Peirce et al., 2019). The probe picture was presented above the three possible target words. Participants were asked to identify which of the three words was most thematically related to the probe. Participants indicated their responses in the same way as in Experiment 1 (see *3.1.4.*). Self-

reported ratings of response confidence were taken for each trial. Ratings of task enjoyment and focus were not gathered due to the fully randomised design. It was thought that asking participants to self-report enjoyment and focus after each trial may cause frustration and negatively affect enjoyment or focus.

Finally, participants completed an episodic memory test to test for a self-reference recognition memory effect, shown previously in SA (Stampacchia et al., 2019). Participants were presented with 30 images, 10 of which had been allocated to them (“Mine”), 10 which had been allocated to the researcher (“*researcher’s name*”), and 10 which were not present in the allocation or testing phase (“New”). Participants indicated which of these three categories they believed each picture belonged to. The same memory test was administered after both sessions. A summary of the Experiment 2 procedure can be seen in Figure 4.

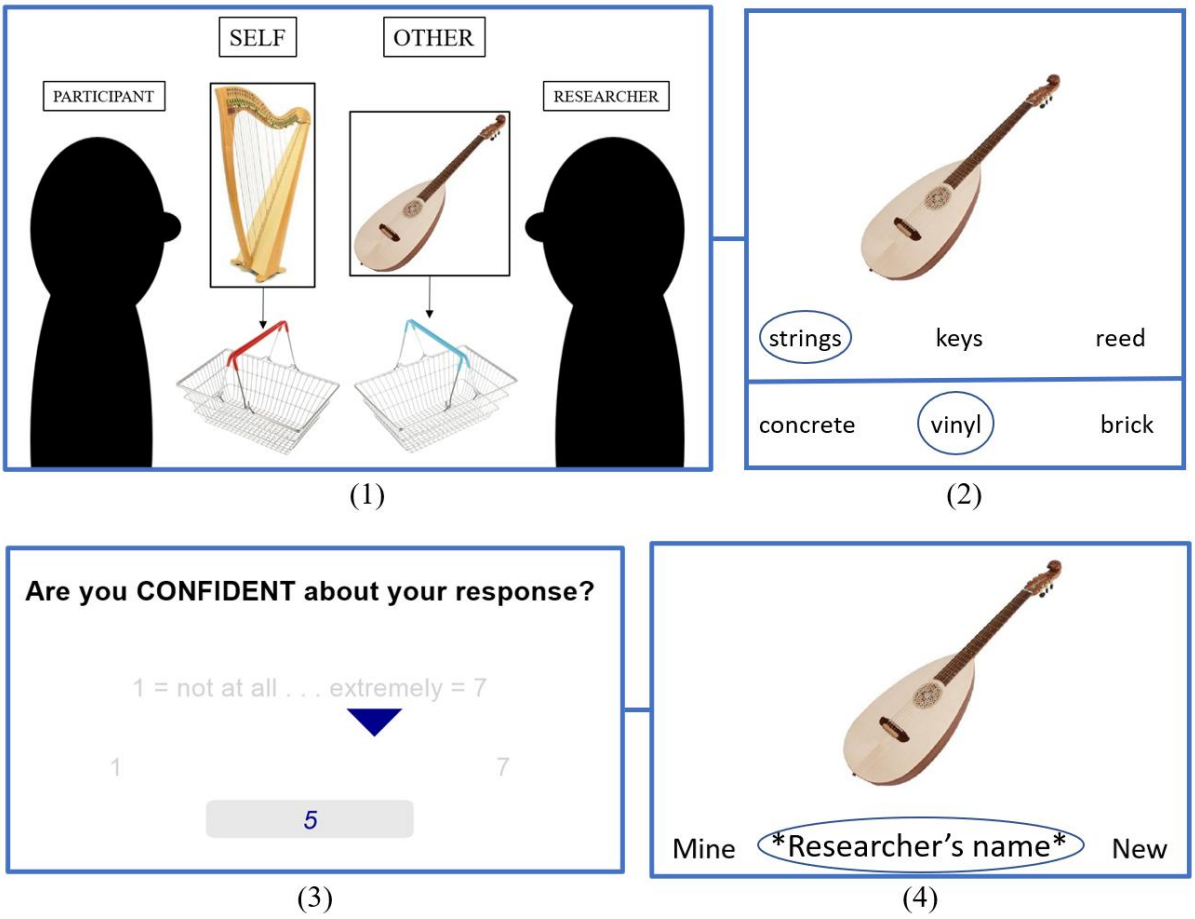

Figure 4: Experiment 2 procedure. (1) One item from each pair of probe pictures was allocated to the participant, and the other to the researcher. (2) Participants completed strong and weak associations for both the self- and other- allocated items in each pair. (3) After each trial participants gave a rating of response confidence. (4) Participants were tested on source memory for 30 pictures.

4.1.5. Data analysis

Accuracy (proportion of correct responses) was our key dependent measure. As benefits of self-reference were only expected for patients on weak association trials, a repeated measures ANOVA was first run for patients only with self-reference condition (self/other) and association strength (strong/weak) as within-subjects variables. Accuracy was then entered into an omnibus mixed ANOVA, adding group (patients/controls) as a between-

subjects variable. A mixed ANOVA was conducted for confidence ratings, using the same design as above. Analysis and interpretation of participants' response time can be seen in Supplementary Table 6. Results of the episodic memory test were analysed using A', a non-parametric measure of recognition memory, based on the ratio of correct 'hits' to false positive responses (Snodgrass & Corwin, 1988). This was calculated for the conditions of self, other, and new. The proportion of correct responses did not vary across sessions for any condition [$p \geq .103$]. Performance was therefore averaged across the two sessions. In cases where memory data was only available for one session (N = 5), data for this one session was entered into the analysis. The effects of group and self-reference on A' were assessed using a mixed ANOVA.

4.2. Results

Participants' A' scores, mean accuracy, and response confidence across self-reference condition, group, and association strength can be seen in Figure 5. Supplementary Table 8 provides metrics for all Experiment 2 dependent variables by group. Results for the recognition memory and whole-group omnibus ANOVAs are in Table 3.

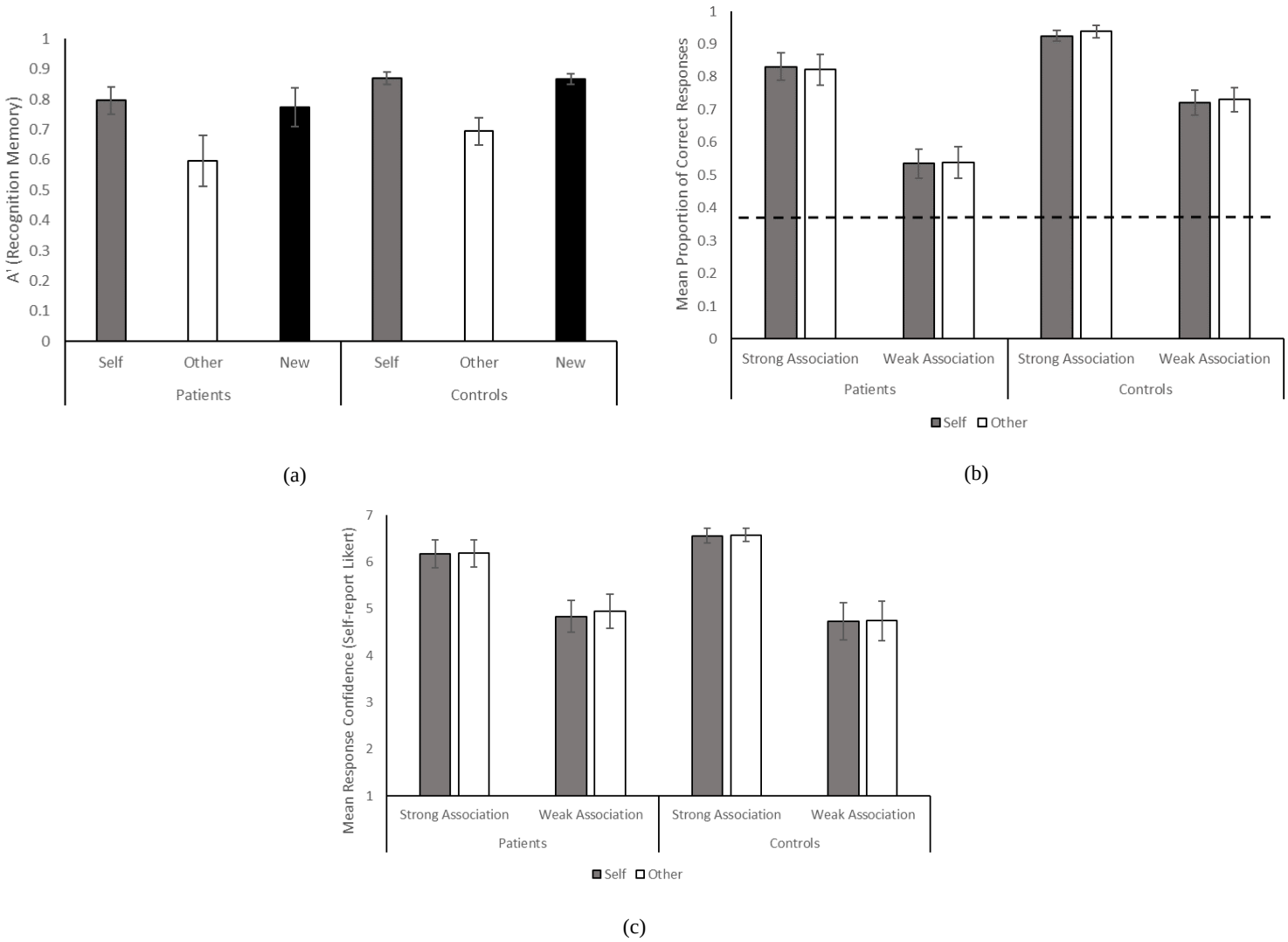

Figure 5: (a) A', a non-parametric signal detection measure of recognition memory based on the proportion of correct hits and false positives, (b) mean proportion of correct responses (dotted line = chance), and (c) mean self-report ratings of response confidence, with standard error of the mean error bars.

4.2.1. Effects of self-reference on recognition memory

We report analysis of recognition memory first in order to show the presence of a self-reference memory effect. As expected, planned comparisons of A' revealed better recognition memory for self-allocated than other-allocated pictures [patients: t(9) = 3.0, *p* =

.014, controls: $t(10) = 5.6$, $p < .001$], and for new than other-allocated pictures [patients: $t(9) = 3.3$, $p = .010$, controls: $t(10) = 4.9$, $p = .001$]. There was no difference between self-allocated and new pictures [patients: $t < 1$, controls: $t < 1$] . Both groups therefore showed the expected self-reference memory effect, as well as effects of novelty.

4.2.2. Effects of self-reference on semantic retrieval in SA patients

For patients' semantic judgements, ANOVA revealed a significant main effect of association strength [$F(1, 9) = 251.1$, $p < .001$, $\eta_p^2 = .97$], with higher accuracy on strong than weak association trials. There was no significant main effect of self-reference [$F < 1$] or self-reference by strength interaction [$F < 1$]. Patients' semantic control composite score positively correlated with overall accuracy [$r_s(8) = .90$, $p < .001$], reflecting more accurate responses in less impaired patients.

4.2.3. Omnibus self-reference ANOVAs

In the omnibus ANOVA comparing performance across groups (see Table 3), controls were more accurate than patients. There was a main effect of association strength, reflecting higher accuracy for strong than weak association trials. There were no significant effects or interactions involving self-reference. Ratings of response confidence were higher for strong than weak association trials.

Table 3

Omnibus ANOVA results for all Experiment 2 (self-reference) dependent variables.

Dependent variable	Main effect/interaction	Results
A' (recognition memory)	Group	$F(1, 19) = 2.1$, $p = .168$, $\eta_p^2 = .10$
	Self-reference	**$F(1.6, 29.5) = 24.3$, $p < .001$, $\eta_p^2 = .56$***
	Self-reference by group	$F(1.6, 29.5) = .1$, $p = .861$, $\eta_p^2 < .01$
Accuracy	Group	**$F(1, 20) = 12.7$, $p = .002$, $\eta_p^2 = .38$***
	Self-reference	$F(1, 20) = .1$, $p = .767$, $\eta_p^2 < .01$
	Self-reference by group	$F(1, 20) = .3$, $p = .595$, $\eta_p^2 = .01$
	Strength	**$F(1, 20) = 113.3$, $p < .001$, $\eta_p^2 = .87$***
	Strength by group	$F(1, 20) = 3.7$, $p = .068$, $\eta_p^2 = .16$
	Self-reference by strength	$F(1, 20) = .1$, $p = .803$, $\eta_p^2 < .01$
	Self-reference by strength by group	$F(1, 20) = .2$, $p = .677$, $\eta_p^2 < .01$
Confidence	Group	$F(1, 20) = .1$, $p = .776$, $\eta_p^2 < .01$
	Self-reference	$F(1, 20) = .3$, $p = .589$, $\eta_p^2 = .02$
	Self-reference by group	$F(1, 20) = .1$, $p = .746$, $\eta_p^2 < .01$
	Strength	**$F(1, 20) = 94.9$, $p < .001$, $\eta_p^2 = .83$***
	Strength by group	$F(1, 20) = 2.9$, $p = .102$, $\eta_p^2 = .01$
	Self-reference by strength	$F(1, 20) = .2$, $p = .688$, $\eta_p^2 < .01$
	Self-reference by strength by group	$F(1, 20) = .2$, $p = .675$, $\eta_p^2 = .01$

4.3. Experiment 2 summary

Experiment 2 examined the effect of self-referential encoding on SA patients' and controls' ability to make thematic associations. As in Experiment 1, controls were more accurate than the patients, and performance was poorer on weak than strong association trials. Greater response confidence was observed for strong versus weak associations. Despite showing a benefit of self-referential encoding for recognition memory, self/other allocation did not affect the retrieval of thematic associations.

5. Discussion

The current study explored the impact of motivation on controlled semantic retrieval in SA patients with multimodal semantic impairment following left frontoparietal stroke. We assessed the impact of performance-contingent extrinsic reward (Experiment 1) and self-referentially encoded pictures (Experiment 2) on patients' and controls' ability to retrieve strong and weak thematic associations. As expected, SA patients showed lower accuracy overall. Both groups showed lower accuracy for weak associations, thought to reflect higher semantic control demands. Importantly, extrinsic reward improved SA patients' but not controls' accuracy. Self-reference did not impact participants' semantic performance, despite boosting recognition memory, suggesting that the manipulation used was insufficient to ameliorate semantic control impairment.

SA patients typically show greater semantic impairment for weak associations, when the retrieval of non-dominant information is required (Thompson et al., 2017). In this study, we did not observe the anticipated interactions between group and strength of association in accuracy, perhaps because the weak association trials were relatively difficult, eliciting substantial numbers of errors even in controls, and perhaps because our patient sample included mildly impaired individuals. Supplementary analyses of response times (see Supplementary Table 6) show the same pattern, with slower responses overall for patients than controls, and for weak than strong associations, but no strength by group interaction. Experiment 1 demonstrated improvements in patients' accuracy for weak associations following high extrinsic reward, but no improvement for strong associations. SA patients showed an effect of reward while controls did not, suggesting that when sufficient control over semantic retrieval is harder to achieve, the benefits of extrinsic reward are maximised. Anticipation of extrinsic reward may increase preparatory cognitive control, supporting the

ability to maintain task-relevant representations and shield against irrelevant information (Goschke & Bolte, 2014). This is consistent with the current finding that high extrinsic reward increased self-reported task focus. Furthermore, explicit knowledge of task goals has been shown to facilitate semantic judgements (Zhang et al., 2021). Reward may benefit semantic control by augmenting goal-maintenance.

Our findings are also consistent with evidence that extrinsic incentives can improve performance on tasks requiring domain-general cognitive control (Capa et al., 2013). Neuroimaging research has shown that introducing extrinsic rewards to cognitive control tasks increases activity across executive regions in MDN (Shashidhara et al., 2019), increases functional connectivity between the ventral striatum and MDN (Cubillo et al., 2019), and improves the decoding accuracy of MVPA classifiers for task-set information (Etzel et al., 2016). This reflects enhanced coding of task-relevant information, in line with suggestions that extrinsic reward improves goal maintenance (Goschke & Bolte, 2014). It is possible that the interaction between reward and semantic control seen in the current study is also attributable to modulation of MDN regions, as well as regions specifically recruited during semantic control. Indeed, MDN regions are recruited during semantic tasks with high control demands (Wang et al., 2020). Furthermore, while semantic control regions including the LIFG and pMTG are frequently lesioned in SA patients (Jefferies, 2013), research has demonstrated compensatory activation in residual semantic control regions in this group (Hallam et al., 2018). Future neuroimaging investigations could elucidate the extent to which motivated semantic control is attributable to modulation or recruitment of intact domain-general control regions.

While there is evidence that semantic and domain-general control draw on separable mechanisms (Gonzalez Alam et al., 2018), patients with SA show an association between performance on tests of these two functions (Thompson et al., 2018). Semantic and executive

control mechanisms may recruit adjacent regions of cortex, such that damage to one system is frequently accompanied by damage to the other (Wang et al., 2018). In line with this, the current study revealed a positive correlation between semantic ability and performance on the Brixton Spatial Anticipation Test, a complex nonverbal executive test. Patients' semantic control composite did not correlate with executive measures with verbal requirements including the difference between parts A and B of the Trail Making Test. Similarly, no correlation was found between patients' semantic control composite and the nonverbal Raven's coloured progressive matrices. While these null results may reflect a lack of statistical power, our results are sufficient to show that associations between semantic and executive performance are not confined to tests with verbal requirements, consistent with evidence that executive task performance is independent of verbal demands in aphasia patients with LIFG lesions (Kendrick et al., 2019; see Chapman et al., 2020 for an alternative view).

The current findings may have implications for aphasia rehabilitation. SA patients benefit from external prompts which allude to intended target concepts, including phonemic cues (Jefferies et al., 2008), contextual cues such as sentences (Noonan et al., 2010), and emotional cues (Lanzoni et al., 2019). The current findings demonstrate that prompts which do not provide additional information concerning target concepts, such as abstract extrinsic incentives, can confer similar benefits. Positive effects of expected rewards are seen in 'gamification' strategies to neurorehabilitation (and education more widely), in which tasks are made more motivating through the incorporation of typical game features, such as rewards and social competition (Landers, 2014). Extrinsic incentives like 'points' are commonly incorporated (Hamari et al., 2014). A recent preliminary investigation demonstrated that a gamified approach may be effective in the rehabilitation of word production following stroke (Romani et al., 2019). The current findings merit further

investigation of the use of gamified extrinsic incentives in addressing post-stroke semantic retrieval impairments.

The current manipulation of self-reference was intended as a proxy for intrinsic motivation, based on evidence of overlapping behavioural effects of self-reference and reward processing (Sui & Humphreys, 2015a), and overlapping neural substrates underlying self-reference and intrinsic motivation (Tamir & Mitchell, 2012). We found the expected effect of self-reference on recognition memory, suggesting that our manipulation successfully evoked self-referential encoding, consistent with prior evidence from SA patients (Stampacchia et al., 2019). However, we did not find evidence that self-reference can modulate semantic retrieval. This null result does not necessarily preclude the role of intrinsic motivation in semantic performance. Rather, the manipulation in the current study may have been insufficient. In future studies, further tailoring may be required to elicit stronger intrinsic motivators. As intrinsic motivation reflects inherent interest or enjoyment (Mori et al., 2018), it may be beneficial to include stimuli which are specifically of interest to, or belong to, the participant.

5.2. Limitations

While evidence of the modulatory effects of reward are promising, the current study is limited in so far as we did not measure several related constructs. Affective abnormalities including apathy (Fishman et al., 2018) and hypo/hyperarousal (Heilman et al., 1978; Laures et al., 2003) are common following stroke. Such abnormalities could interfere with extrinsic reward sensitivity. This has been demonstrated in relation to apathy, following damage to subcortical reward processing regions (Rochat et al., 2013). The current study cannot account for these effects. It is worth noting, however, that in the current sample, subcortical and medial regions associated with reward processing were relatively intact (see *2.2.*). Future investigations into reward processing in post-stroke aphasia may benefit from measuring

apathy, reward sensitivity, and physiological arousal, to better elucidate the relationship between these constructs and effects of abstract rewards.

5.1. Conclusion

The current study demonstrates that extrinsic reward can improve SA patients' ability to make thematic associations. As with domain-general cognitive control, extrinsic reward may bolster semantic retrieval through increased proactive control. These findings have practical implications for the rehabilitation of post-stroke semantic impairment; language therapy activities for SA patients could be facilitated using a gamification-based approach incorporating external rewards. Effects of self-reference on semantic performance were not observed.

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