The interplay between control processes and feature relevance: Evidence from dual task methodology

Maria Montefinese^{a,*}, Glyn Hallam^b, Hannah Elizabeth Thompson^c, Elizabeth Jefferies^b

^aDepartment of Experimental Psychology, University College London, London, WC1H 0AP, United Kingdom

^bDepartment of Psychology, University of York, York, YO10 5DD, United Kingdom

^cSchool of Psychology, University of Surrey, Guildford, GU27XH, United Kingdom

*Corresponding author:

Maria Montefinese

Department of Experimental Psychology, University College London,

26 Bedford Way, WC1H 0AP, London, United Kingdom

Email: maria.montefinese@gmail.com , m.montefinese@ucl.ac.uk

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Abstract

Neuropsychological studies suggest a distinction between (i) semantic knowledge and (ii) control processes that shape the retrieval of conceptual information to suit the task or context. These aspects of semantic cognition are specifically impaired in patients with semantic dementia and semantic aphasia respectively. However, interactions between the structure of knowledge and control processes that are expected during semantic retrieval have not been fully characterised. In particular, domain-general executive resources may not have equal relevance for the capacity to promote weak yet relevant features (i.e., “controlled retrieval), and to ignore or suppress distracting information (i.e., “selection”). Here, using a feature selection task, we tested the contribution of featural relevance to semantic performance in healthy participants under conditions of divided attention. Healthy participants showed greater dual-task disruption as the relevance value of the distracter feature linearly increased, supporting the emerging view that semantic relevance is one of the organizing principles of the structure of semantic representation. Moreover, target relevance, word frequency and inter-correlational strength affected overall performance, but they did not show an interaction with dual-task conditions. These results suggest that domain-general control processes, disrupted by divided attention, are more relevant to the capacity to efficiently avoid distracting information during semantic decision-making than to the promotion of weak target features. The present study therefore provides novel information about the nature of the interaction between structured conceptual knowledge and control processes that support the retrieval of appropriate information, and relates these results to a new theoretical framework, termed controlled semantic cognition.

Keywords: semantic control process; feature-based models; feature relevance; feature selection; dual task.

Introduction

In the course of our life, we acquire an enormous amount of knowledge about the world from experience, and semantic cognition allows us to make productive use of this knowledge to understand stimuli and to guide our thoughts and behaviour in a rich environment. It relies on at least two interacting components: 1) stored semantic knowledge (i.e., semantic representation) and 2) control processes which help to direct and control semantic activation in line with current goals and constraints (Jefferies, 2013; Jefferies & Lambon Ralph, 2006; Noonan, Jefferies, Visser, & Lambon Ralph, 2013). Semantic representation might be of little utility in isolation, without semantic control to shape the pattern of retrieval, since only particular aspects of our knowledge are relevant in any given situation. For example, we know many different things about MAGAZINES: they '*are sold in stores*', '*have a cover*', '*have articles*' etc..... One of the first things that come to mind is that MAGAZINES are '*used for reading*': this is a dominant property that is thought to be retrieved relatively automatically. In contrast, retrieval of the knowledge that MAGAZINES can be '*used for covering*' when it rains might require greater control, since this non-dominant property is unlikely to emerge strongly from spreading activation from the concept itself (Corbett, Jefferies, & Lambon Ralph, 2009; Jefferies & Lambon Ralph, 2006; Noonan, Jefferies, Corbett, & Lambon Ralph, 2010; Whitney, Grossman, & Kircher, 2009). Thus, it has been argued that semantic control processes are a necessary component of semantic cognition and interact with stored semantic knowledge during the retrieval of meaning.

Semantic representation and control can be impaired separately, yielding dissociations between semantic dementia (characterized by degradation of the store of conceptual knowledge following anterior temporal lobe atrophy) and semantic aphasia (SA), which results in deficits of semantic control and difficulties in manipulating semantic knowledge in the context of an intact semantic store (Corbett, Jefferies, Ehsan, & Lambon Ralph, 2009; Corbett, Jefferies, & Lambon Ralph, 2009; Jefferies, Baker, Doran, & Ralph, 2007; Jefferies & Lambon Ralph, 2006; Rogers, Patterson, Jefferies, & Lambon Ralph, 2015). Converging evidence for a contribution of left inferior frontal gyrus, posterior middle temporal gyrus and intraparietal sulcus to semantic control is also

provided by functional neuroimaging and transcranial magnetic stimulation studies in healthy participants (Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Davey et al., 2016; Noonan et al., 2013; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Wagner, Paré-Blagoev, Clark, & Poldrack, 2001; Whitney, Kirk, O'Sullivan, Lambon Ralph, & Jefferies, 2012). Control processes engage some of the regions composing the so-called multiple-demand network (Duncan, 2010) including the inferior frontal sulcus and inferior parietal sulcus (see review by Lambon Ralph, Jefferies, Patterson & Rogers, 2017), irrespective of the type of representation that has to be controlled; however, also other regions, such as the posterior middle temporal gyrus and the ventral prefrontal cortex, are specifically involved in semantic control processes, and potentially allow the interaction of domain-general control processes and semantic representations (Badre et al., 2005; Davey et al., 2016).

The controlled retrieval of weakly-activated semantic knowledge is a form of controlled cognition that might be specific to memory. In line with this expectation, controlled retrieval is thought to be supported by anterior/ventral parts of inferior prefrontal cortex within the default mode network; these brain regions are not implicated in domain-general control (Davey et al., 2016). In contrast, the selection of goal-relevant semantic knowledge over irrelevant competitors (Badre et al., 2005; Whitney et al., 2012) is thought to be supported by posterior/dorsal parts of inferior prefrontal cortex and the adjoining inferior frontal sulcus and precentral sulcus, which overlap with the multiple-demand system (Davey et al., 2015; 2016) and which are implicated in aspects of control beyond the semantic domain (for example, they are activated by demanding phonological judgements; Gough, Nobre & Devlin, 2005; Krieger-Redwood, Gaskell, Lindsay & Jefferies, 2013; Noon et al., 2013). This dissociation between large-scale brain networks potentially corresponds to the distinction between “controlled retrieval” (i.e., identifying and promoting weak yet relevant aspects of knowledge) and “selection” (i.e., dealing with competition between representations). In controlled retrieval tasks, participants have to choose a target that is weakly related to a given cue, as opposed to strongly related to the cue. For strong associations, performance is supported by the automatic

spread of activation in the semantic network, while additional control resources are required to recover the weak associations. In selection tasks, in contrast, participants have to select the target related to the cue whilst ignoring distractors that are task-irrelevant but strongly related to the cue (see Figure 1). SA patients show impairments in both of these situations: (i) difficulties in retrieving non-dominant or distant associations with improvement following cues that provide external constraints on retrieval (i.e., poor controlled retrieval) (Corbett, Jefferies, & Lambon Ralph, 2011; Jefferies, Patterson, & Lambon Ralph, 2008); (ii) difficulties in selecting non-dominant associations over more dominant, but irrelevant, competitors (i.e., impaired semantic selection) (Noonan et al., 2010); (iii) equivalent impairment across modalities when control demands are held constant (Corbett, Jefferies, Ehsan, et al., 2009; Corbett, Jefferies, & Lambon Ralph, 2009; Gardner et al., 2012) and (iv) other control deficits that parallel problems in the semantic domain (Jefferies & Lambon Ralph, 2006). These patients are thus vulnerable to the presence of strong distractors in semantic judgement tasks and also find it difficult to link together concepts that share fewer features (e.g., linking SHOWER with OVEN as household items, compared to SHOWER with BATH; Noonan et al., 2010). Additionally, for words with multiple meanings, dominant interpretations remain accessible when subordinate meanings are no longer understood (e.g., GAME with TOY compared to GAME with HUNT).

These findings make the general prediction that semantic performance should reflect an interaction between the capacity for semantic control and the structure of the knowledge being probed (Sartori & Lombardi, 2004). According to the feature-based models of semantic representation (McRae, Cree, Seidenberg, & McNorgan, 2005; Montefinese, Vinson & Ambrosini, 2018; Vinson & Vigliocco, 2008), each concept in the semantic store has a distributed network of associated features, such as the concept TIGER characterized by the semantic features ‘has legs’, ‘has teeth’, ‘has stripes’ (Kremer & Baroni, 2011; Vinson & Vigliocco, 2008; Montefinese, Ambrosini, Fairfield, & Mammarella, 2013a, 2013b; 2013c; Montefinese, Zannino, & Ambrosini, 2015). These sets of features contribute with different weights to the meaning (Cree, McRae, & McNorgan, 1999; McRae,

2004; Montefinese, Ciavarro, & Ambrosini, 2015). Indeed, the importance of a feature to a concept is thought to be related to its: (i) dominance (e.g., the proportion of people who list the feature as connected to the concept; Kremer & Baroni, 2011; Montefinese et al., 2013b; Vinson & Vigliocco, 2008); and (ii) distinctiveness (identifiable and distinguishing feature – e.g., UDDER is more distinctive than EYES at identifying the concept COW (Cree, McNorgan, & McRae, 2006; Cree & McRae, 2003; Garrard, Lambon Ralph, Hodges, & Patterson, 2001; McRae, Cree, Seidenberg, & McNorgan, 2005; Montefinese & Vinson, 2015).

A feature-based construct, termed *semantic relevance*, is a nonlinear combination of dominance (the local component, which reflects the importance of a property for a concept) and distinctiveness (the global component, which reflects the salience of the same feature for the whole set of concepts) (Sartori, Gnoato, Mariani, Prioni, & Lombardi, 2007; Sartori & Lombardi, 2004; Sartori, Lombardi, & Mattiuzzi, 2005). Semantic relevance thus captures the “core” meaning of a concept (Mechelli, Cappa, & Sartori, 2011; Sartori et al., 2007; Sartori & Lombardi, 2004). It has been found to predict performance more closely than either featural dominance or distinctiveness alone (see Montefinese, Ambrosini, Fairfield & Mammarella, 2014a) and other featural measures alone. Moreover, it has been shown to account for many of the phenomena in semantic representation disorders and, in particular, in category-specific deficits (Sartori & Lombardi, 2004), suggesting that the relevance of semantic features may be an organizing principle in semantic representation.

Semantic relevance might also interact with control processes, since highly relevant features have reduced requirements for controlled retrieval, while distractors with highly-relevant features that irrelevant to the ongoing task increase selection demands. Semantic relevance denotes the strength of the relationship between two elements in the semantic store, that is, between a feature and a concept. The target-feature relevance for a concept thus reflects the ease with which that feature will be automatically retrieved, while the distractor-feature relevance for a concept reflects the strength of competition from the distracter during target selection. In this study, we investigated the interaction between semantic representation and semantic control process by exploring the impact of featural

relevance on performance when the overall capacity for cognitive control was temporarily reduced in healthy people due to divided attention (c.f., dual-task methodology, Almaghyuli, Thompson, Lambon Ralph, & Jefferies, 2012). We varied both the semantic relevance of the target to the probe (i.e., the requirement for controlled retrieval) and the relevance of distractors (i.e. the need to resolve competition through selection). Previous studies of controlled semantic cognition in healthy participants did not test how semantic control processes are influenced by a continuous dimension of featural salience for the concept meaning, such as semantic relevance (Almaghyuli et al., 2012; Whitney et al., 2012). More importantly, little behavioural research has tried to separate semantic selection and controlled retrieval processes (Thompson-Schill & Botvnick, 2006) and thus, disambiguate in a fine-grained way the contribution of both distractor and target features to semantic performance, respectively.

Here, we tackled this issue with a semantic selection task, combined with a dual task manipulation expected to reduce the capacity for domain-general cognitive control. We examined the effect of dual task demands on both the retrieval of weak targets with low relevance features, and the capacity to resolve competition from distractor words with high-relevance features. If a concurrent task affects domain-general control, including selection amongst competing representations brought about by the presence of a strong distractor, we might expect a significant fine-grained interaction between the relevance value of the distracter feature and single vs. dual task conditions – there should be a greater decrease in performance in the dual task condition as the relevance value of the distracter feature increases. Moreover, if a non-semantic concurrent task does not disrupt controlled retrieval processes that are partially separate from domain-general control, there should be no interaction with the relevance of the target feature, even though target feature relevance is expected to predict performance overall. Alternatively, if there is little or no distinction between control processes that underpin controlled retrieval and selection, we might expect dual-task demands to interact similarly with target feature relevance and distractor feature relevance. In this way, we tested different accounts of the cognitive underpinnings of different forms of semantic control.

Methods

Participants

Twenty-six right-handed native English speakers (twenty-one females; mean age: 20.58 years, $SD = 2.21$) from the University of York participated in this study. They participated for £5 or course credit. Participants had normal or corrected-to-normal vision and gave written informed consent before the beginning of the study. The study was approved by the local ethics committee and was performed in accordance with the ethical standards of the 2013 Declaration of Helsinki for human studies (World Medical Association).

Apparatus and Stimuli

Auditory-verbal 1-back task

Each trial involved the auditory presentation of random digits (from 1 to 9). The auditory stimuli were digitally recorded by a female native English speaker in a sound-attenuated chamber at 32-bit resolution and sampling rate of 44.1 KHz. The average duration of the auditory stimuli was 620 ms ($SD = 95.72$ ms) and they were presented at a presentation rate of roughly 0.77 Hz at a constant (but comfortable) intensity using stereo headphones.

Semantic feature selection task

We selected the stimuli and the relative lexical/semantic measures from McRae and colleagues' (2005) database (the complete set of stimuli can be found in our project on the Open Science Framework at osf.io/vsx7z). There were 128 English words denoting exemplar-level concepts (cue concepts) and the same number of targets, related distracters, and unrelated distracters. In each trial, a cue concept was presented above a row of three words denoting two features of the cue concept (one target feature and one distracter) and one unrelated distracter.

We created four blocks of 32 trials for four different semantic relations according to Wu and Barsalou's taxonomy (in McRae et al.'s norms): the target feature (underlined) could indicate: 1) the

category to which the concept belonged (e.g., KNIFE – sharp, cutlery, musician); 2) a part of the concept (e.g., ONION – skin, decoration, tears); 3) an action that the concept could do (e.g., TOAD – friendly, croaks, amphibian); or 4) the material that the concept was made of (e.g., CIGAR – tobacco, expensive, meat). The related distracter could share any other semantic relationship with the cue concept, except the four types of relationship used as target features, and was randomly chosen from those included in the McRae et al.’s (2005) norms (see Figure 1 and supplementary materials for the details about the stimuli and relative semantic measures at osf.io/vsx7z).

<p>HAMSTER</p> <p><u>PET</u> PARAMEDIC <i>DRINKS</i></p>	<p>KNIFE</p> <p><i>SHARP</i> <u>CUTLERY</u> MUSICIAN</p>	<p>Category: Find the word that denotes the category to which the top word belongs</p>
<p>CUCUMBER</p> <p><i>VINES</i> EFFICIENT <u>SEEDS</u></p>	<p>ONION</p> <p><u>SKIN</u> DECORATION <i>TEARS</i></p>	<p>Part: Find the word that denotes a part of the top word</p>
<p>TOAD</p> <p>FRIENDLY <u>CROAKS</u> <i>AMPHIBIAN</i></p>	<p>GOAT</p> <p><u>CLIMBS</u> CONVENIENT <i>BEARD</i></p>	<p>Action: Find the word that denotes an action that the top word can do</p>
<p>CIGAR</p> <p><u>TOBACCO</u> EXPENSIVE MEAT</p>	<p>MAGAZINE</p> <p><i>READING</i> <u>PAPER</u> BACON</p>	<p>Material: Find the word that denotes the material with which the top word is made</p>

Figure 1. Example trials.

Participants had to select the target feature (underlined) that may take different degrees of relevance for the probe concept above, in one of the following semantic dimensions: 1) category; 2) part; 3) action; 4) material. One distracter (in italics) may take different degrees of relevance for the concept as well, but it was irrelevant to the dimension of knowledge being probed. The other distracter was unrelated to the probe concept (in regular font).

To test our hypothesis, we parametrically manipulated the semantic relevance (i.e., the strength of the relationship) between the cue concept and feature word (target or distracter) (see Figure 1 for examples). The semantic relevance value for each true feature-concept pair was calculated as $k_{ij} = x_{ij} \times \ln(I/I_j)$ (see Sartori et al., 2007), where x_{ij} indicates the dominance of a feature j in a concept i and represents the local component of k_{ij} , I indicates the total number of concepts in McRae et al.’s norms (i.e., 541), I_j indicates the number of concepts in which the feature j appears, and $\ln(I/I_j)$ represents the global component of k_{ij} .

To match the other confounding variables, we matched the semantic relevance of target and distracter features as well as the other lexical-semantic variables (see Table 1) across the single and dual tasks within each of the four blocks ($t_{(126)} < 1.399$; $p > .167$; Cohen's $d < .248$) (see Table 2 for the descriptive statistics of these variables). Concept and feature names were only presented once in the experiment. In addition to using matched materials, we controlled for the effect of these variables on participants' performance in the analyses.

Table 1. Semantic/lexical variables derived from McRae et al.'s norms (2005) that were matched across the single and dual task conditions.

Variable	Explanation
Stimulus length	Total number of letters in concept and feature
Word frequency	Natural logarithm of frequency (sum of singular and plural uses) of the words used as concepts derived from the British National Corpus
Familiarity	Mean familiarity rated by 20 participants (1–9 scale, 9 = <i>extremely familiar</i>)
Number of features	Total number of features, listed for a given concept
Inter-correlational Strength	Summed percentage of shared variance across all of the other concept's features with which the target feature is significantly correlated

Table 2. Descriptive statistics of lexical/semantic variables across the single and dual task conditions.

	Single		Dual	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Target Relevance	1.75	1.03	1.76	1.13
Distracter Relevance	1.83	1.16	1.72	1.16
Stimulus length	25.67	0.80	25.59	0.77
Word frequency	6.84	1.26	6.51	1.59
Familiarity	5.74	1.96	5.77	1.93
Number of features	15.52	3.34	14.73	3.02
Inter-correlational Strength	52.06	79.80	47.98	66.34

Procedure

The presentation of stimuli was controlled by the E-prime software (Schneider, Eschman, & Zuccolotto, 2002). The experiment was presented in 6 blocks: (i) 1-back task under single task

conditions; (ii) 4 blocks of the feature selection task, corresponding to the 4 types of semantic relations, (iii) a final block of the 1-back task under single task conditions. Trials in the feature selection task in the middle phase of the experiment were sometimes performed under dual task conditions (i.e., with the concomitant 1-back task), while on other trials within the same block, semantic judgements were performed under single task conditions. Single and dual task trials were presented in a random order in each block.

For the 1-back task, a series of ten random digits from 1 to 9 were presented in each trial and participants listened to the first number of the series without responding. For each subsequent number, they attempted to say the digit that they heard on the previous trial. A fixation cross was presented on the screen while the participants repeated the numbers and they commenced each trial by pressing the spacebar key. In the initial block, there were twelve trials of training followed by further twelve trials used as a baseline measure of 1-back performance prior to the feature selection task. Next, participants were given six practice trials on the feature selection task (with and without a concurrent secondary task) followed by four blocks of the feature selection task (see above). The order of presentation of the four feature selection blocks was randomized across participants. Following the feature selection task, in the last block, participants performed the 1-back task (fourteen trials) under single task conditions again.

Participants were instructed to start doing the 1-back task if a number sequence was presented. After a variable interval (3–5 digits in the 1-back sequence), a semantic trial was presented while the 1-back task continued; in contrast, in single task semantic trials, the feature selection task was presented visually after fixation, in the absence of a number sequence (see above). A word denoting a cue concept was presented at the top of the computer screen in each trial, with three words denoting semantic features beneath. The target, related distracter and unrelated semantic features occurred with equal probability in the three positions on the screen across trials/conditions. At the beginning of each of these blocks, a slide indicated the type of semantic relation (indicated by the target feature) that the participants had to use to respond (see Stimuli section), along with an example trial. Participants

were asked to indicate which of the three features shared that particular semantic relation with the cue concept, by pressing buttons 1, 2, 3 on the keyboard corresponding to the position on the screen of the feature chosen. They had a maximum of 10000 ms to provide their answer.

Participants completed 128 experimental trials, 64 under single task conditions, and 64 requiring simultaneous 1-back performance (task manipulation), presented in a mixed fashion. Participants controlled the presentation of each trial by pressing the spacebar on the keyboard.

Data analysis

First, we tested whether the performance in the 1-back task was modulated by the dual task. We calculated the participants' accuracy in reporting the digits. Accuracy in the two 1-back blocks (at the beginning and end of the experiment) was averaged to provide a global measure of 1-back single task performance – as the two single blocks did not differ significantly (see below). Then, we compared the accuracy in 1-back blocks under the single and dual conditions with a two-tailed paired-sample *t*-test to evaluate the effect of the simultaneous semantic task.

Second, we investigated the effect of the concomitant 1-back task on semantic performance, both in terms of accuracy and response times. Incorrect responses and omissions ($RT > 10000$ ms) were excluded from the RT analysis (6.64%). We logarithmically transformed the remaining RT data.

For both accuracy and RT, we examined whether the selection of the target feature over the competing feature was affected by the task factor (i.e., the single- vs. dual-task condition under which the semantic selection task was performed) using linear mixed-effect modelling, as implemented by the function *lmer* from the *lme4* (Bates, Maechler, Bolker & Walker, 2012; version 1.1-13;) and *lmerTest* (Kuznetsova, Brockhoff, Haubo, Christensen, 2017; version 2.0-33) packages in R (version 3.3.3; R Core Team, 2016).

In all of the tested models, we allowed for the random effects of Subjects and Concepts. We also included by-subjects random slopes for Trial, which accounted for potential longitudinal effects of fatigue or familiarization across participants and was coded by the trial number vector zero-

centered to remove the (possible) spurious correlation between the by-subjects random intercepts and slopes. For fixed effects, we used the log-likelihood ratio test to determine the final model (i.e., the simplest and best-fitting model; for a detailed description of the procedure, see Montefinese et al. 2014) according to standard procedures (Baayen et al. 2008; Quené and van den Bergh 2008). The final model included fixed effects of Intercept and Trial, as well as parameters for the fixed effects of interest. These included task factor (single vs dual) as well target and distracter relevance values (rel_{targ} and rel_{distr} , respectively) treated as continuous variables, and the second-order interactions between these factors. Moreover, we also tested for the inclusion of parameters for the effect of confounding variables (e.g., word frequency, inter-correlational strength; see Table 1). Variables were scaled to facilitate model convergence. The final model was re-fitted after excluding observations with absolute standard residuals greater than 3 (0.69% and 4.15% of analysed trials for RT and accuracy, respectively).

We also tested additional control models to rule out the possibility that our results were biased by the effect of lexical-semantic confounding variables (see below).

For reaction times, we report the estimated coefficient (b), standard error (SE), and t and p values for each parameter included in the final model. For the mixed-effect modelling of accuracy, we used a binomial distribution and the logit link function. Note that in this case we provided b , SE , z and p values for each parameter.

Results

1-back task performance

There was no significant difference between the first and last 1-back blocks in accuracy (respectively, $M = 95.41\%$ and 96.54% ; $SD = 4.04\%$ and 3.98% ; $t_{(25)} = 1.746$, $p = .093$, Cohen's $d = .342$). Consequently, we averaged participants' the mean proportion of accuracy across the two blocks, to obtain a unique index of 1-back performance without concurrent semantic task. Next, in order to test the effect of simultaneous task on the participants' performance, we compared their accuracy under single and

dual task conditions. There was a significant effect of the task factor (for Single and Dual tasks, respectively, $M = 95.98\%$ and 93.03% , $SD = 3.65\%$ and 4.69% ; $t_{(25)} = 4.650$, $p < .001$, Cohen's $d = .912$); the concurrent semantic task impaired performance on the 1-back task.

Feature selection task performance

Accuracy

We investigated whether the dual task interacted with the linear influence of either the selection of the target feature or the inhibition of the distracter feature, by means of a linear mixed-effect analysis. The final model included two parameters for the random effects of subjects and concepts, and fixed effects of trial number, task (single vs. dual) and rel_{distr} , as well as a parameter for the interaction between task and rel_{distr} . The inclusion to the final model of further parameters accounting for the effects of confounding variables (e.g., word frequency; see Table 3) was not justified (likelihood ratio test: $\chi^2_{(1)} < 2.893$, $p > .089$). The parameters and the corresponding statistics of the final model are shown in Table 3.

Table 3. Estimated parameters and statistics of mixed-effects modelling of accuracy.

	Estimate	<i>SE</i>	<i>z</i>	$p(> z)$
Intercept	11.4031	1.6577	6.879	< 0.0001
cTrial	1.4878	0.3551	4.190	< 0.0001
Dual Task	-1.2266	0.9845	-1.246	0.2128
Rel_{distr}	-0.2239	0.6370	-0.351	0.7253
Dual task: Rel_{distr}	-2.2263	0.9266	-2.402	0.0163

cTrial = Zero-centered vector for the Trial effect; Rel_{distr} = Relevance of the distracter.

The main effect of trial was significant ($b = 1.488$, $SE = .355$, $z = 4.190$, $p < .001$), revealing that participants' accuracy increased during the course of the experiment. The main effects of task ($b = -1.223$, $SE = .985$, $z = -1.246$, $p < .213$) and rel_{distr} ($b = -.224$, $SE = .637$, $z = -.351$, $p < .725$) were not significant. However, the task by rel_{distr} interaction was significant ($b = -2.226$, $SE = .927$, $z = -2.402$,

$p < .016$), showing that the relevance value of the distracter feature linearly decreased the participants' verification accuracy under dual task conditions only (see Figure 2).

Reaction times

We carried out linear mixed-effect modelling to investigate the linear effect of the relevance value of both targets and distracters, as well as whether task (i.e., single or dual conditions) influenced the selection of the target feature or the inhibition of the distracter feature. We first included three parameters for the random effects of subjects and concepts and the by-subjects random slope for trial, plus fixed effects accounting for several confounding variables (word frequency; inter-correlational strength; see Table 4) as evidenced by the likelihood ratio test (likelihood ratio test: both $\chi^2_{s(1)} > 3.950$, $ps < .049$). The inclusion of further confounding parameters was not justified ($\chi^2_{s(1)} < 2.404$, $ps > .121$).

Table 4. Estimated parameters and statistics of mixed-effects modelling of reaction times.

Parameters	Estimate	<i>SE</i>	<i>t</i>	<i>p</i> (> <i>t</i>)
Intercept	7.4468	0.0480	154.998	< 0.0001
cTrial	-0.0280	0.0130	-2.151	0.0418
Word Frequency	-0.0271	0.0126	-2.155	0.0332
Inter-correlational Strength	-0.0248	0.0126	-1.985	0.0495
Dual Task	0.2841	0.2467	11.515	< 0.0001
Rel _{distr}	0.0026	0.0184	0.139	0.8899
Rel _{targ}	-0.0352	0.0140	-2.514	0.0133
Dual task: Rel _{distr}	0.0511	0.0249	2.050	0.0425

cTrial = zero-centered vector for the Trial effect, Rel_{distr} = Relevance of the Distracter

Next, to test our primary hypotheses, we included the three parameters for both the main effects of task and rel_{distr} and for their interaction based on model fit ($\chi^2_{(3)} = 98.283$, $p < .001$). We also included a parameter for the effect of rel_{targ} ($\chi^2_{(1)} = 9.343$, $p = .002$). However, the inclusion of the task by rel_{targ} was not justified ($\chi^2_{(1)} < 1.130$, $p = .288$) and neither was the inclusion of parameters for the higher order interaction or other interactions involving the factor task ($\chi^2_{(3)} < 1.258$, $ps > .739$). After the exclusion of outlier observations (see Data Analysis), the final trimmed model accounted for 51.498% of the variance (R^2).

The parameters and the corresponding statistics of the final trimmed model are shown in Table 4. Feature selection times linearly decreased for trials including concepts with higher word frequency ($b = -.271$, $SE = .013$, $t = -2.155$, $p = .033$) and target features that were more inter-correlated with the other features of that concept ($b = -.025$, $SE = .013$, $t = -1.985$, $p = .0495$). The analysis also revealed that as the relevance of the target feature increased, participants' response times linearly decreased ($b = -.035$, $SE = .014$, $t = -2.514$, $p = .013$). The main effect of task was highly significant ($b = .284$, $SE = .025$, $t = 11.515$, $p < .001$), showing the strong detrimental effect of concurrent 1-back task on participants' semantic performance. Moreover, although the linear effect of the rel_{distr} variable was not significant, the task by rel_{distr} interaction showed that RT increased with the relevance value of the distracter feature under dual task conditions only ($b = .051$, $SE = .025$, $t = 2.050$, $p =$

.043) (see Figure 3). Thus, conceptually-relevant yet task-inappropriate distracters were harder to ignore when attention was divided.

Figure 3. Response time results, task by distractor relevance interaction.

The plot shows the participants' log-transformed response times (y axis) predicted by the final mixed-effect model as a function of the (scaled) distractor relevance (x axis) and the task (single vs. dual, in blue and orange, respectively). Shaded regions indicate the 95% confidence interval.

Discussion

We examined the interaction of the relevance of a feature to a concept and the availability of resources to control semantic cognition in one experiment on healthy participants under dual task methodology. To the best of our knowledge, there are two main novel aspects of this study. First, this is the first study that relates semantic selection process and feature-based semantic representations, in line with the distributed models of semantic representation (Grondin, Lupker, & McRae, 2009; Vigliocco, Vinson, Damian, & Levelt, 2002; Vigliocco, Vinson, Lewis, & Garrett, 2004) and investigates the fine-grained impact of the relevance of both target and distracter features on the semantic selection process. Young healthy participants were asked to make judgements based on particular semantic dimensions while controlling task-irrelevant aspects of the concept. This semantic control process requires a strategic top-down approach to feature retrieval ("semantic selection", Badre et al., 2005). Second, our results revealed that the relevance value of the target feature did not modulate the effect of the dual task on performance; instead, distracter strength appeared to be key – divided attention particularly interfered with the control of task-irrelevant distracter features in healthy

participants. This result suggests that domain-general control processes are more relevant to avoiding distracting information during semantic decision-making (i.e. “selection processes”) than to the capacity to promote relatively weak target features (i.e., “controlled retrieval”). Whilst these components of semantic control are unlikely to operate independently within a task, they do appear to rely differentially on control processes beyond the semantic domain. However, to corroborate these results, future research should consider using a secondary task selective to the disruption of controlled retrieval process.

These results are consistent with the view that semantic cognition emerges from the interaction of control and representational systems (Jefferies, 2013; Lambon Ralph & Jefferies, 2006; Lambon Ralph, Jefferies, Patterson & Rogers, 2017). They thus suggest that features with different degrees of importance in conceptual representation (i.e., low vs. high relevance features) contribute with different weights to representation of meaning (Montefinese et al., 2014a; Cree et al., 2006; Sartori et al., 2004; 2007). Moreover, they suggest that the feature semantic relevance parametrically influences selection demands and interacts with the capacity for control only if it denotes the relation between distracter feature and cue concept, as revealed by the significant interaction between task and the relevance value of the distracter feature (in terms of participants’ accuracy and reaction times). More importantly, this result is specific for the relevance dimension, suggesting the idea that this measure is one of the principals involved in the interplay between semantic representation and control processes. However, target relevance did not interact with the dual task in the way that distractor relevance did. This is broadly consistent with the view that selecting among competitors loads more strongly on domain general control processes compared to the controlled retrieval of a specific semantic relationship that is currently task relevant (Davey et al., 2016). Indeed, this latter type of control process might be more specific to the domain of memory.

We assessed the effects of another variable that strongly affects performance and task difficulty, word frequency, which reflects how often words are used (Forster & Chambers, 1973; Whaley, 1978) and modulates the ease with which they can be recognised and produced (Cree &

McRae, 2003; Duncan, 1977; Forster & Chambers, 1973; McRae, Jared, & Seidenberg, 1990). Results showed that word frequency, as expected, significantly predicted participants' feature selection times in general. Healthy participants show a processing advantage overall for concepts with higher word frequency in semantic tasks such as synonym judgment (Almaghyuli et al., 2012) and speeded feature verification (Montefinese et al., 2014a). However, while frequent words have some natural processing advantages, they are used in a broader range of contexts and this 'contextual diversity' may sometimes increase the need to employ control to shape retrieval such that it is focussed on aspects of knowledge that are relevant to the current context (Hoffman et al., 2011). In summary, while low-frequency concepts and words may have an overall processing disadvantage (e.g., in processes such as mapping phonology to meaning), they appear *not* to have increased control demands. These processing disadvantages of high frequency words (as well as their advantages) might explain why SA patients with semantic control deficits are typically insensitive to word frequency, unlike those with semantic dementia (Hoffman et al., 2011; Almaghyuli et al., 2012), and why word frequency did not ameliorate the effect of the secondary task load, despite making the judgements easier overall.

In accordance with previous findings (McRae, Cree, Westmacott, & de Sa, 1999; McRae et al., 1997), the inter-correlational strength of the target feature also significantly predicted response time, confirming the crucial role of this variable in the organization of semantic representation. Neuropsychological studies have suggested that feature correlations are important for explaining the nature of semantic deficits in Alzheimer's disease: correlated concept features may be more resistant to diffuse, mild, neurological damage, due to collateral activation that they receive from each other (Devlin, Gonnerman, Andersen, & Seidenberg, 1998; Gonnerman, Andersen, Devlin, Kempler, & Seidenberg, 1997; Tyler & Moss, 2001). Inter-correlational strength also influences semantic retrieval in speeded online tasks in healthy participants: correlated features are activated more quickly and automatically, in line with the feature-based distributed view of semantic representation (Montefinese et al., 2014a; 2015; McRae et al., 1997; 1999). Given these results, inter-correlational strength is

expected to generally benefit performance (e.g., by supporting automatic spreading activation between different semantic features), yet in the feature selection task we used, this spread of activation would not necessarily be helpful (since the judgements required access to a specific type of feature). This might explain why the dual task effect was not significantly modulated by this variable: similar to word frequency, inter-correlational strength might have benefitted the processing of the specific word, yet not reduced the control demands of the decision. Thus, target relevance, word frequency and inter-correlational strength (i.e., the correlation between the target feature and other features of the concept) affected overall performance (in terms of reaction times), but not the magnitude of the secondary task effect.

To conclude, the present study helps to characterise the interplay between feature-based semantic representations and semantic control, in particular, the interplay between the relevance dimension of a feature for a concept and the semantic selection process. We found that featural relevance modulates the degree of semantic control required during a feature matching task. In particular, the selection of a given target requires greater semantic control, in healthy participants under conditions of divided attention, as the relevance of distracter features increases. Our results reveal that semantic control is essential for suppressing task-irrelevant aspects of knowledge, especially when these are a highly-relevant part of the concept being probed. Domain-general control processes are more relevant to the capacity to efficiently avoid distracting information during semantic decisions, than to the promotion of relatively weak target features. Moreover, these results suggest that semantic relevance may be considered one of the organizing principles of the structure of semantic representation. Taken together, these results are consistent with the *controlled semantic cognition* framework, which anticipates highly interactive interplay between distributed feature-based semantic representations and semantic and domain-general control processes. Further research should address the interplay between semantic control and other featural semantic variables.

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