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So many options, so little time: The roles of association and competition in underdetermined responding

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Abstract

How do we make decisions when faced with multiple options? In the domain of language, some evidence suggests that we exert cognitive control to respond in such underdetermined situations when a good option is hard to find, but not when we must select among competing options. However, this conclusion, and conclusions about the neural substrates supporting underdetermined responding, are based on measures that confound retrieval and selection demands. The current study introduces measures based on latent semantic analyses that better capture the underlying theoretical constructs of association strength and competition. These measures revealed independent effects of retrieval and selection demands on reaction times in verb generation and sentence completion tasks. These results challenge existing accounts of underdetermined responding, and highlight the need for unconfounded measures of association strength and competition in studies of localization. We propose a new model governed by both absolute and relative activation levels of alternative responses.

Introduction

Cognitive control mechanisms allow us to respond flexibly and efficiently to the changing demands of our environment, such as when a situation affords multiple possible responses. We are constantly faced with the task of choosing one option from among many — such as when we select words to express a thought. In the domain of language, there is broad consensus that our ability to respond in such underdetermined situations requires cognitive control and relies on left prefrontal cortical regions (e.g. Nathaniel-James & Frith, 2002; Persson et al., 2004; Thompson-Schill et al., 1998). For example, left prefrontal areas are more active and responses are slowed when people name pictures with low versus high name-agreement (Kan, Kable, Van Scoyoc, Chatterjee, & Thompson-Schill, 2006; Kan & Thompson-Schill, 2004), generate verbs for nouns with multiple verb associates versus one strong associate (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997), and complete open-ended versus well-constrained sentences (Nathaniel-James & Frith, 2002). However, the nature of the cognitive control processes involved, and the role of specific neural substrates in supporting underdetermined responding, is strongly debated, in part because the two dominant theories have not yet been definitively tested.

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According to the *selection hypothesis*, the need for cognitive control arises from competition between multiple automatically-activated representations, which must be resolved to select a single response for output (e.g. Botvinick, Braver, Barch, Carter, & Cohen, 2001; Thompson-Schill et al., 1997). The less differentiated the activation pattern across all possible responses, the longer it should take to resolve the competition (Thompson-Schill & Botvinick, 2006). In contrast, according to the *controlled retrieval hypothesis*, the need for cognitive control arises when it is difficult to retrieve a response from semantic memory, requiring effortful, controlled retrieval (Martin & Cheng, 2006; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001). Thus, the weaker the connection between the stimulus and the most accessible response (association strength), the longer it should take to retrieve a response (Martin & Cheng, 2006).

One recent attempt to test the effects of competition and association strength seems to support the controlled retrieval hypothesis. In a verb-generation task, reaction times for producing a verb in response to a noun were predicted by association strength (operationalized as the proportion of a norming sample giving the most common response, i.e. *agreement*) but not by competition (operationalized as the ratio of the first to the second most frequent responses in the norming sample) (Martin & Cheng, 2006). However, these results and others (e.g., Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Nathaniel-James & Frith, 2002; Persson et al., 2004; Thompson-Schill et al., 1997) may reflect operationalizations that confound competition and association strength, and fail to adequately capture either theoretical construct. First, association strength has been described as an a priori parameter that arises through semantic and linguistic experience (e.g. Wagner et al., 2001); thus, the association strength between any given stimulus and response should be independent of the alternative responses. However, agreement is a proportion measure, and thus relative to these alternative responses. Consider a noun (e.g., ball) with several strongly associated verb responses (e.g. throw, catch, roll, toss). If participants in the norming sample spread their responses fairly evenly between them, this item would be (incorrectly) classified as having low association strength, when in fact it has both high association strength and high competition between alternatives. Second, the measure of competition, ratio, only considers the two most frequent responses, rather than competition between all active representations, but the latter is supported by evidence from other semantic tasks (e.g. Howard, Nickels, Coltheart, & Cole-Virtue, 2006). Thus, the ratio and agreement measures do not fully capture the constructs of competition and association strength respectively.

In addition, these agreement and ratio measures are strongly correlated (Table 1), such that conditions differing on one measure differed on the other as well. Attempts have been made to match stimulus sets on one variable (Martin & Cheng, 2006), but this process can introduce other confounds (Thompson-Schill & Botvinick, 2006). Thus, continuous measures of association strength and competition (and corresponding multilevel modeling analyses) seem critical for assessing the independent effects of each factor controlling for the other, but such methods have been lacking.

Moreover, the use of flawed measures of association strength and competition has limited progress in identifying the roles of specific neural substrates in underdetermined responding. For example, a synthesis of the controlled retrieval and selection hypotheses has been proposed (Badre et al., 2005; Badre & Wagner, 2007; c.f. Gold et al., 2006), positing that separate areas of left ventrolateral prefrontal cortex (VLPFC) support controlled retrieval of semantic knowledge from posterior conceptual stores and post-retrieval selection between active representations, irrespective of whether these representations were retrieved in an automatic or controlled manner. However, these accounts have been based on neuroimaging evidence using flawed measures of association strength and competition, which have prevented cleanly separating these factors. Therefore, the issue remains far from settled, leading some to continue to argue that competition does not play an independent role (e.g. Martin & Cheng, 2006).

The current study remedies the limitations of previous research in three ways. First, we introduce new measures that more accurately reflect the theoretical constructs, based on latent semantic analysis (LSA). LSA is a technique for extracting the similarity of words and passages by analyzing large bodies of text, capturing contextual as well as co-occurrence information (Landauer, Foltz, & Lahem, 1998), consistently out-performing co-occurrence alone in predicting human data, (Landauer et al., 1998) including recall from semantic memory (Griffiths, Steyvers, & Tenenbaum, 2007). LSA has been shown to successfully capture human semantic knowledge and behavior, for example, simulating detailed patterns of lexical priming (Landauer & Dumais, 1997), semantic clustering (Lahem, 1997) and free-recall order (Sirotin, Kimball, & Kahana, 2005), accuracy (Tse & Altarriba, 2007), and latency (Howard, 2002), and scoring as well as average test-takers on synonym tests (Landauer & Dumais, 1997). LSA provides a powerful tool for representing association strength, and thus predicting the degree to which responses are activated by the presentation of a stimulus. Because LSA association values are absolute, using LSA-based measures eliminates the problems with the relative measures based on norming data, making purer measures of both association strength and competition possible.

Second, we consider a new measure of competition (entropy, computed over LSA association values), which reflects competition between all alternative responses, rather than just the two most active responses.[1] Third, we examine independent effects of association strength and competition by using continuous measures.

We contrast the former and current measures of association strength and competition within two tasks: verb generation and sentence completion. Verb generation has been used in studies supporting both the selection (e.g. Thompson-Schill et al., 1997) and controlled retrieval (e.g. Martin & Cheng, 2006) hypotheses, and thus allows for direct comparison with prior work, while sentence completion is an arguably more naturalistic language task, and tests the generalizability of results beyond the verb generation paradigm. We predict that (1) association strength, but not competition, will appear to play a role using the previous, flawed measures, (2) the improved LSA-based measures will reveal independent effects of association strength and competition, and (3) competition between all active representations (entropy) will provide increased predictive power over competition between the two most active representations (ratio). These results would support a new model of underdetermined responding governed by both absolute activation levels (determined by association strength) and relative activation levels of alternative responses (determined by competition).

Methods

Subjects

Subjects were 40 undergraduate students who spoke English as their first language and did not report a diagnosis of any reading disability. One subject was excluded because of a self-reported reading disorder, and two due to equipment failure.

Tasks and Procedure

Participants completed sentence completion and verb generation tasks as part of a larger battery of tasks (which will not be reported here).

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[1]A previous neuroimaging study (Barch, Braver, Sabb, & Noll, 2000) included a related measure of spread (kurtosis of the frequency distribution of the five most frequent verb responses produced by a norming sample); the LSA entropy measure offers two improvements, by (1) avoiding the problems associated with proportion based measures, as discussed previously, and (2) considering all alternative responses, rather than only the five most frequent.

Sentence completion

Materials were 200 sentences with the final word missing, from Bloom and Fischler (1980). All responses from a norming sample (*n*=100), and the proportion giving each, were available from Bloom and Fischler (1980). Sentences varied from highly constrained, with most subjects giving one answer (e.g. “He mailed the letter without a ___.”) to highly underdetermined (e.g. “He couldn't think of anyone less ___”). Subjects were instructed to complete each sentence with the first word that came to mind that could end the sentence. Subjects completed four practice sentences followed by four blocks of 50 trials each. Trial order was randomized for each subject. Sentences appeared in four segments of 1-3 words each (1000 ms/segment, with previous segments remaining visible). The final segment always contained only the last word, followed by a blank (“___.”). Subjects responded using a microphone, followed by a fixation point on the left side of the screen for 1500 ms (where the first word of the next trial appeared).

Verb generation

Materials were 96 concrete nouns drawn from Thompson-Schill et al. (1997), and ranged from highly constrained (e.g. “scissors”) to highly underdetermined (e.g. “cat”). New norming data on these items was collected (*n*=54), as the original norms were no longer available. Subjects were instructed to say the first verb that came to mind that was something the noun did, or that you could do with it, and were given an example. Subjects completed four practice items, followed by four blocks of 24 trials each. Trial order was randomized for each subject. Subjects responded using the microphone, followed by a fixation in the center of the screen for 1500 ms before the next trial.

Measures and Analyses

Five key measures are examined. Agreement, the formerly used measure of association strength, is operationalized as the proportion of participants in the norming sample (Bloom & Fischler, 1980 for sentence completion, our data set for verb generation) giving the most frequent response. Ratio, the formerly used measure of competition, is calculated as the ratio of the first to the second most frequent response. Thus, the smaller the ratio, the greater the conflict from the closest competitor. Three new measures were calculated based on LSA, using the “general reading up to first year college” topic space (300 factors), term-to-term comparison for verb generation, and document-to-term comparison for sentence completion (http://lsa.colorado.edu/). All responses given by two or more subjects in the norming samples were included. LSA association strength was defined as the LSA cosine between the stimulus and the response given by the subject. LSA ratio was defined as the ratio of the response with the highest LSA cosine to the second highest. LSA entropy, a measure of competition between all alternative responses, was defined as $H = -\Sigma(p(i) \cdot \ln p(i))$, where p(i) is the cosine between the stimulus and each alternative response, divided by the sum of LSA cosines across alternative responses. Thus, entropy is zero when there is only one associate (i.e. when p(i)=1) and increases as multiple alternatives are more equally associated with the stimulus. Correlations between independent measures are provided in Table 1.

Subject responses were transcribed and trials where the microphone was incorrectly triggered (e.g. by a cough) were removed. Reaction times were log transformed, and subjected to a three standard deviation trim. Analyses were then carried out using multilevel modeling, as implemented in SAS. Multilevel modeling is equivalent to running a multiple regression analysis for each subject individually, then testing the reliability of the regression coefficients across subjects, except that that estimation is done simultaneously rather than sequentially. All effects are the effect of that independent measure, controlling for all other measures in the model, and for random subject effect. Thus, multilevel modeling controls for individual differences while allowing the use of continuous independent measures, which is extremely important when analyzing psycholinguistic data (Blozis & Traxler, 2007).

Results

Previously used measures

As in Martin & Cheng (2006), agreement but not ratio predicted reaction times, in both the verb generation and sentence completion tasks (Table 2). Reaction times increased with decreasing Agreement, controlling for Ratio.

LSA based measures

However, our improved measures revealed that association strength and competition each predicted reaction times, in both the verb generation and sentence completion tasks (Table 3). Contrary to predictions from each of the major existing accounts, reaction times increased with both decreasing association strength and increasing competition, controlling for the other variable. Entropy provided a more complete measure of competition than ratio, accounting for the same variance and providing additional predictive power (Table 4). Controlling for the other variables in the model, reaction times increased as LSA entropy increased and LSA association strength decreased.

Discussion

Using previous measures of retrieval demands (agreement) and selection demands (ratio), the current study replicated the finding that only retrieval demands predict reaction times in underdetermined tasks (Martin & Cheng, 2006). However, the agreement measure of retrieval demands masks the effects of selection demands. When purer, more theoretically-justified measures of retrieval demands (LSA strength) and selection demands (LSA ratio and entropy) are considered, independent effects of each factor on reaction times are revealed. The superiority of the entropy measure over the ratio measure suggests that competition among multiple alternatives, rather then conflict from the nearest competitor only, drives selection demand. All of these effects hold across the tasks of completing sentences and generating verbs in response to nouns.

Purer measures of retrieval and selection also suggest a reinterpretation of earlier data. For example, Martin and Cheng (2006) reported an effect of association strength but not competition on underdetermined responding, based on measures computed over response frequencies. However, with purer LSA-based measures, Martin and Cheng's (2006) high association strength/high competition and high association strength/low competition conditions do not actually differ in competition ($t(28)=-0.492$, $p=.627$), while their high association strength/high competition and low association strength/high competition conditions do differ in LSA association strengths for the most frequent response ($t(28)=2.332$, $p=.027$). Thus, their pattern of findings likely reflects the fact that association strength was successfully manipulated, but competition was not.[2]

These findings challenge both the controlled retrieval and selection hypotheses in their current forms. The activation levels of all possible responses in these tasks may be visualized as a landscape, characterized in terms of both absolute height (determined by association strength) and topography (determined by competition). The controlled retrieval hypothesis does not capture the overall topography, because it has focused on only the most strongly associated response (Martin & Cheng, 2006), while the selection hypothesis has not captured the overall height of the landscape, because it has focused on competition based on relative, rather than absolute, strength (Thompson-Schill & Botvinick, 2006).

[2]We calculated competition in terms of LSA ratio for these analyses, because the full set of norming data and participant responses were no longer available, such that LSA entropy could not be calculated. We thank Randi Martin for supplying the stimuli for this analysis.

The processes leading to independent effects of the height and topography of the response space remain speculative, but we posit the following model. First, when a stimulus is presented, activation automatically spreads to associated representations (e.g. “ball” activates throw, catch, etc.), as demonstrated by semantic priming effects (Hutchison, 2003). The higher the association strength, the more quickly responses pass threshold for production, and the faster the reaction times. Second, when multiple associated responses become partially active, one response must be selected for output. The less differentiated the activation levels of the alternative responses, the longer it takes for competition to be resolved, and the slower the reaction times.

A major contribution of the present study is to provide improved, unconfounded measures of association strength and competition that can be used in future neuroimaging studies to clarify questions of localization. Given the limitations of prior measures of association strength and competition, it remains to be seen which neural substrates support controlled retrieval and selection. One question is whether these processes rely on distinct regions (e.g., of left VLPFC, Badre et al., 2005; Badre & Wagner, 2007; Gold et al., 2006), or might instead tap common regions and mechanisms. For example, the active maintenance of prefrontal task representations (e.g. via excitatory recurrent connections, Stedron, Sahni & Munakata, 2005) may serve to both increase initially weak activation of posterior cortical representations when association strength is low, and enhance contrast among initially close activation levels of posterior cortical representations when competition is high (e.g. Hahnloser, Sarpeshkar, Mahowald, Douglas & Seung, 2000). Further neuroimaging work using unconfounded measures of association strength and competition is needed to test such theories. Additionally, these unconfounded measures may help to test theories about other neural substrates in cognitive control, such as the role of the anterior cingulate in monitoring for conflict or competition (e.g. Barch et al., 2000; Botvinick et al., 2001; cf. Holroyd & Coles, 2002).

The independent roles of association strength and competition found in the current study have parallels in cognitive phenomena from diverse domains. In the domain of memory, as the number of facts known about a particular concept increases, the time to retrieve any given fact also increases. This fan effect may arise because association strengths between concepts and facts decrease (Anderson & Reder, 1999), and competition between representations increase (Radvansky, 1999). In mathematical cognition, students have more difficulty with arithmetic problems with larger digits (e.g. 7 × 8) than smaller digits (e.g. 3 × 4) (e.g. Zbrodoff, 1995). Digits may be associated with multiple competing responses (e.g. 7 × 8 automatically activates other multiples of 7 or 8, and their sum). Since large digit problems are learned later, they suffer from increased competition, as previously learned multiples (e.g. 14, 16) may also become active, while the correct response may be more weakly associated with the digits (Barrouillet, Fayol, & Lathuliere, 1997; Zbrodoff, 1995). Thus, seemingly disparate phenomena may be understood in terms of automatic activation of multiple responses followed by selection among these competing alternatives. While LSA based measures have been focused on linguistic tasks, similar methods could be used to capture the structure of any large corpus of inputs, such as arithmetic problems (cf. Siegler, 1988). Such analyses of environmental input may prove valuable in exploring the effects of association strength and competition in variety of domains. The current study establishes a new approach for testing the independent contributions of these factors, so that future work can explore their neural underpinnings and generality across domains.

The pervasiveness of underdetermined responding in everyday life extends far beyond the domains of language production, memory retrieval and arithmetic. What may the relatively fast, non-conscious processes involved in language production have in common with the sometimes agonizingly slow, deliberative processes involved in other underdetermined situations, such as choosing what to eat? While underdetermined responding in different contexts may differ in important ways, effects of association strength and competition among alternatives may be broadly relevant.

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Table 1

Correlations Among Measures of Retrieval and Selection Demands

	Agreement	Ratio	LSA strength	LSA ratio
Verb Generation				
Agreement	-	-	-	-
Ratio	.784	-	-	-
LSA strength	.412	.326	-	
LSA ratio	.424	.479	.233	-
LSA entropy	-.760	-.661	-.412	-.474
Sentence Completion				
Agreement	-			
Ratio	.706	-		
LSA strength	.156	.042	-	
LSA ratio	.283	.180	.087	-
LSA entropy	-.812	-.773	-.085	-.489

Note. Correlations among measures of retrieval demands (agreement and LSA strength) and measures of selection demands (ratio, LSA ratio, and LSA entropy): Previous measures of retrieval and selection demands are highly correlated, while purer LSA-based measures are uncorrelated to moderately correlated.

Table 2

Effects of Previous Measures of Retrieval and Selection Demands on Reaction Times in the Verb Generation and Sentence Completion Tasks

	***t*(36)**	***p***	**Effect size (r^2)**
Verb Generation			
Agreement	-11.72	<.001	.792
Ratio	1.03	.310	.029
Sentence Completion			
Agreement	-14.99	<.001	.862
Ratio	-1.39	.173	.051

Note. Previous measures replicate previous findings: Reaction times in underdetermined responding are predicted by agreement but not ratio, suggesting the influence of retrieval demands but not selection demands. All effects are controlling for the other variable in the model.

Table 3

Effects of LSA Measures of Retrieval and Selection Demands on Reaction Times in the Verb Generation and Sentence Completion Tasks

	***t*(36)**	***p***	**Effect size (r^2)**
Verb Generation			
LSA strength	-14.04	<.001	.845
LSA ratio	-6.05	<.001	.504
Sentence Completion			
LSA strength	-7.57	<.001	.614
LSA ratio	-10.25	<.001	.745

Note. Purer LSA-based measures challenge previous findings and existing accounts of underdetermined responding: Reaction times are predicted by both strength and ratio, measures of retrieval and selection demands, respectively. All effects are controlling for the other variable in the model.

Table 4

Effects of the LSA Entropy Measure of Selection Demand on Reaction Times in the Verb Generation and Sentence Completion Tasks

	***t*(36)**	***p***	**Effect size (r^2)**
Verb Generation			
LSA strength	-9.57	<.001	.717
LSA ratio	-.21	.835	.001
LSA entropy	11.25	<.001	.778
Sentence Completion			
LSA strength	-6.22	<.001	.518
LSA ratio	-.09	.929	.000
LSA entropy	18.11	<.001	.901

Note. Selection demands are driven by more than the top two competitors: Entropy (competition among all responses) accounts for variance beyond that accounted for by ratio (competition between the top two responses). All effects are controlling for the other variables in the model.