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Effects of Semantic Diversity and Word Frequency on Single Word Processing

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Some research suggests that semantic diversity (SemD), a measure of the variability of contexts in which a word appears, plays an important role in language processing, determining the availability of word representations (e.g., Adelman et al., 2006) and causing task-specific benefits or detriments to performance (e.g., Hoffman & Woollams, 2015). Some researchers have claimed that word frequency has no effect once such diversity measures are taken into account (Adelman et al., 2006). Taking advantage of the power of five large-scale databases, we investigated the effects of SemD, word frequency, and their interaction in five tasks, including word reading, lexical and concreteness decision, object picture naming, and word repetition. We found: (a) word frequency and SemD effects were consistently distinct; (b) effects of SemD were facilitatory in nearly all tasks, but inhibitory effects were also found; contrary to existing claims, we conclude that inhibitory SemD effects do not necessarily imply semantic selection requirements; (c) the presence of SemD effects minimally influenced the size of frequency effects when SemD was left uncontrolled, suggesting that SemD does not explain absent frequency effects in the patient literature; and (d) word frequency and SemD only interact in the largest data sets. Results are discussed in the context of rational models of memory (Anderson & Milson, 1989; Anderson & Schooler, 1991) and the Controlled Semantic Cognition framework (Lambon Ralph et al., 2017).

Keywords: aphasia, frequency, mega-studies, semantic control, semantic diversity

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Since the 1950s, psycholinguistic research has suggested that the frequency of a word's occurrence plays an important role in language processing—with higher frequency words being easier to understand and produce than lower frequency words (e.g., Andrews & Heathcote, 2001; Balota & Chumbley, 1984; Oldfield & Wingfield, 1965). A number of theoretical proposals have been made regarding the manner in which frequency facilitates lexical retrieval. For instance, in the classic logogen model, a word's frequency determines its threshold for recognition, with higher frequency resulting in lower thresholds (Morton, 1969). More recent work suggests a more general role for frequency of occurrence in memory, assuming that greater word frequency creates stronger connections between levels of representation (or stronger resting activation levels), which speeds processing between words' orthographic, phonological, and semantic representations (Coltheart et al., 2001; Dahan et al., 2001a; Dell, 1989; McClelland & Rumelhart, 1981; Plaut et al., 1996). Such models suggest that repeated encounters implicitly strengthen memory representations for a word.

An alternative approach comes from "rational" models of memory (e.g., Anderson & Milson, 1989), which claim that the likelihood that a word will be needed in a given situation, rather than frequency of exposure to the word, determines the strength of the word's representation. In favor of such models, Adelman et al. (2006) claim that a word that appears in a greater number of different contexts will be more readily available from the lexicon, as it is more likely to be needed in any given situation. Adelman et al. explored this claim with a measure they called contextual diversity (CD; referred to by Steyvers & Malmberg, 2003 as "contextual dispersion"), which was operationalized as the number of documents in which a word appears (Adelman et al., 2006). In theory, CD may be considered a measure of semantic richness, because its goal is to capture contextual variation. However, researchers have argued that CD, unlike other semantic richness measures (e.g., a word's number of senses or features; Yap & Pexman, 2016; Yap et al., 2011), provides an explanation for standard frequency effects. In support of this notion, studies in several languages have found that CD explains 1% to 4% more variance than frequency in response times and accuracy of lexical decision and single word reading, typically reducing the independent effect of frequency to zero or, less often, revealing a detrimental effect (Adelman et al., 2006; Cai & Brysbaert, 2010; Dimitropoulou et al., 2010; Perea

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et al., 2013; Soares et al., 2015). Other studies in single word processing and reading also show reduced or eliminated frequency effects when CD is controlled (Chen et al., 2017; Perea et al., 2013; Plummer et al., 2014), a phenomenon not observed for other semantic richness measures (Pexman et al., 2017; Yap et al., 2011). Because of these results, several studies have claimed that frequency effects are actually CD effects and that frequency does not independently contribute to lexical processing (Adelman et al., 2006; Perea et al., 2013).

However, critics have pointed out that CD is so highly correlated with word frequency ($r > .95$) that it is hard to argue that these variables are distinct (Hoffman et al., 2013; Hsiao & Nation, 2018). It is possible that CD is simply a better measure of real word frequency than word count, given that the effect of log CD on lexical decision and single word reading is more linear than that of log frequency and that certain words create idiosyncratic effects on frequency count (e.g., proper nouns; see Brysbaert & New, 2009). One may additionally argue against the conclusion that CD *explains* typically observed frequency effects, as it is unwarranted to conclude that shared variance between two variables is attributable only to the variable with a significant unique contribution (Cohen et al., 2003). That is, the overlapping variance between CD and frequency may be attributable to frequency, and the small unique variance for CD (1% to 3%) may reflect something added by CD over frequency. Furthermore, some studies suggest that CD effects and frequency effects are independent. Vergara-Martínez et al. (2017) showed independent electrophysiological effects of frequency and CD in lexical decision, and Steyvers and Malmberg (2003) showed independent effects of frequency and contextual variability (a measure identical to CD) in recognition memory for word lists. It is possible that these studies suffer from overly selective and small samples of stimuli, but they nevertheless provoke the question of whether CD and frequency truly represent the same construct.

Improving on Contextual Diversity

More recent research has proposed measures of "semantic diversity" (SemD; sometimes also referred to, as "semantic distinctiveness" or, confusingly, "contextual diversity"; Jones et al., 2012; Johns, Dye, et al., 2016), which, like CD, strive to capture variation of the contexts in which words appear. Unlike CD, measures of SemD explicitly quantify the semantic relationships between those contexts (Hoffman, Rogers, et al., 2011; Jones et al., 2012). Such measures are likely better than CD at representing the diversity of contexts in which a word appears because they compensate for a problematic aspect of CD—that is, a word might show up in several documents, but many of those documents may instantiate highly similar semantic contexts. Hoffman et al. (2013) use the word *tax* as an example. If *tax* appeared in many different corpus documents surrounded by similar financial language, it would appear to have high contextual diversity despite the similarity of the contexts in which it was used. Thus, SemD measures are preferable to CD on theoretical grounds from the perspectives of rational models of memory and lexical processing: they account for aspects of the actual semantic context in which a word appears. Compared with CD, an influence of SemD gives one a stronger reason to believe that something qualitatively different than frequency is being measured.

Two prominent measures of SemD, one put forward by Jones et al. (2012) and one by Hoffman, Rogers, et al. (2011), have provided evidence that lexical processing is affected by the semantic distinctiveness of contexts in which a word appears. The SemD measure of Jones and colleagues (Johns et al., 2014; Johns, Dye, et al., 2016; Jones et al., 2012) is built for each word by a computational model that "learns" the word's semantic representation. The model is fed a stream of documents and continuously updates words' representations as they are encountered in new documents. The first time a word is encountered, its representation reflects only the words of the single context in which it has appeared, but as the word occurs in new documents, the representation is revised to the degree that the surrounding words in the document differ from those of the previous context. In this way, repetitions of redundant contexts have a smaller impact on the word's representation than do novel contexts. The semantic representations generated by the model are then condensed into a single number reflecting the semantic diversity of the contexts in which it appears. Jones and colleagues showed that their SemD measure accounts for a larger proportion of variance in lexical decision and word reading in megastudy data sets than does either frequency or CD (Jones et al., 2012), and they replicated this finding in a sample of monolingual and bilingual adults with a smaller set of words (Johns, Sheppard, et al., 2016). Similar to results from studies of CD, these studies revealed little to no frequency effect after accounting for CD and SemD. Notably, CD effects sometimes remained significant, suggesting independent effects of SemD and CD—if indeed CD is not simply a superior measure of word frequency. Furthermore, the independence of CD (and perhaps frequency) from SemD is illustrated by the interaction between CD and SemD observed in the lexical decision times of the English Lexicon Project (Balota et al., 2007) by Jones et al. (2012). This interaction showed that words with higher CD receive a larger benefit from contextual variation than do words with lower CD. One potential drawback of the SemD measure of Jones et al., is that, like CD, it correlates strongly with frequency measures drawn from the same corpora ($r > .96$). This correlation may mean that the traditional frequency effect largely reflects this semantic component, or it may mean that Jones et al.'s SemD does not capture much information beyond word frequency count.

Hoffman, Rogers, et al. (2011) also attempted to capture the effect of a word's context. Their approach sees SemD as a measure of semantic ambiguity (Hoffman & Woollams, 2015), assuming that word meanings, even within individual word senses, vary continuously based on the context in which they occur. Whereas the SemD measure of Jones and colleagues essentially uses the raw overlap between words in different contexts to build its representations, the SemD measure of Hoffman et al. is built by using latent semantic analysis (Landauer & Dumais, 1997) to compare the semantic distance of the contexts in which a word occurs. Before a word's representation is created, the individual contexts of a corpus are decomposed into simplified representations. Then, a word's SemD is derived by taking the average of the cosine distances between all pairs of contexts in which the word appears, log transforming it, and reversing its sign. Higher SemD in this measure therefore means that there are larger average semantic distances between contexts in which a word appears. Effects of Hoffman et al.'s SemD measure independent of frequency have been shown in lexical decision (Hoffman & Woollams, 2015; Sidhu et al., 2016), semantic relatedness decisions to word pairs (Hoffman & Woollams, 2015), concreteness decisions (Pexman et al., 2017),

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word reading (Plummer et al., 2014; Sidhu et al., 2016), past tense verb generation (Sidhu et al., 2016), syntactic classification of nouns (Yap & Pexman, 2016), and children's lexical decision and word reading (Hsiao & Nation, 2018). Unfortunately, none of these studies has directly compared Hoffman SemD and CD effects. Hoffman et al.'s SemD measure also correlates to a smaller degree with word frequency than do CD measures and the SemD of Jones et al. ($r \sim .50$; Hoffman et al., 2013), presumably because of the abstraction caused by using latent semantic analysis rather than direct word co-occurrence to determine similarity of contexts.

Facilitatory and Inhibitory Effects of Semantic Diversity

SemD is further distinguished from frequency and CD by the fact that its effect has been shown to vary depending on task demands. Unlike high word frequency and CD, which are nearly always beneficial for word processing (for an exception, see Balota et al., 2000); high SemD as measured by Hoffman et al., is sometimes beneficial—that is, in lexical decision (Hoffman & Woollams, 2015; Pexman et al., 2017; Yap et al., 2015), word reading (Plummer et al., 2014), concreteness decisions (to abstract words, Pexman et al., 2017), and past tense verb generation (Sidhu et al., 2016)—and sometimes detrimental—that is, in word pair semantic relatedness decisions (Hoffman & Woollams, 2015), concreteness decisions (to concrete words, Pexman et al., 2017), and syntactic classifications (Yap & Pexman, 2016). In this way, effects of SemD are akin to other effects of semantic richness, such as a word's number of senses, ambiguity, semantic neighborhood, or contextual variability. Such varying effects of SemD are not clearly explained by rational models of memory, which would predict only beneficial SemD effects. That is, rational models simulate only retrieval of a specific memory, which is a positive function of the likely need of a memory trace (Anderson & Milson, 1989; Anderson & Schooler, 1991). Therefore, they make no prediction that likely need, if this is indeed what SemD indexes, can lead to poorer performance.

Hoffman and colleagues have claimed that the direction of SemD effects depends on the degree to which a specific semantic representation is accessed (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011; Hoffman & Woollams, 2015). These claims are in line with evidence from other semantic richness variables (e.g., ambiguity, contextual dispersion, number of distant semantic neighbors, number of senses), which shows that tasks requiring access to specific semantic representations show more inhibitory effects of semantic richness than do tasks requiring no such access (Armstrong & Plaut, 2008; Hino et al., 2006; Hoffman & Woollams, 2015; Mirman & Magnuson, 2008; Pexman et al., 2008, 2017; Plummer et al., 2014; Rabovsky et al., 2016; Sidhu et al., 2016; Steyvers & Malmberg, 2003; Yap et al., 2011, 2015; Yap & Pexman, 2016). Inhibitory effects from multiple activated meanings are also relevant in the semantic transparency of compound words (Schmidtke et al., 2018). When a task does not constrain the meaning of a word, Hoffman et al. claim that activation spreads from a word and its semantic representation to all contextually related semantic representations. For example, "dog" will activate its corresponding semantic attributes—furry, four legs, tail, and so forth—as well as semantic attributes of different senses of the word—for example, "the detective will dog your footsteps" (Hoffman, Rogers, et al., 2011, p. 2434)—and features of different contexts in which you have encountered a dog—at home, the park, your cousin's house, and so forth. The array of coactivated information, the authors claim, may be useful in tasks such as lexical decision because any increase in semantic activation helps to support the decision that an observed letter string is a word; on the other hand, an abundance of activated information may cause difficulty in tasks such as semantic relatedness decision (e.g., are *brace* and *support* related?) because one must distinguish relevant from irrelevant activated information (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011; Hoffman & Woollams, 2015). Similar claims about opposing effects of contextually related semantic information have been made about effects of contextual dispersion, a measure similar to SemD (Pexman et al., 2008; Steyvers & Malmberg, 2003). Whether activation spreads from the representation of a word to contextually related semantic information, as claimed by Hoffman et al., is unclear from the literature. One recent study found that LSA contextual relationships between words did not contribute to semantic priming (Hutchison et al., 2008), whereas another showed that other co-occurrence and contextual measures, such as BEAGLE (Jones & Mewhort, 2007), may influence semantic priming (Jones & Golonka, 2012).

SemD, Semantic Control, and Frequency Effects

For situations in which one must distinguish relevant aspects of meaning from among irrelevant aspects, evidence suggests that cognitive control (or executive control) mechanisms are recruited (e.g., Schnur et al., 2006; Thompson-Schill et al., 1997). Hoffman, Rogers et al. (2011) claim that the resolution of competition among activated semantic information depends on a domain-specific cognitive control mechanism known as semantic control. This mechanism is one of two major components of the semantic system, along with semantic representations themselves, in the Controlled Semantic Cognition framework of semantic processing (Lambon Ralph et al., 2017). The authors of the framework propose that semantic control is necessary for understanding the contextually relevant aspects of a spoken or written word. For example, one must focus on different aspects of the word "piano" depending on whether one will play music on it or move it across the room (Jefferies & Lambon Ralph, 2006; Saffran, 2000).

Semantic control is relevant to the relationship between SemD and word frequency, as it has been used to explain anomalously absent or reversed effects of word frequency (i.e., superior performance with low frequency words) that are sometimes observed for stroke patients with aphasia who have multimodal semantic deficits (Hoffman, Rogers, et al., 2011). For instance, Jefferies and Lambon Ralph (2006), reported that these aphasic patients failed to show familiarity effects (which are highly related to frequency effects) for picture naming and for picture-word matching, whereas patients with a degenerative disorder of semantic processing (semantic dementia) with similar overall levels of performance showed typical familiarity effects. Proponents of the Controlled Semantic Cognition theory of semantics have claimed that the individuals with aphasia (referred to as "semantic aphasia" patients) have a semantic control deficit, which affects their ability to focus on some aspects of a word's meaning and inhibit others in a task-appropriate manner (Jefferies & Lambon Ralph, 2006; Lambon Ralph et al., 2017). The logic for the role of semantic

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control in absent or reversed frequency effects is as follows (per Hoffman, Rogers, et al., 2011; Hoffman & Woollams, 2015). When one performs a task that requires them to make a decision based on specific semantic information, such as a synonym selection task, activation spreads from an accessed word representation to its associated semantic information. To make a decision in this task, one must distinguish relevant from irrelevant activated semantic information by using semantic control. The degree to which semantic control is recruited depends on a word's SemD, as activation should spread to a larger amount of semantic information for words with higher SemD, and the distinction of relevant from irrelevant information should be harder when more semantic information is activated. Therefore, if the semantic control mechanism is damaged, the degree to which performance suffers on the task is a positive function of the SemD of the word. Because high frequency words also tend to have higher SemD than low frequency words, patients with semantic control deficits are more likely to struggle with high frequency words than low frequency words, and the typical advantage for high frequency words may disappear or even reverse for these patients.

Evidence for the role of SemD in obscuring frequency effects of semantic aphasia patients was shown by Hoffman, Rogers, et al. (2011). They tested a group of thirteen semantic aphasia patients on a synonym selection task and then predicted their response accuracy with a number of lexical variables. When accuracy on this task was predicted by word frequency alone, the patients failed to show a typical frequency effect, but after SemD was controlled, a typical word frequency effect was revealed. Furthermore, SemD was detrimental to performance, as the authors predicted would be the case if patients had a semantic control deficit. Hoffman et al. (2013) used the same synonym task and found the same lexical effects in healthy older adults—the frequency effect became larger when SemD was controlled and higher SemD had a detrimental effect on performance. The latter result suggests that inhibitory SemD effects observed in healthy populations could also be generated by the semantic control demands of high SemD words (Hoffman et al., 2013). The study additionally showed that SemD accounted for a larger percentage of variance in synonym selection errors than did contextual diversity, showing the relative importance of SemD in this task. Thus, Hoffman and colleagues (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011) have claimed that, in tasks requiring semantic selection, semantic competition created by SemD reduces or eliminates word frequency effects for aphasic patients with multimodal semantic deficits and healthy older adults.

Why Might SemD Reduce Frequency Effects?

The regression results of Hoffman et al. (2013; Hoffman, Rogers et al., 2011) for synonym selection imply independent effects of frequency and SemD in that task—a beneficial effect of frequency and an inhibitory effect of SemD. It appears, owing to the difference in the distribution of SemD for high and low frequency words (see Hoffman et al., 2013, Figure 2), that the inhibitory effect of high SemD affects high frequency words more than low frequency words—that is, if high and low frequency words were equally affected, there would be no change in the frequency effect. Whereas the findings of Hoffman et al. (2013; Hoffman, Rogers, et al., 2011) are consistent with independent main effects of frequency and SemD, their results would also be consistent with an interaction between SemD and frequency, such that SemD has a greater effect for high frequency words than low frequency words. Such an interaction has not been directly investigated in healthy adults, though the interaction of CD and SemD by Jones et al. (2012) suggests that a similar frequency-SemD interaction is also likely to be found, with SemD effects increasing as frequency increases. Furthermore, models positing that word frequency determines the strength of lexical representations or lexical activation (Coltheart et al., 2001; Dahan et al., 2001a; Dell, 1989; McClelland & Rumelhart, 1981; Plaut et al., 1996) might predict such an interaction. That is, competing semantically related contextual information might be more highly activated for high frequency words than low frequency words because a stronger spread of activation from high frequency words leads to more highly activated competing information from associated contexts, making selection more difficult. For low frequency words, associated contextual representations would have lower levels of activation.

An interaction between frequency and SemD would be unsurprising, insofar as single word processing tasks (e.g., lexical decision and single word reading) have revealed interactions of frequency with many other semantic variables, including concreteness (de Mornay Davies, & Funnell, 2000; James, 1975; Kroll & Merves, 1986), imageability (de Groot, 1989; Strain et al., 1995), contextual variability (equivalent to CD; Steyvers & Malmberg, 2003), and ambiguity (Hino & Lupker, 1996; Jager et al., 2015; Lichacz et al., 1999). However, the form of previously observed interactions does not match our prediction that frequency will exaggerate effects of activation at the semantic level of processing. In previous interactions the semantic variable usually has a stronger effect in low frequency than high frequency words, with high frequency words showing little or no effect. Ambiguity effects found by Jager et al. (2015) are an exception to this pattern, as they varied depending on the task. In a lexical-decision task, low frequency words showed an advantage of higher ambiguity, whereas high frequency words showed a disadvantage. The opposite pattern was observed in a semantic categorization task: low frequency words showed a disadvantage of high ambiguity, whereas high frequency words showed an advantage. In total, the previously observed interactions of frequency and semantic measures provide little support to the hypothesized interaction of frequency and SemD. However, the fact that SemD encapsulates aspects of a word's context—a multiword discourse—rather than a single word's features may cause it to show different effects from other semantic richness variables. That is, SemD captures the assumption that semantic activation may spread to contextually associated information, which may include a much wider array of representations than the individual features and meanings that could be activated due to concreteness, imageability, or ambiguity. One might reasonably expect the influence of such activation on the form of representations and on the selection of responses in a lexical task to differ from effects of arrays of concept features or meanings. Furthermore, correlations between SemD measures and other semantic measures are generally low to very low (see Table S1 in the online supplemental materials), suggesting the potential for distinct effects. Whatever its form, an observed interaction between

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frequency and SemD would add weight to the conclusion that the two measures reflect different underlying constructs.[1]

The Current Study

Whereas SemD has been explored to some extent as a measure of likely need for a word (Johns, Dye, et al., 2016; Jones et al., 2012) and as a measure of semantic richness (Pexman et al., 2017; Sidhu et al., 2016), few studies have explored the influence of SemD on activation within the semantic system and the implications of these dynamics in language processing. According to Hoffman and colleagues (Hoffman, Rogers, et al., 2011), SemD may index the degree of activation in the semantic system, because it reflects the degree to which contextual information associated with a target word is activated. One implication of this theory is that SemD provides an explanation for why word ambiguity tends to be facilitatory in tasks such as lexical decision but inhibitory in tasks such as semantic relatedness decision (Hoffman & Woollams, 2015). Furthermore, we believe this theory implies that SemD effects have an important interaction with word frequency effects. Given the ubiquity of word frequency as a measure of lexical processing and as a proxy for ease of processing in language and memory models, the dependence of frequency effects on SemD would have a broad impact on language and memory research. Our primary focus in this study was to explore the extent of this relationship and its form across a wide range of language processing tasks. Specifically, we were interested in whether frequency and SemD show independent effects across a wide range of language tasks and whether they interact because frequency scales the degree of activation of a word's associated semantic representations. If frequency and SemD do interact, then SemD may play an important modulating role in frequency effects while at the same time being a distinct construct from frequency.

Another principal goal of the current study was to provide further evidence on how SemD effects differ due to the semantic selection requirements of different tasks. Although a large literature exists on semantic selection mechanisms (e.g., Gold & Buckner, 2002; Thompson-Schill et al., 1997; Wagner et al., 2001), only a few studies examine the degree to which SemD affects semantic selection (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011; Hoffman & Woollams, 2015). Consequently, the evidence that SemD creates opposing beneficial and detrimental effects based on semantic selection requirements is limited. We aimed to expand this evidence by investigating a set of tasks with and without semantic selection requirements. Furthermore, there is currently little evidence that high SemD diminishes typical word frequency effects in tasks with strong semantic selection requirements. Only two studies to date have investigated suppressive effects of SemD on word frequency effects (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011), and the generalizability of their results is limited by small sample sizes. Thus, we sought to investigate whether findings from these previous studies are robust in different tasks and with larger samples.

With the above considerations, we explored effects of SemD and word frequency on lexical processing in a set of large, publicly available psycholinguistic databases. Such databases are a boon for a project like this one, because they allow language phenomena to be explored in robust data sets across different tasks and also allow relatively easy follow-up investigations and verification by other researchers. Because our theoretical interests pertained not only to the presence of independent and interacting effects of frequency and SemD but also to the variation of SemD effects according to task demands and the influence of deficits in semantic cognition, we examined tasks with varying semantic demands and incorporated databases with results from healthy and brain damaged patients. We selected tasks requiring single word or picture processing, either in production or comprehension, as such tasks minimize the complexity of contextual effects on lexical processing. Tasks included word repetition, oral single word reading (also known as "word naming"), lexical decision, concreteness decision, and picture naming; participants included young and old healthy subjects as well as stroke patients with aphasia.

A Note on Age of Acquisition

An additional variable that could be relevant to our investigation is age of acquisition (AoA). In contrast to the relatively recent proposals that CD or SemD may explain frequency effects, there has been a longer-standing debate about whether and to what extent frequency effects may be explained by AoA. Currently, researchers largely agree that frequency and AoA effects are separable, given the many behavioral studies that show independent or interacting effects of the two variables (see review by Juhasz, 2005) and computational models incorporating both AoA and frequency show effects of both variables (Ellis & Lambon Ralph, 2000). Thus, AoA effects are unlikely to supplant frequency effects. However, effects of AoA have also been argued to be semantic, making AoA potentially relevant to SemD effects (Brysbaert et al., 2000; Brysbaert & Ghyselinck, 2006). One well-supported hypothesis on the effects of AoA suggests that early-learned concepts are easier to retrieve than later-learned concepts because the former are either better encoded, owing to the relatively greater plasticity of the system in early life (Ellis & Lambon Ralph, 2000), or have more connections to other concepts because they are more likely to be used as an anchor for understanding later-learned concepts (Steyvers & Tenenbaum, 2005). In either case, the form of the representations is shaped by the order in which acquisition occurs, and we may consider how such representations relate to the aims of the current study.

Based on their proposed effects on semantic representations, AoA and SemD could be expected to have parallel effects. CD and SemD have been claimed to explain frequency effects owing to the principle of likely need. High CD and SemD can be motivated as related to likely need because a word associated with many contexts is more likely to be needed in the next context. If concepts that are acquired earlier tend to have more connections to other concepts—including contextually related concepts—then AoA and SemD could be expected to have parallel effects related to likely need. The computational models of Steyvers and

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[1] Hsiao and Nation (2018) failed to find an interaction between frequency and SemD in single word reading and lexical decision in their study on whether high SemD improves reading performance in children. However, their measure of SemD was (a) calculated on a corpus of texts written for children and (b) correlated far less strongly ($r = .22$) with word frequency than did the adult corpus-derived SemD measure of Hoffman et al. (2013) ($r \sim .50$). For these reasons, we expect frequency and SemD may relate differently in adult language performance than they did in children's language performance in Hsiao and Nation (2018).

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Tenenbaum (2005) do not explicitly include contextual relationships as a form of connections between concepts, but they do not rule out the possibility. Thus, the overlap between frequency and AoA effects in the literature may reasonably be linked to the principle of likely need. However, given that the principle of likely need predicts that SemD effects should explain frequency effects, the clear independence of AoA and frequency effects from the previous literature dispels the notion of a link between AoA and the principle of likely need.

Regarding other predicted effects, parallel predictions for AoA with SemD do not hold. First, whereas SemD has shown opposing facilitatory and inhibitory effects depending on semantic task demands, AoA consistently shows facilitatory effects, even in tasks requiring deep semantic processing (Brysbaert et al., 2000). AoA is also unlikely to explain diminished frequency effects in aphasic picture naming performance, as has been claimed for SemD: AoA's facilitatory effects seem to be largest in picture naming and an inhibitory effect would be required to decrease the frequency effect as seen in Hoffman et al. (2013). Second, the current study aims to explore interactions between frequency and SemD, where we predict that frequency may scale facilitatory or inhibitory SemD effects. The corresponding interaction between frequency and AoA has already been explored in many studies, and frequency scaling of AoA effects does not occur (see Juhasz, 2005). Therefore, we did not consider it well-motivated to use AoA in place of either frequency or SemD in the analyses of the current study.

Lexical Processing and Predicted SemD Effects

For our predictions, it was important for us to consider how SemD might affect each task's performance, as effects of SemD are predicted to affect the degree of activation in the semantic system (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011). According to the literature (e.g., Hoffman & Woollams, 2015; Pexman et al., 2017; Piercey & Joordens, 2000), SemD should cause a detrimental effect only when semantic selection is required by a task.

Models of Written Word Processing

Given that three tasks of the five we analyzed involve processing a single written word, it is valuable to consider each of these tasks relative to the features of visual word processing models. Prominent models include the dual route cascaded (DRC) model of Coltheart et al. (2001), the triangle model (Plaut et al., 1996), and the CDP++ model (Perry et al., 2007). The DRC model includes three pathways by which a printed word may be read: a nonlexical route, a nonsemantic lexical route, and a semantic lexical route (see Figure 6 in Coltheart et al., 2001). The nonlexical route involves a direct conversion of sublexical orthographic units (i.e., graphemes) to sublexical phonological representations (i.e., phonemes). The nonsemantic lexical route involves mapping lexical orthographic representations directly to lexical phonological representations, whereas the semantic lexical route involves mapping from lexical orthographic representations to semantic representations to lexical phonological representations. The triangle model (Plaut et al., 1996) eschews lexical representations, instead incorporating a connectionist mapping of sublexical-orthographic representations to both sublexical phonological representations and to semantic representations. The semantic representations are also mapped to the sublexical phonological representations. The CDP++ model (Perry et al., 2007) includes a combination of features of the DRC and triangle models, with a lexical route involving a mapping of lexical orthographic to lexical phonological representations (with some possible influence of semantics) and a connectionist mapping of graphemes to phonemes.

Whereas different visual word processing models differ in their claims about the relative influence of the lexical and nonlexical routes in eventual pronunciation of a word, all assume a possible role for semantics. However, none of these models is elaborate in its treatment of semantic processing and, in fact, the semantic component has not been implemented computationally in any. Thus, it is not well-specified exactly how semantic information that is contextually related to a target word would become activated in these models. Therefore, regardless of how the information is activated, we derive our predictions from the assumption of Hoffman et al. (2013; Hoffman, Rogers, et al., 2011) that SemD reflects the activation of contextually related semantic information to a target word within the semantic layer of processing.

Single Word Reading

Studies of single word reading have found that semantic variables explain relatively little unique variance in single word reading times (e.g., 2%) compared with lexical & phonological variables (e.g., 40%; Yap et al., 2011). Thus, nonlexical or nonsemantic routes seem to predominate processing in this task, and competition from semantic selection seems unlikely to be relevant. However, small, significant facilitatory semantic effects have been consistently found in large studies of single word reading (Baayen et al., 2006; Balota et al., 2007; Yap et al., 2011). Thus, we predicted that SemD would show a small facilitatory effect in this task.

Lexical Decision

As in single word reading, semantic variables in lexical decision explain relatively little unique variance in decision times (2%) compared with lexical variables (60%; Yap et al., 2011), suggesting relatively little role for the semantic processing route—and thus semantic selection—in this task. However, because semantic variables consistently show small but significant facilitatory effects in lexical decision (Yap et al., 2011), and Hoffman's SemD itself has shown facilitatory effects in lexical decision (Hoffman & Woollams, 2015; Pexman et al., 2017), we predicted that SemD would also show facilitatory effects in lexical decision in the current study.

Concreteness Decision

Surprisingly, variance in concreteness decision times is also explained better by lexical variables (20%) than semantic variables (7%; Yap et al., 2011). However, this disparity is far smaller than that observed for single word reading and lexical decision, and the influence of semantic processing is obviously stronger in concreteness decision. Unlike single word reading and lexical decision, concreteness decision necessitates the use of semantic information and therefore requires that the semantic level be accessed before a decision can be made (Van Orden, 1987). It is not clear, however,

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that a specific semantic representation must be selected, or even fully activated, to make a concreteness decision, as a concreteness judgment can rely on particular semantic attributes rather than requiring a more holistic understanding of a concept. For instance, merely activating some amount of sensory information may be sufficient to make a concrete/abstract judgment, given that concrete words tend to be associated with more image-based information than abstract words (Paivio, 1991). Alternatively, one could make a concreteness decision by recognizing readily available contextual information related to the word (Schwanenflugel et al., 1988). In either case, one need not necessarily retrieve the full semantic representation to make a decision, as one can rely on the relative richness of concrete words' semantic representations compared with those of abstract words (see Plaut & Shallice, 1993). Concreteness decisions are starkly different in this respect from decisions in some other semantic tasks, such as semantic relatedness judgment, where we have more reason to believe that semantic selection per se is relevant. In a semantic relatedness judgment, one cannot rely on the relative richness of the representation being accessed but must, for example, identify multiple semantic attributes and detect which features show a similarity (e.g., *cash* and *purse*; Hoffman & Woollams, 2015). Whereas semantic selection may not be *required* in concreteness decision, selection may occur nevertheless during access to semantic representations due to the relevance of the semantic level of processing. It also remains possible that one must select a semantic representation to associate the activated semantic features with the particular word that is being viewed. In either of these cases, concreteness decisions would be likely to show an inhibitory effect of SemD as a result of selection requirements.

SemD effects in concreteness decisions have been previously investigated in results from one database that we investigate here, the Calgary Semantic Decision Project (CSDP), by the authors of the database, Pexman et al. (2017). They showed that SemD effects in CSDP latencies differ based on a word's classification: abstract words showed a benefit of SemD, concrete words showed a detriment of SemD. Pexman et al. (2017) treat this difference only minimally, suggesting that it may be due to SemD's role as a measure of ambiguity, where ambiguity effects may differ for abstract and concrete words. According to the proposals of Hoffman et al. (2013; Hoffman, Rogers, et al., 2011) discussed above, it may be that concrete words require semantic selection, whereas abstract words do not, although it is difficult to say why this would be the case. Based on the results of Pexman et al. (2017), we predicted a beneficial effect of SemD for abstract words and a detrimental effect of SemD for concrete words.

A Model of Picture Naming

In contrast to models of word reading, where semantic processing requirements may be minimal, there is strong evidence that picture naming involves access to a semantic representation of the picture prior to accessing the phonological representation of its name (Nickels, 2000). One prominent model of picture naming is the two-step interactive model of lexical access proposed by Dell and colleagues (Dell et al., 1997, 2007; Foygel & Dell, 2000), which has also been used to model word repetition. This model includes a semantic layer, a lexical (word) layer, and a phonological layer, and is an interactive activation model. In picture naming, this model posits that activation spreads from a semantic representation generated from the picture to word representations and finally to phonological representations. Activation in the model flows bidirectionally in a cascading manner across all model levels, and, in some versions of the model, the degree of activation depends on the weight or strength of connections and the rate of decay of activation. Notably, semantic units in the two-step interactive activation model are typically discussed as features of a concept that can overlap between different word nodes. The literature on this model does not speak of semantic nodes as representing contextually associated information, but we must assume for the purposes of the present study that such information is represented and may become active during the course of processing as a function of SemD.

Consistent with the involvement of semantics in picture naming, many semantic effects have been observed in the task. For example, item imageability and concreteness have been shown to facilitate picture naming (Alario et al., 2004; Bates et al., 2001), and the presence of semantically related written distractors slows picture naming, as does the repeated naming of items selected from the same semantic category (e.g., Damian et al., 2001; Damian & Martin, 1999; Schnur et al., 2006). However, picture naming does not clearly involve a high degree of semantic selection, in terms of selecting one meaning of a word from among competing meanings. Inhibitory selection demands from SemD are claimed to be driven by the need to focus on particular, task-relevant aspects of a concept over other, irrelevant aspects (Hoffman et al., 2013). In picture naming no such ambiguity exists about which conceptual aspects are relevant, as the picture provides a strong context for selecting the appropriate meaning. That is, the relevant conceptual features would seem to be strongly constrained by the visual features of the picture from which the semantic representation is accessed. To reprise our earlier example, the word "dog" has several potential meanings and much contextual information associated with it, but the visual features of a pictured dog should map only onto a narrow set of relevant conceptual features for producing the word "dog." Although activation may spread to semantically and associatively related lexical representations from these features (e.g., "cat" and "wolf"), especially if they have residual activation from a previously seen word or picture, the resolution of competition from these activated features appears to be carried out at the lexical rather than the semantic level (Schnur & Martin, 2012; Schriefers et al., 1990).

Thus, it does not seem that higher SemD should have an inhibitory effect on object picture naming, even though the task requires access to a particular meaning. Importantly, however, Jefferies and Lambon Ralph (2006) reported that aphasic individuals with multimodal semantic deficits did not show familiarity effects in picture naming (and in other tasks, such as picture-word matching) and attributed the lack of familiarity effects to a semantic control deficit. On these grounds, one might predict an inhibitory effect of SemD on picture naming, which could result from patients' control deficits impacting their ability to select from competing representations. The argument would follow along the same lines as the absent frequency effect in aphasic patients' synonym judgment performance, as reported by Hoffman et al. (2013; Hoffman, Rogers, et al., 2011). Perhaps such an inhibitory effect could be accommodated in the two-step interactive model through feedback from the lexical level to the semantic level, which would serve to

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activate associated semantic information not only for the target word but for words which share semantic features with the target, leading to difficulty in selection.

In healthy individuals, semantic selection seemed unlikely to be necessary in object picture naming. However, considering the presence of other semantic effects, such as imageability effects, on object picture naming in the literature, we suspected that SemD was likely to have an effect. Plaut and Shallice (1993) suggested that imageability benefits picture naming because higher imageability reflects a richer semantic representation, which is easier to identify at the semantic level. Following this principle and considering SemD another measure of semantic richness, we considered it likely that healthy individuals would show facilitatory SemD effects in object picture naming like those seen for imageability. If inhibitory effects of SemD were not found in aphasic patients, we predicted that they may show facilitatory effects for these same reasons.

Word Repetition

The two-step interactive activation model has also been used to model repetition. In doing so, most aspects of the architecture remain the same as for picture naming (Dell et al., 2007). The difference is that in word repetition, semantic activation is not strictly necessary during processing. That is, activation flows from phonological representations activated from the spoken input to the word level, where a lexical representation is selected and then back to the phonological level, where a phonological representation is selected. The minimal relevance of semantic processing to word repetition is evident in the types of errors made by aphasic patients in word repetition relative to picture naming with the same items. In a set of 65 aphasic patients tested on both tasks, Dell et al. (2007) found that less than 1% of repetition responses were semantic errors, compared with 5.7% of responses (16% of errors) in picture naming. Such a minimal role for semantics suggests that semantic selection is not relevant to word repetition.

However, as in all of our lexical processing tasks, semantic effects have been found in word repetition, suggesting at least a small influence of semantic processing. Individuals with aphasia show effects of concreteness and imageability on accuracy of repetition, and concreteness affects the type of errors they make (Hanley et al., 2002; Hanley & Kay, 1997; Martin & Saffran, 1997). These effects may arise for patients as a result of deficits in the retention of phonological information, which leads to a greater reliance on semantic information when attempting to repeat. Such effects are not observed in healthy control participants, likely because the effects are usually measured in accuracy and because performance of healthy controls in repetition is near ceiling. Rather than being attributable to semantic selection, the observed semantic effects in repetition have been claimed as artifacts of feedback from the semantic to the word layer during processing (Dell et al., 2007). This feedback would also provide a good explanation for why patients with semantic dementia, who are argued to have semantic representation deficits, have shown better word list recall for words whose semantics are not degraded (Jefferies et al., 2004, 2005). Given the semantic influence of feedback and previous observations of concreteness and imageability effects in word repetition, we predicted that the aphasic patients we analyzed would show effects of SemD in word repetition. We predicted that these effects would be facilitatory, in parallel to the semantic richness effects of concreteness and imageability in picture naming.

SemD in the Current Study

Our analyses in the current study focused primarily on the measure of SemD proposed by Hoffman and colleagues (Hoffman et al., 2013) because: (a) in contrast to measures of contextual diversity, it uses the semantic relatedness of different contexts in its computation, which more clearly distinguishes its construct from word frequency, and (b) some of the phenomena we were interested in studying had only been previously tested using Hoffman's SemD: beneficial versus detrimental effects of SemD (Hoffman & Woollams, 2015) and the power of SemD to obscure word frequency effects (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011). However, because the SemD measure of Jones is theoretically similar to that of Hoffman et al., we also provide reports of analogous models with Jones' SemD in the text.

Predictions

Our analyses of large language processing databases tested the following predictions:

1. If the typical benefits of high frequency derive principally from SemD, as claimed by some research (Adelman et al., 2006; Jones et al., 2012) then frequency effects should be nonsignificant or inhibitory in models where frequency and SemD are included as predictors of task performance. Independent main effects of frequency and SemD or an interaction between the two variables would suggest that the two variables represent separate constructs.

2. If the degree to which inhibitory SemD effects are present in a task depends on the semantic selection requirements of the task (as predicted by Hoffman & Woollams, 2015), then the size and direction of SemD effects should vary across tasks depending on semantic selection requirements. That is, tasks that require participants to focus attention on specific semantic information in contrast to other semantic information to provide a response should show an inhibitory effect of SemD. Tasks may show a benefit of high SemD if their demands are such that greater activation of a range of semantic representations aids performance. Per our discussion above, we predicted that semantic selection demands may be relevant in concreteness decisions to concrete words, so this task should show detrimental effects of SemD. We predicted that semantic selection would not be relevant to single word reading, lexical decision, concreteness decisions to abstract words, or word repetition, and we predicted that all of these tasks would show facilitatory effects of SemD. The predictions for picture naming were less clear-cut with arguments on both sides regarding whether selection demands would be relevant.

3. If the strength of connections between target words and their associated meanings depends on word frequency (an extrapolation from the implementation of frequency in standard language models; Coltheart et al., 2001; Dell, 1989; McClelland & Rumelhart, 1981; Plaut et al., 1996),

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and if SemD reflects the breadth of semantic information associated with a word's representation (as predicted by Hoffman et al., 2013; Hoffman, Rogers, et al., 2011), then, to the extent that SemD affects task performance, the size of SemD effects should depend on word frequency. Such a dependency would appear as an interaction between SemD and word frequency. Where spreading activation to additional semantic information aids performance, benefits of SemD should improve as frequency increases. Where spreading activation is a detriment to performance, detriments of SemD should increase as frequency increases.

4. Patients with multimodal semantic deficits should show strong inhibitory effects of SemD under the following conditions: if multimodal semantic deficits imply a semantic control deficit in aphasic patients (per Jefferies & Lambon Ralph, 2006); if semantic control deficits create difficulties with high SemD words (per Hoffman et al., 2013; Hoffman, Rogers, et al., 2011); and if the task requires semantic selection. We predicted that picture naming may show inhibitory effects of SemD based on previous findings of absent frequency effects in aphasic patients with multimodal semantic deficits (Jefferies & Lambon Ralph, 2006). Such an inhibitory effect, by our other predictions, would imply that the task requires semantic selection. However, we also reasoned that picture naming is unlikely to require semantic selection based on a well-known model of picture naming (Dell et al., 1997, 2007; Foygel & Dell, 2000) and may be predicted to show facilitatory effects parallel to those found for other semantic richness variables, such as imageability and concreteness (Alario et al., 2004; Bates et al., 2001; Hanley et al., 2002; Hanley & Kay, 1997; Martin & Saffran, 1997). Word repetition was predicted to show a small facilitatory SemD effect in aphasic patients based on the same logic.

5. If inhibitory effects of SemD weaken frequency effects, as has been proposed in patients with multimodal semantic deficits and healthy older adults (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011), then, where inhibitory SemD effects are present, we should observe greater benefits of frequency after controlling for SemD than before. These effects should be observed regardless of the presence of a multimodal semantic deficit, given that the cited inhibitory SemD effect was previously observed both in patients with multimodal semantic deficits and in healthy older adults.

Method

Participants and Stimuli

Data were retrieved from five public databases containing results from language processing tasks: lexical decision and single word reading data from the English Lexicon Project (ELP; Balota et al., 2007); lexical decision data from the British Lexicon Project (BLP; Keuleers et al., 2012); concreteness decision (i.e., concrete/abstract) data from the Calgary Semantic Decision Project (CSDP; Pexman et al., 2017); object picture naming data from the International Picture Naming Project (IPNP; Szekely et al., 2004); and object picture naming and word repetition data from the Moss Aphasia Psycholinguistics Project Database (MAPPD; Mirman et al., 2010). In the CSDP, responses to concrete and abstract words were analyzed separately (hereafter, CSDP concrete and CSDP abstract), given that they show diverging effects of SemD in the literature (Pexman et al., 2017). Word stimuli from these databases were lemmas for MAPPD repetition, but not for any task from the ELP, BLP, or CSDP, which sometimes included multiple forms of the same word (e.g., centaur and centaurs) or inflected word forms (e.g., cats). All of the 9,513 words used in the BLP lexical decision analysis were present in the ELP analyses. Participant and stimuli sample sizes by study are shown in Table 1. Table 2 shows stimulus frequency (Zipf SUBTLEX frequency; Brysbaert & New, 2009; for information on the Zipf scale, see van Heuven et al., 2014) and SemD (Hoffman et al., 2013) for each data set.

Participants across all databases were healthy, younger adults (<45 yrs), except for participants from the MAPPD database, who were either older control participants or participants with aphasia

Table 1

Participant Information Across Studies

ID	Study	Task	Participants	Analyzed words
1	ELP	Lexical decision	818	16,804
2	ELP	Single word reading	460	16,804
3	BLP	Lexical decision	78	9,513
4	CSDP	Conc. Decision (abs.)	312	3,736
5	CSDP	Conc. Decision (conc.)	312	2,830
6	IPNP	Picture naming (objects)	50	423
7	MAPPD	Picture naming (PNT)	20, 36, 110*	166
8	MAPPD	Word repetition (PRT)	38, 111*	166

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database; PNT = Philadelphia Naming Test; PRT = Philadelphia Repetition Task.

* MAPPD PNT participants are (older adults; nonsemantic; and semantic patients), PRT participants are only aphasic patients (nonsemantic; and semantic patients).

Table 2
Word Stimuli Characteristics Across Studies

Measure		Zipf frequency				SemD			
Task ID	*n*	*M*	*SD*	Min	Max	*M*	*SD*	Min	Max
1	16,804	3.31	0.86	1.59	7.62	1.59	0.33	0.18	2.41
2	16,804	3.31	0.86	1.59	7.62	1.59	0.33	0.18	2.41
3	9,513	3.57	0.88	1.59	7.62	1.60	0.32	0.27	2.41
4	3,736	3.10	0.72	1.59	6.72	1.71	0.28	0.30	2.41
5	2,831	3.26	0.73	1.59	6.72	1.39	0.30	0.18	2.32
6	423	4.16	0.63	2.74	6.72	1.54	0.23	0.64	2.32
7	166	4.31	0.64	2.98	6.72	1.57	0.23	0.64	2.32
8	166	4.31	0.64	2.98	6.72	1.57	0.23	0.64	2.32

Note. For task ID referents, see Table 1.

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following left hemisphere stroke (see Mirman et al., 2010, for details). Aphasic patients were classified as having a multimodal semantic deficit if they performed worse (scores $>$ 2 standard deviations lower) than older controls on two nonverbal semantic tasks (Camel and Cactus Test – Bozeat et al., 2000; Pyramid & Palm Trees – Howard & Patterson, 1992) and one verbal semantic task (synonymy triplets – Saffran et al., 1988). Patients who satisfied these criteria were considered "semantic" patients, and those who did not meet these criteria were considered "nonsemantic" patients. Participant groups in different tasks within the same database were nonoverlapping (e.g., ELP lexical decision and word reading) except for MAPPD, where 107 semantic and 36 nonsemantic patients were tested on both Philadelphia Repetition Task (Dell et al., 2007) and Philadelphia Naming Task (Roach et al., 1996). All of the 175 items of the Philadelphia Naming task were also present in picture naming in the IPNP.

Analyses

Various measures, tasks, and data sets required specific treatment for analysis. In all RT analyses, only correct trials were analyzed and RTs were log transformed for the sake of normalization. For each lexical decision study (i.e., ELP & BLP), only word trials were analyzed. In the IPNP data set, we counted items as correct only if they matched the dominant U.S. response for a given picture, given that the dominant response provided the word upon which lexical variables were based.

Also, databases with large numbers of words included many function words in addition to content words. To examine whether function words, which tend to have extremely high frequency and high semantic diversity, affected our results, we performed two separate versions of each analysis: one including all words and one including only words predominantly used as nouns, verbs, adjectives, adverbs, or names according to the U.S. SUBTLEX database (Brysbaert & New, 2009). Separate analyses for content words were not required for IPNP or MAPPD object naming, as the items in these tasks elicited only content words.

The data were analyzed with linear and generalized linear mixed effect models using the lme4 package (Bates et al., 2015) in R v4.0 (R Core Team, 2020). Fixed effects included SUBTLEX Zipf word frequency, SemD, the interaction between frequency and SemD, plus a number of psycholinguistic variables known to affect word processing: word length in letters (Balota et al., 2007), orthographic neighborhood density (OLD20 – Yarkoni et al., 2008), phonological neighborhood density (PLD20 – Suárez et al., 2011), and concreteness (Brysbaert et al., 2014). We used OLD20 and PLD20 values calculated from the ELP word set. To control for learning effects across the course of a task, we controlled for trial, block, and session number, depending on which variables were relevant for each task. Scatterplots of our dependent variables (log RT and error) with word frequency and SemD revealed curvilinear effects for both variables in some tasks; therefore, we also included squared frequency and SemD terms as predictors in all models.

Our control variables were the same across tasks, despite the fact that some tasks did not require the explicit use of orthography (i.e., picture naming and repetition) or phonology per se (i.e., lexical decision and concreteness decision) and so did not necessarily require controlling orthographic and phonological neighborhood density. One reason for this is that considerable evidence implicates automatic activation of phonological codes from written word input (Lesch & Pollatsek, 1993; Van Orden, 1987) and some evidence indicates a role for orthography in spoken word production (e.g., Rastle et al., 2011), so there was a possibility that we would indeed see an influence of these variables. Another reason for maintaining the same control variables was that doing so ensured a uniform analysis could be performed across tasks and differences in results could not be tied to differences in control variables. Despite these efforts, models of picture naming in control participants in the MAPPD database would not converge with PLD in the model, so it was dropped as a control variable from these analyses.

A separate set of analyses was run including age of acquisition (AoA; Kuperman et al., 2012) as an additional control variable. These analyses were run to control for the possibility that any observed frequency effects might actually be AoA effects, given the strong correlation typically found between frequency and AoA (see Brysbaert & Biemiller, 2017) and because of the potential semantic effects of AoA (see Juhasz, 2005). Another set of analyses was run using the SemD of Jones et al. (2012; hereafter Jones SemD)[2] in place of Hoffman et al.'s SemD measure to investigate whether effects of SemD were similar across measures. Jones and Hoffman SemD in the current study correlate at roughly r = .50.

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[2] We acquired the Jones et al. (2012) SemD vSDM measure by personal communication with the authors. However, a public version of the same SemD measure calculated on a different corpus was released by Johns et al. (2020).

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Table 3
Participant Error Proportions Across Studies

Database	Task	*n*	*M*	*SD*	Skew	Min	Max
ELP	Word reading	16,804	0.04	0.07	3.07	0.00	0.76
ELP	Lexical decision	16,804	0.09	0.11	2.29	0.00	0.88
BLP	Lexical decision	9,513	0.08	0.12	2.64	0.00	0.90
MAPPD (controls)	Object naming	166	0.02	0.05	2.49	0.00	0.25
IPNP	Object naming	423	0.15	0.16	1.21	0.00	0.72
CSDP	Conc. decision (abs.)	3,736	0.13	0.14	1.77	0.00	0.87
CSDP	Conc. decision (conc.)	2,831	0.14	0.15	1.57	0.00	0.87
MAPPD (Sem Pts)	Word repetition	166	0.16	0.10	1.76	0.02	0.65
MAPPD (Nonsem Pts)	Word repetition	166	0.11	0.08	1.81	0.00	0.58
MAPPD (Sem Pts)	Object naming	166	0.42	0.13	0.53	0.17	0.85
MAPPD (Nonsem Pts)	Object naming	166	0.21	0.13	0.96	0.00	0.67

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database; Sem = semantic; Nonsem = nonsemantic; Conc = concreteness.

Correlations between frequency, AoA, SemD, and other semantic variables are available in Table S1 in the online supplemental materials.

Random intercepts were estimated for participants and items. Because some data sets were prohibitively small to estimate random slopes (i.e., MAPPD & IPNP picture naming, MAPPD repetition), and so that identical models could be run on all data sets, no random slopes were estimated.[3] We estimated *p* values using the Satterthwaite approximation for degrees of freedom from the R package lmerTest (Kuznetsova et al., 2017). All predictor variables were standardized prior to modeling. Main effects were acquired from models excluding all two-way interaction terms (including squared terms). In cases where models included three-way interactions, two-way interactions were obtained from models without a three-way interaction term.

RT outliers were determined in a three-step process. First, any trial with a raw RT less than 200 ms or greater than 10,000 ms was removed, because we deemed these responses too fast or too slow to be a true indicator of the cognitive process being probed. Second, we fit a model including the interaction term and a model excluding the interaction term on the entire data set. Third, we updated the models using only data points with residuals fewer than three standard deviations away from the residual mean in models with and without interactions. Where models failed to converge we used the methods for resolving convergence problems suggested within the lme4 package documentation (Bates et al., 2015).

In MAPPD patients, we investigated differences between groups by including group as a control variable and including interactions of group with frequency, SemD, and the Frequency × SemD interaction in our analyses.

To quantitatively assess the relative contributions of frequency and SemD to our models, we looked at two measures. First, we performed one degree of freedom likelihood ratio tests, which allowed us to examine quantitative changes in model fit with the Bayesian Information Criterion (BIC). Several comparisons were made: (a) we compared models with only frequency or SemD to models with both variables, which allowed us to see the unique contribution of each variable to model fit; (b) we compared models with only covariates to models with frequency or SemD added, which allowed us to see the shared contribution of frequency and SemD to model fit (when unique contributions were subtracted); and (c) we compared models with both frequency and SemD to models also containing the interaction of the two, which allowed us to see the unique contribution of the interaction to model fit. None of these models contained squared frequency or SemD effects. As a second measure, we also estimated the variance explained (marginal R^2) by each of these models in comparison with each other using the MuMIn package in R (Barton, 2020). The same model comparisons were made using both BIC and R^2.

Code for reproducing the current study can be found at osf.io/scb49.

Results

A summary of error proportions and RTs across all words in the included studies are listed in Table 3 and Table 4. Appendix A (see Tables A1 to A11) shows correlations between dependent variables, frequency, and SemD for all tasks, databases, and participant groups. Results for analyses containing only content words were roughly identical to analyses containing content and function words (see Appendix B; Tables B1 and B2). Tables 5 and 6 contain error and RT model coefficients and their significance in each model of healthy participant performance. Model-based outlier procedures removed .6 to 1.9% of observations from log RT analyses. Effects of variables of interest were not changed by the exclusion of outliers.

Effects of Word Frequency and SemD

Main effects of word frequency and SemD were relevant to several of our hypotheses. First, we predicted according to rational models of memory and their proponents (Adelman et al., 2006; Jones et al., 2012) that if SemD effects explain typical frequency effects, then frequency effects should not appear when SemD is included in the model. Second, we predicted based on previous findings (e.g., Hoffman & Woollams, 2015; Pexman et al., 2017) that the presence of beneficial or detrimental SemD effects would depend on task requirements, with only CSDP concrete likely to

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[3] We were able to successfully run a model with random slopes for frequency and Hoffman SemD on ELP lexical decision log RTs, and the size, direction, and significance of frequency and SemD effects remained nearly identical. This result provides evidence that the results for these variables in models without random slopes are unlikely to be spurious.

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Table 4

Participant RTs Across Studies

Database	Task	*n*	*M*	*SD*	Skew	Min	Max
ELP	Word reading	16,804	6.53	0.13	0.80	6.23	7.56
ELP	Lexical decision	16,804	6.55	0.14	0.57	6.18	7.23
BLP	Lexical decision	9,513	6.38	0.11	0.57	6.14	6.88
IPNP	Object naming	435	6.85	0.19	0.35	6.48	7.45
CSDP	Conc. decision (abs.)	3,736	6.90	0.11	0.39	6.57	7.48
CSDP	Conc. decision (conc.)	2,831	6.82	0.15	0.34	6.46	7.36

Note. Sem = semantic; Nonsem = nonsemantic; Conc = concreteness.

show a detrimental effect. Third, we predicted based on findings in older adults and aphasic patients (Hoffman et al., 2013) that controlling SemD, compared with not controlling SemD, may change the apparent size of the frequency effect. In the presence of an inhibitory SemD effect, we predicted that controlling SemD would increase the observed frequency effect; in the presence of a facilitatory SemD effect, we predicted that controlling SemD would decrease the observed frequency effect.

In analyses that did not include higher order terms, facilitatory main effects of word frequency independent of SemD were observed in log RTs for all tasks ($p < .001$) and for most tasks in error rates ($p < .001$), with the exception of MAPPD control picture naming and CSDP abstract, where error effects were nonsignificant. The same results were found when only content words were analyzed. In analyses controlling AoA, all previously significant frequency effects remained significant except that for errors in IPNP object naming (see Appendix C; Tables C1 and C2). In analyses using Jones SemD, the same pattern of frequency effects was observed as with Hoffman SemD, except that CSDP abstract showed a significant inhibitory error effect and no log RT effect (see Appendix D; Tables D1 and D2). Table 7 summarizes the significance and direction of frequency and SemD effects and their interaction across models with Hoffman SemD, models without content words, models controlling AoA, and models with Jones SemD.

Where frequency effects were significant in both the Hoffman SemD model and the Jones SemD model, effects were always numerically larger in analyses with Hoffman SemD. This result likely reflects that frequency and Jones SemD capture more common variance in performance across tasks than do frequency and Hoffman SemD, consistent with the higher correlation of Jones SemD and frequency. Significant frequency effects reflected faster and more accurate performance with high frequency than with low frequency items in all but one case (CSDP abstract errors with Jones SemD). These results show that, in single word processing tasks and in naming pictures of objects, word frequency plays a facilitatory role that cannot be attributed to a confounding effect of SemD, given that SemD was controlled in these analyses.

Facilitatory main effects of SemD were significant ($p < .001$) in log RTs for all tasks except CDSP concrete, where the effect was nonsignificant. For errors, facilitatory effects of SemD were also obtained for most tasks ($p < .001$), with the exception of the object naming tasks (IPNP & MAPPD), where the effects were nonsignificant, and CSDP concrete, where the effect was inhibitory.[4] Thus, for all tasks but CSDP concrete, SemD was facilitatory in latencies or error rates (or both). The same pattern of results was found in analyses with only content words and in analyses controlling AoA, except that the log RTs of CSDP concrete showed a significant ($p < .05$) inhibitory effect of SemD in the analysis controlling AoA. The pattern of SemD effects was identical in analyses using Jones SemD, except that the SemD effect in the log RTs of IPNP object naming was only marginally significant ($p < .10$). Main effects of SemD were consistent with predictions, supporting the notion that SemD effects tend to be facilitatory, except where a task may require semantic selection —that is, in all tasks but CSDP concrete.

Comparing the Size of Frequency and SemD Effects

When the size of significant, beneficial frequency and SemD coefficients were compared, frequency showed a larger independent effect than SemD in errors and log RTs, except in CSDP abstract, where the SemD effect was larger in errors and nearly equal in log RTs. This pattern was similar for analyses with Jones SemD, except that coefficients sometimes showed smaller differences and there were a few exceptional cases (see Appendix D). The same pattern was upheld when unique BIC and variance explained for frequency and SemD were compared—frequency always carried more explanatory power than did SemD, except in CSDP abstract (see Appendix E; Tables E1 and E2). This was true regardless of the SemD measure. The degree to which frequency showed more explanatory value over SemD varied by task and by DV (RT vs. error rate); the difference tended to be largest in lexical decision and word reading tasks and smaller in object picture naming and concreteness decisions to concrete words.

These results contradict those of Jones et al. (2012), who found that unique effects of frequency were typically much smaller than unique effects of SemD in ELP lexical decision and single word reading. The largest difference between our study and that of Jones et al. (2012) is that their SemD and frequency measures were drawn from the same corpora (a combination of the TASA, WIKI,

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[4] Interestingly, we did not observe the positive (inhibitory) SemD effect observed by Pexman et al. (2017) in our log RT analysis of CSDP concrete. This positive effect was, indeed, smaller than the negative effect observed in CSDP abstract in that study, which may be a clue to why we did not observe it. The difference may also be driven by one or more of several differences that existed between our analyses: Pexman et al. (2017) used hierarchical linear regression, whereas we used linear mixed effects models; they included two orthographic neighborhood variables and an additional semantic variable, average radiance of co-occurrence, and did not include phonological neighborhood; their frequency measure was different than our own; their analysis included about 25 more words than our own; and their analysis used raw RTs. However, after conducting additional analyses to see whether these factors impacted our SemD effect in the log RT analysis, we still did not find a positive SemD effect.

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Table 5

Standardized Coefficients From Error Mixed Models

Database	Test	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × Freq	Conc.	Length	Ortho N.	Phon N.
ELP	Word reading	480861	16,804	460	−0.580***	0.971***	−0.134***	−0.013	−0.057***	−0.232***	−0.327***	0.081*	0.326***
ELP	Lexical decision	572497	16,804	818	−0.810***	0.566***	−0.129***	0.154*	−0.003	−0.160***	−0.765***	0.421***	−0.010
BLP	Lexical decision	370918	9,513	78	−1.011***	1.449***	−0.249***	0.529***	−0.035^	−0.279***	−0.659***	0.232***	−0.029
MAPPD	Obj. naming	3,320	166	20	−0.240	−0.421	−0.093	3.804^	−0.149	−0.220	0.921	−0.566	—
IPNP	Obj. naming	21,700	423	50	−0.527***	2.434*	−0.091	−0.058	−0.020	−0.223*	0.598*	−0.626*	−0.027
CSDP	Conc. decision (abs.)	116550	3,736	312	−0.003	0.074	−0.337***	−0.247	−0.031	1.867***	−0.332***	−0.051	0.110*
CSDP	Conc. decision (conc.)	88,343	2,831	312	−0.280***	−0.321^	0.094***	0.496***	0.018	−2.389***	0.115***	−0.215***	−0.078

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity squared; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. All main effects are from models with no higher order terms.
^ $p < .10$. * $p < .05$. *** $p < .001$.

and New York Times corpora; see Jones et al., 2012), whereas the SemD and frequency measures in our analyses were from different corpora (from the British National Corpus for Hoffman SemD; and SUBTLEX-US for word frequency). Correlations were high but far from perfect between SUBTLEX Zipf frequency and both BNC frequency (r = .76) and Jones' frequency measure (r = .84). In additional analyses (see Tables S2 and S3 in the online supplemental materials), we found that using the frequency measure from the same corpora as Jones SemD led to larger independent effects of Jones SemD than frequency in seven out of eight cases. For example, in Table S2 in the online supplemental materials one can see that weights were -.033 and -.06 for frequency and SemD in the log RT model of ELP word reading when Jones' frequency and SemD were used. Notably, frequency effects were significant and facilitatory in every analysis, even when smaller than SemD effects. However, these analyses also showed that frequency effects remained larger than SemD effects in all models using Hoffman SemD and frequency from the British National Corpus (BNC). The crucial factor leading to differences in the relative size of the frequency and SemD effects seems to be the correlation between the frequency and SemD measures. In the ELP data set (n = 16,804), where Jones et al. (2012) found that frequency effects were negligible in the presence of SemD effects, Jones SemD correlates with the Jones frequency measure from the same corpus r = .97 and with SUBTLEX Zipf frequency r = .82 in the ELP data set. By contrast, Hoffman SemD correlates with BNC log frequency r = .45 and with SUBTLEX Zipf frequency r = .36 in the ELP data set. Given the extremely high correlation between Jones' SemD and their frequency measure, it is not surprising that one variable would show a much larger independent effect. We will return in the discussion to whether one SemD measure is preferable to the other. For now, we reiterate that the similarities in the effects of Hoffman and Jones SemD are remarkable, given the measures' different correlations with word frequency and that both measures robustly show independent effects of frequency and SemD.

Task-Dependent Effects of SemD

Although we observed differing inhibitory and facilitatory SemD effects across tasks in the above analyses, we believed that the difference in effects deserved a direct comparison. The best comparison of these opposing task effects would involve the same stimuli across tasks and would include task as a factor in the analysis. To this end, we contrasted the errors of CSDP concrete with those of ELP lexical decision and single word reading on the set of overlapping words between data sets. The ELP tasks were chosen for having the largest data sets with which to compare facilitatory SemD effects with the inhibitory effects of CSDP concrete. Only errors were analyzed because CSDP log RTs did not show a significant inhibitory effect of SemD. The analyses were identical to the above analyses, except that task and its interaction with frequency, SemD, and the Frequency × SemD interaction were included in the models.

The results of these analyses (see Table 8) showed that task interacted with the SemD effect such that the SemD effect was more positive in CSDP concrete than in ELP lexical decision and ELP word reading. To examine these interactions, we

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modeled the tasks individually on the shared subset of word stimuli. The Task × SemD interactions reflected significant facilitatory effect of SemD in the ELP task subsets and a significant inhibitory effect of SemD in the CSDP concrete subset. These results are consistent with the differences we observed in the full model analyses of ELP lexical decision, ELP word reading, and CSDP concrete, and they show that the opposing effects of SemD across tasks were not driven by differences in the word samples of the tasks.

Impact of SemD Effects on Frequency Effects

To investigate the impact of SemD effects on frequency effects, we compared the size of frequency effects across models with and without SemD. The models with and without SemD did not include any higher-order terms (i.e., interactions or squared terms). Results of these comparisons showed that significant SemD effects always changed frequency effects in the expected direction based on the correlation between frequency and SemD: The frequency effect increased when an inhibitory SemD effect was controlled in the errors of CSDP concrete, and the frequency effect decreased when significant facilitatory SemD effects were controlled in all other tasks (see Tables S4 and S5 in the online supplemental materials). Change in frequency effect coefficients of log RT models ranged from .005 to .011 (from 7% to 12% of the size of the effect in the model without SemD), and change in error models ranged from .035 to .109 (from 6% to 97% of the size of the effect in the model without SemD). For CSDP concrete errors, where there was an inhibitory SemD effect, the frequency effect changed from −.245 without controlling SemD to −.28 when controlling SemD, a change of about 14%. The largest change (97%) was in CSDP abstract errors, where the frequency effect went from significant to nonsignificant with the introduction of SemD, but the remainder of changes ranged from 6% to 23%. Notably, all other frequency effects remained significant and facilitatory regardless of whether SemD was included in the model. When such models were analyzed with Jones SemD, results followed the same pattern. These results provide little support for the claims of Hoffman et al. (2013; Hoffman, Rogers, et al., 2011) that uncontrolled, inhibitory SemD effects have masked the frequency effects of semantically impaired patients in previous studies, as we found only a small effect of SemD on frequency effects in most cases, even when the SemD effect was inhibitory.

Interactions of Word Frequency and SemD

As shown in Tables 5 and 6, significant interactions between SemD and word frequency ($p < .001$) were observed in two cases: the errors of ELP word reading and the log RTs of ELP lexical decision. Both interactions were negative, reflecting that as frequency increases, facilitatory effects of SemD increase and as SemD increases, facilitatory effects of frequency increase. The same pattern of significant interactions was observed when only content words were analyzed (see Appendix B) and when controlling for AoA (see Appendix C). Given the unexpected result that the SemD × Frequency interaction was observed in one lexical decision megastudy data set but not the other, we carried out follow-up analyses of BLP lexical decision replacing SUBTLEX Zipf frequency with log frequency from the British National

Table 6
Standardized Coefficients From Log RT Mixed Models

Database	Test	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × Freq	Conc.	Length	Ortho N.	Phon N.
ELP	Word reading	448308	16,803	460	−0.038***	0.059***	−0.012***	0.005	0.000	−0.014***	0.022***	0.010***	0.023***
ELP	Lexical decision	512833	16,804	818	−0.063***	0.071***	−0.012***	0.016***	−0.002***	−0.016***	0.015***	0.024***	0.024***
BLP	Lexical decision	336420	9,513	78	−0.063***	0.070***	−0.013***	0.023***	−0.001	−0.017***	−0.007***	0.012***	0.002
IPNP	Object naming	18,117	423	50	−0.081***	0.228*	−0.027***	−0.057	0.003	−0.043***	0.044^	−0.042	−0.012
CSDP	Conc. decision (abs.)	100818	3,736	312	−0.023***	0.004	−0.021***	−0.007	0.002	0.098***	0.001	−0.016***	0.022***
CSDP	Conc. decision (conc.)	75,246	2,830	312	−0.045***	−0.033*	0.001	0.032*	0.003	−0.198***	0.033***	−0.025***	0.000

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database; Freq = frequency, SemD = semantic diversity, Freq sq = frequency squared; SemD sq = semantic diversity squared; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations, Ss = subjects. All main effects are from models with no higher order terms.
^ $p < .10$. * $p < .05$. *** $p < .001$.

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Table 7

Effects of Word Frequency and SemD Across Models

			Frequency				SemD				Frequency × SemD			
Database	Task	Measure	Hoffman SemD model	Hoffman (content)	Hoffman (-AoA)	Jones SemD	Hoffman SemD model	Hoffman (content)	Hoffman (-AoA)	Jones SemD	Hoffman SemD model	Hoffman (content)	Hoffman (-AoA)	Jones SemD
ELP	Word reading	errors	–	–	–	–	–	–	–	–	–	–	–	n.s.
		log RTs	–	–	–	–	–	–	–	–	n.s.	n.s.	n.s.	–
ELP	Lexical decision	errors	–	–	–	–	–	–	–	–	n.s.	n.s.	n.s.	–
		log RTs	–	–	–	–	–	–	–	–	–	–	–	–
BLP	Lexical decision	errors	–	–	–	–	–	–	–	–	(–)	(–)	n.s.	(–)
		log RTs	–	–	–	–	–	–	–	–	n.s.	(–)	n.s.	–
IPNP	Obj. naming	errors	–	NA	n.s.	–	n.s.	NA	n.s.	n.s.	n.s.	NA	n.s.	n.s.
		log RTs	–	NA	–	–	–	NA	–	(–)	n.s.	NA	n.s.	n.s.
CSDP	Conc. decision (abs.)	errors	n.s.	n.s.	n.s.	+	–	–	–	–	n.s.	n.s.	(–)	–
		log RTs	–	–	–	n.s.	–	–	–	–	n.s.	n.s.	n.s.	n.s.
CSDP	Conc. decision (conc.)	errors	–	–	–	–	+	+	+	+	n.s.	n.s.	n.s.	–
		log RTs	–	–	–	–	n.s.	n.s.	+	n.s.	n.s.	n.s.	n.s.	+
MAPPD	Obj. naming	errors	n.s.	NA	n.s.	n.s.	n.s.	NA	n.s.	n.s.	n.s.	NA	n.s.	n.s.

Note. – = significant negative effect; + = significant positive effect; (–) marginal negative effect, $p < .10$; n.s. = nonsignificant effect; NA = test not conducted; ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database.

Corpus (BNC). We considered that a British frequency measure may better capture frequency effects in speakers of British English, and we opted for BNC frequency because Hoffman SemD was derived from the BNC corpus. In models with log BNC frequency, frequency and SemD interacted in the same direction as in ELP lexical decision in log RTs (coefficient = $-.006$, $p < .001$) and errors (coefficient = $-.119$, $p < .001$). Plots of these interactions can be found in Figures S5–S8 in the online supplemental materials. These effects were consistent when analyzing only content words and when controlling for AoA, except that the log RT interaction was only marginally significant after controlling for AoA (see Appendix F; Table F1). The direction and significance of frequency and SemD main effects were not changed by the inclusion of log BNC frequency compared with SUBTLEX Zipf frequency.

The pattern of Frequency × SemD interactions was quite different in analyses with Jones SemD, presumably owing to differences in the correlation between SUBTLEX Zipf frequency and the SemD measure. Significant interactions overlapped with Hoffman SemD analyses only in ELP lexical decision log RTs, where both showed significant negative interactions. Significant negative interactions with Jones SemD were also observed in the errors of ELP lexical decision, CSDP abstract, and CSDP concrete, as well as in the log RTs of ELP word reading and BLP lexical decision. Jones SemD showed a positive interaction with frequency in the log RTs of CSDP concrete. In models with log BNC frequency in place of SUBTLEX Zipf frequency, BLP lexical decision showed a significant interaction in errors (coefficient = .102, $p < .05$) but not log RT (coefficient = .003, $p > .1$). All of the observed significant interactions provide further evidence that SemD and frequency reflect different constructs. In analyses of ELP tasks where frequency and SemD measures were drawn from the same corpus, interactions were observed in both tasks in nearly every comparison, providing further confirmation that frequency and SemD are not tapping the same construct (see Table S2 in the online supplemental materials).

Our primary interest in exploring the SemD × Frequency interaction was whether word frequency would exaggerate main effects of SemD, as might be expected if the activation level of semantic information scales with frequency and SemD reflects spreading activation to a target's contextually related semantic information (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011). Our results provide some evidence for this hypothesis, given that the observed interactions with Hoffman SemD were in the predicted direction. However, interactions were not always present, even when both frequency and SemD effects were present, suggesting that the observed interactions could have occurred for a different reason. The fact that significant interactions were present in the databases with the largest samples suggests that SemD × Frequency interactions could be present in other tasks if there were power to detect it. Deliberate manipulations of frequency and SemD in future studies of picture naming and semantic decisions could clarify whether this is the case.

Effects of SemD and Frequency in Patients in the MAPPD Database

As discussed above, we considered two plausible hypotheses regarding effects of SemD and their relationship with effects of word frequency in the picture naming performance of aphasic

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Table 8
Task SemD Effect Comparison Models (Errors)

Databases	ELP LDT, CSDP Conc	ELP LDT	CSDP Conc	ELP WR, CSDP Conc	ELP WR	CSDP Conc
DV	Errors	Errors	Errors	Errors	Errors	Errors
Task	0.579***	—	—	1.329***	—	—
Freq	−0.410***	−0.854***	−0.280***	−0.325***	−0.522***	−0.280***
Freq sq	−0.032	0.244	−0.322^	−0.108	0.444^	−0.322^
SemD	−0.020	−0.163***	0.094***	0.045^	−0.135***	0.094***
SemD sq	0.346**	−0.006	0.496**	0.380**	−0.003	0.496**
SemD × Freq	0.007	−0.038	0.018	0.024	−0.003	0.018
Task × Freq	0.458***	—	—	0.169***	—	—
Task × SemD	0.441***	—	—	0.407***	—	—
Task × Freq × SemD	0.051*	—	—	0.001	—	—
Conc.	−0.985***	−0.356***	−2.390***	−1.513***	−0.331***	−2.390***
Length	0.198***	−0.809***	0.115**	0.175***	−0.379***	0.115**
Ortho N.	−0.227***	0.616***	−0.215***	−0.250***	0.149	−0.215***
Phon N.	−0.152***	−0.209**	−0.078	−0.084^	0.155^	−0.078
Observations	184775	96,432	88,343	169337	80,994	88,343
Words	2,831	2,831	2,831	2,831	2,831	2,831
Ss	1,130	818	312	772	460	312

Note. ELP = English Lexicon Project; CSDP = Calgary Semantic Decision Project; LDT = lexical decision; WR = word reading; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity squared; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. All main effects are from models with no higher-order terms. Two-way interactions are from models with no three-way interaction term.
^ $p < .10$. * $p < .05$. ** $p < .01$. *** $p < .001$.

patients. One hypothesis was that aphasic patients with multimodal semantic deficits would show inhibitory effects of SemD in an object picture naming task. This hypothesis derived from (a) the fact that patients with multimodal semantic deficits have previously failed to show typical familiarity effects (which are correlated with frequency effects) in picture naming (Jefferies & Lambon Ralph, 2006) and (b) other studies with such patients have claimed that their difficulty processing high SemD words causes them not to show typical frequency effects when SemD remains uncontrolled (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011). These facts entail not only that we should observe an inhibitory effect of SemD but also that controlling for SemD should increase the observed frequency benefit in picture naming for patients with multimodal semantic deficits. Observing such results would provide support for the claim that absent frequency and familiarity effects observed in previous studies were due to effects of SemD. Patients without multimodal semantic deficits served as a useful group for comparison, as they should not have damaged semantic control and therefore should not show as strong a detriment of high SemD, though they should also show the impact of any inhibitory SemD effect on the size of frequency effects.

The alternative hypothesis concerning SemD effects in picture naming was that all patients would show facilitatory effects, consistent with effects of other semantic richness variables in the literature, such as concreteness (Alario et al., 2004; Bates et al., 2001) and the lack of semantic selection requirements inferred from models of picture naming (Dell et al., 1997, 2007; Foygel & Dell, 2000).

By contrast with our split expectations for picture naming, we expected that both patient groups would show a facilitatory effect of SemD, if any, in word repetition, given that SemD effects may be similar to concreteness and imageability effects seen in this task in other patients in the literature (Hanley et al., 2002; Hanley & Kay, 1997; Martin & Saffran, 1997). However, given that semantic processing seems to play a negligible role in immediate repetition (Dell et al., 2007), it was not clear whether any effect of SemD would be present.

In models predicting errors in MAPPD picture naming and word repetition, we observed no main effect of Hoffman SemD across groups, and neither task showed a significant difference in SemD effects across groups (see Table 9). In models with Jones SemD, we observed no main effect of SemD across groups in either task, but there was a significant negative interaction between group and frequency and a positive interaction between group and SemD in picture naming. The interaction of Group × Frequency reflected a stronger frequency effect in semantic patients (coefficient = −.392, $p < .001$) than in nonsemantic patients (coefficient = −.204, $p < .10$) when SemD was controlled. The interaction of Group × SemD reflected a nonsignificant detrimental effect of high SemD in semantic patients (coefficient = .043, $p > .10$) and a nonsignificant facilitatory effect in nonsemantic patients (coefficient = −.125, $p > .10$). Neither Hoffman nor Jones SemD models showed a significant frequency by SemD interaction or a three-way interaction with patient group in either task.

Because of the significant interaction of group with Jones SemD, we also investigated the difference between frequency effects in models before and after controlling Jones SemD. Frequency effects changed in each patient group according to the direction of the group's nonsignificant SemD effects. In semantic patients, frequency effects were weaker before controlling SemD (coefficient = −.358, $p < .001$) compared with after (coefficient = −.392, $p < .001$); in nonsemantic patients, frequency effects were stronger before controlling SemD (coefficient = −.302, $p < .001$) compared with after (coefficient = −.204, $p < .10$). These results provide evidence that, although its effects were nonsignificant, SemD impacted the observed frequency effects of semantic and nonsemantic patients differently. However, contrary to the predictions derived from the results of Jefferies and Lambon Ralph (2006), frequency effects in picture naming in semantic patients

Table 9
MAPPD Patient Mixed Models

Test	Hoffman SemD			Jones SemD		
		Patients			Patients	
	Controls Obj naming	Obj naming	Repetition	Control Obj naming	Obj naming	Repetition
Group	—	1.486***	0.463^	—	1.489***	0.466^
Freq	−0.240	−0.364***	−0.327***	−0.339	−0.350***	−0.271**
Freq sq	−0.421	0.448	0.503	2.954	3.235**	0.911
SemD	−0.093	0.029	0.028	0.051	0.005	−0.045
SemD sq	3.804^	0.042	0.210	4.671	1.267	−2.627
SemD × Freq	−0.149	0.090	0.038	−0.394	−0.254	0.108
Group × Freq	—	0.013	−0.093	—	−0.150*	−0.072
Group × SemD	—	−0.042	−0.100	—	0.155*	−0.097
Group × SemD × Freq	—	0.020	0.045	—	0.021	0.073
Concreteness	−0.220	−0.186***	−0.116*	−0.211	−0.189***	−0.118*
Length	0.921	0.185	−0.055	0.926	0.178	−0.053
Ortho N	−0.566	−0.254	0.155	−0.579	−0.224	0.177
Phon N	—	0.507***	0.312*	—	0.490***	0.288*
Obs	3,320	24,236	24,734	3,360	24,528	25,032
Word	166	166	166	168	168	168
Ss	20	146	149	20	146	149

Note. MAPPD = Moss Aphasia Psycholinguistics Project Database; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity squared; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. Nonsemantic patients were used as the baseline group. All main effects are from models with no interaction terms and no higher order effects. Two-way interactions are from models with no three-way interaction term.
^ $p < .10$. * $p < .05$. ** $p < .01$. *** $p < .001$.

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were quite strong even before SemD was controlled. Ultimately, the fact that frequency effects in picture naming of semantic patients were significant even before controlling SemD and did not show an extreme change after controlling SemD provides evidence against the explanation that SemD effects are the source of absent frequency effects in some aphasic patients' picture naming.

Discussion

In this study, we explored effects of a lexical variable, semantic diversity (SemD), that appeared to have intriguing and understudied effects in the literature. SemD, a measure of the variety of semantic contexts in which a word appears, has been argued by some researchers to explain the typical frequency effect, as words that appear in more variable contexts are more likely to be needed in future contexts and therefore need to be more readily available in the lexicon (Adelman et al., 2006; Jones et al., 2012). Additionally, prior research with healthy adults and aphasic patients provided evidence that SemD is a variable that creates difficulty in performing tasks where a specific semantic representation must be selected (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011; Hoffman & Woollams, 2015) and a benefit in performing many other lexical tasks without semantic selection demands (Hoffman & Woollams, 2015; Hsiao & Nation, 2018). Also intriguing were findings showing that SemD appears to modulate typical word frequency effects in healthy older adults and patients with semantic comprehension deficits, as inclusion of SemD in regression analyses uncovered an otherwise unobservable frequency effect in a synonym selection task (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011).

Hoffman et al. claim that SemD weakens the frequency effect in synonym selection because participants perform more poorly with high SemD words than low SemD words and this weakens the typical advantage of high frequency as a result of the correlation between SemD and frequency. The authors further claim that poor performance with high SemD words occurs because higher SemD necessitates the use of an executive semantic control mechanism in tasks requiring semantic selection. The semantic control mechanism, they claim, is used to resolve competition between activated, contextually related semantic representations. Low SemD words do not necessitate such a mechanism, as they activate fewer contextually related representations. Strong semantic control requirements, the authors claim, slow processing in healthy individuals and cause errors in comprehension-impaired aphasic patients, whose semantic control is impaired.

Thus, SemD was claimed not only to be independent of word frequency but to have a crucial relation to it—one where the presence of a SemD effect changes the apparent size of frequency effects when left uncontrolled. The results of Hoffman et al. (2013; Hoffman, Rogers, et al., 2011) suggest a crucial role for SemD in some anomalous absent frequency effects observed in patients with multimodal semantic deficits. These results suggested to us a potential interaction between SemD and word frequency effects, whereby word frequency may modulate the strength of activation of semantic information associated with a word—represented by SemD. Such an interaction between frequency and SemD had not been previously investigated in healthy adult language processing.

Our goal was to generally explore the effects of SemD and to explore the relationship between SemD and word frequency across a variety of simple language processing tasks: single word reading, word repetition, lexical decision, concreteness decision, and object naming. Across two distinct measures of SemD, we observed that word frequency and SemD show distinct effects, and word frequency effects are typically larger. SemD was typically facilitatory, except in the case of concreteness decisions to concrete

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words, where SemD was inhibitory. Inhibitory SemD effects tended to weaken frequency effects, and facilitatory SemD effects to strengthen frequency effects, when SemD was not controlled, although these effects were typically small. The interactions we observed between frequency and SemD converge with the observed main effects on the conclusion that frequency and SemD represent distinct constructs. Frequency × SemD interactions were only seen in data sets with the largest number of observations, providing some tentative evidence that that frequency may scale the spreading of activation in the semantic system reflected by SemD, but it is clear that further research is necessary. When we explored the impact of SemD on the performance of aphasic patients with and without multimodal semantic deficits, frequency effects, even in semantic patients, were present both before and after controlling SemD, providing evidence contrary to the claim that problems with SemD create absent frequency effects in patients with multimodal semantic deficits. Across all of our results, the complex relationship observed between frequency and SemD suggests that effects of an influential psycholinguistic variable, word frequency, remain relevant to understanding language processing and depend on a less-studied variable, SemD. This relationship has broad implications for models of language processing.

Are Frequency Effects Just Effects of Contextual Diversity?

Some researchers, appealing to rational models of memory, have claimed that contextual diversity or SemD provides a better explanation of the traditional frequency effect than does the explanation that frequency of exposure strengthens memory traces (Adelman et al., 2006; Jones et al., 2012). Evidence in favor of these accounts has shown that contextual diversity (in the form of corpus document count) explains more variance in word processing measures than does word frequency count, often completely eliminating frequency effects (Adelman et al., 2006; Brysbaert & New, 2009; Cai & Brysbaert, 2010; Dimitropoulou et al., 2010; Soares et al., 2015). We discussed above the fact that document count is difficult to disentangle from frequency, given the extremely high correlation ($r > .96$) between the two variables. This relationship is, indeed, even stronger when certain other factors, such as the inclusion of proper names, are controlled (Brysbaert & New, 2009). Thus, the increased variance explained by contextual diversity measures may only show that contextual diversity is an improved measure of the frequency construct.

Two measures called SemD (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011; Jones et al., 2012) improved upon the formulation of the contextual diversity variable by accounting for overlapping content of the contexts in which a word appears. Proponents of one of these measures have maintained the same claims as proponents of contextual diversity and shown that SemD can also account for more variance in processing than does frequency (Jones et al., 2012). Interestingly, this measure also shares a strong correlation with word frequency ($r > .97$). The other measure of SemD, on the other hand, has shown a pattern of results exhibiting the independence of SemD and word frequency constructs (Hoffman et al., 2013). Studies using Hoffman et al.'s SemD have shown inhibitory effects, which are not explained by the framework of rational models of memory, and these studies often also show distinct, facilitatory effects of frequency (Hoffman et al., 2013; Hoffman, Rogers, et al., 2011; Hoffman & Woollams, 2015; Pexman et al., 2017; Plummer et al., 2014; Sidhu et al., 2016; Yap & Pexman, 2016). Such results provide evidence against the account from rational models of memory—in that frequency effects are independent of SemD—and they support accounts of SemD as a measure of semantic richness.

Our results showed that frequency and SemD effects were consistently distinct. Frequency effects were found in nearly all analyses, even when SemD was controlled and regardless of which SemD measure was used. Although not always observed, interactions between frequency and SemD also indicated that the two variables represent distinct constructs. These results show that frequency effects cannot be explained by SemD. Notably, neither frequency nor SemD effects were removed by the presence of age of acquisition in our analyses, showing that age of acquisition cannot explain their effects. Thus, we must consider frequency and SemD as independent constructs, contrary to prior claims. Furthermore, consistent with previous studies, we found both facilitatory and inhibitory effects of both Jones and Hoffman SemD measures.

Together, our results provide strong evidence against accounts of SemD as a measure of likely need, per rational models of memory (Anderson & Milson, 1989; Anderson & Schooler, 1991). Instead, SemD should be considered a measure of semantic richness, given the match between its inhibitory and facilitatory effects and those of richness measures, such as semantic neighbors, number of senses, or number of meanings, in the literature. Our results parallel the results of other studies reporting opposing effects of richness, comparing facilitatory effects in lexical decision to inhibitory effects in semantic categorization (Hino et al., 2006; Jager et al., 2015), semantic relatedness decisions (Hoffman & Woollams, 2015), or reading connected text (Piercey & Joordens, 2000). Mirman and Magnuson (2008) even found opposing effects of near and distant semantic neighbors within the same task, semantic categorization. Hoffman and Woollams (2015) conceived of SemD as eliciting activation consistent with the variability of the contexts in which it occurs. They argue that in novel contexts, or other situations in which the required meaning of a word is not clear, that activation in the semantic system for a high SemD word, "may settle into a noisy, somewhat underspecified state that represents a blend of the possible semantic patterns associated with the word" (p. 387). Such an underspecified state may be useful when no specific representation need be retrieved, as in lexical decision, but it would be detrimental when a specific representation is required for processing. This conception is similar to that of Rodd et al. (2004) in their PDP model of polysemy, where words with multiple related meanings develop broader attractor basins, making them easier for the network to move into. However, settling on a specific semantic pattern in this system was more difficult for these ambiguous words compared with unambiguous words. These models suggest potential ways in which SemD could affect processing in the semantic system.

Given that frequency effects are distinct from SemD effects, where exactly do they occur during processing? Our study provides no novel evidence regarding the locus of the frequency effect—except evidence that it does indeed have an effect—but a long literature has addressed this question in detail (see Kittredge et al., 2008; Knobel et al., 2008; Liu et al., 1996). In language production, evidence for a phonological locus of the frequency effect

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comes from frequency inheritance effects in translation (Jescheniak & Levelt, 1994; Jescheniak et al., 2003; although see Bonin & Fayol, 2002; Caramazza et al., 2001), frequency distractor manipulation in picture-word interference tasks (Miozzo & Caramazza, 2003), and aphasic picture naming errors (Kittredge et al., 2008). Kittredge et al. (2008) also provide evidence for a weaker effect of frequency on semantic processing in aphasic picture naming errors. Consistent with this research, models of word processing often implement frequency at the level of activation thresholds within a lexical layer of the model or connection weights from a lexical layer (Coltheart et al., 2001; Dahan et al., 2001a; Dell, 1989; McClelland & Rumelhart, 1981; Plaut et al., 1996).

In tasks without a production element, such as lexical decision, the locus of the frequency effect is typically discussed in terms of whether the effect occurs pre- or postlexical access (Balota & Chumbley, 1984; Grainger, 1990; Liu et al., 1996) rather than discussing specific levels of the language system (e.g., phonological, semantic). Based on the fact that larger frequency effects are typically observed in lexical decision than in single word reading, some have argued that the frequency effect in single word reading occurs during early processing and the increased frequency effect in lexical decision occurs because of the decision component that is present in lexical decision but not single word reading (Balota & Chumbley, 1984). However, subsequent studies showed that frequency effects in single word reading and lexical decision can be made roughly equal by manipulating lexical attributes in one task or the other (Grainger, 1990; Monsell, Doyle, & Haggard, 1989), suggesting an early influence of frequency. Further evidence for early frequency effects has been provided by studies investigating single word reading and lexical decision using Chinese characters (Liu et al., 1996), eye tracking while following spoken instructions to move pictures with a computer mouse (Dahan et al., 2001b), and from authors assuming an activation-verification model of lexical processing (Allen et al, 2005), although Liu et al. (1996) also attribute 40% of the frequency effect in lexical decision to the decision component. Thus, a large amount of evidence suggests that frequency effects occur early and are related to the phonological level of processing, but other evidence leaves open the possibility that frequency effects also arise from semantic processing and later word processing components.

Comparing Jones and Hoffman SemD

Given the two different measures of SemD, it is reasonable to ask whether one is preferable over the other in representing the variability of contexts in which a word appears. One insight into this question comes from the impact of the correlations between frequency and SemD. The degree to which SemD effects were larger than frequency effects in our results depended on the correlation between the SemD and frequency measures being used. We found that the larger the correlation, the larger SemD effects were in relation to frequency effects; and the correlation between SemD and frequency measures tended to be higher when the two measures were drawn from the same corpus. Thus, SemD effects were generally smaller than frequency effects when the measures were drawn from different corpora, but the difference decreased or reversed when both measures were drawn from the same corpus. The latter point is where the different SemD measures diverge—Jones SemD often showed larger effects than did frequency when both were drawn from the same corpus, but Hoffman SemD effects remained smaller than frequency effects even when both were drawn from the same corpus. Crucially, the two measures correlate with frequency to very different degrees. Restricting the comparison to when both measures are drawn from the same corpus, Jones SemD correlates with log frequency, $r = .99$, and Hoffman SemD correlates with log frequency, $r = .41$.

Outside of assessing their correlations with word frequency, comparing the merits of these two SemD measures is difficult. They have been used to pursue different theoretical goals, and therefore their effects have be explored in different sets of tasks. The SemD of Hoffman et al. was derived to capture the notion that a word's meaning may vary continuously based on the contexts in which it is found and has been explored in several studies as a measure of semantic richness or semantic ambiguity (e.g., Hoffman et al., 2013; Hoffman, Rogers, et al., 2011; Hoffman & Woollams, 2015; Yap et al., 2015); the SemD of Jones et al., on the other hand, was derived to provide a more accurate test of rational models of memory than did Adelman et al.'s (2006) CD and has been explored more often in relation to artificial and natural language learning (e.g., Johns, Dye, et al., 2016; Jones et al., 2012). The typical use of Hoffman et al.'s SemD made it more relevant to the goals of the current study, as its effects across different tasks—sometimes detrimental, sometimes beneficial—have begun to be explored in the literature (Hoffman & Woollams, 2015; Pexman et al., 2017). Furthermore, Hoffman SemD has been shown to relate to other semantic variables in the literature, providing a starting point from which to compare it to existing measures (Hoffman et al., 2013). The same is not true of Jones et al.'s SemD. It remains an empirical question whether Jones SemD would show the same detrimental effects in tasks such as synonym selection or word pair semantic association judgments, although we may expect it to show similar effects to the SemD of Hoffman et al. (2013), given that Jones' SemD showed the same pattern of main effects as Hoffman's SemD in the present study.

The SemD measures of Hoffman et al. and Jones et al. have many differences in the way they are calculated, but their most consequential difference is in the contextual representations used to derive the SemD of a given word. Hoffman et al. and Jones et al. each derive their SemD measures from the similarity of contextual representations—the former by averaging across pairwise similarities between contexts in which a word appears, the latter by incrementally updating SemD values and semantic representations by comparing current semantic representations with new contextual representations. Hoffman et al. (2013) quantified their contexts with latent semantic analysis (LSA; Landauer & Dumais, 1997): first, each context is given a vector of zeroes and ones that represents whether each possible word across all contexts is present in that context; second, those values are transformed to reduce the influence of extreme values; and third, each vector is subjected to Singular Value Decomposition (SVD) to produce a smaller set of vectors that is predictive of the contexts from which it was derived and should measure the higher order similarity structure among the words (Landauer & Dumais, 1997). Jones et al. (2012) quantified their contexts by first creating sparse ternary vectors to represent each possible word—2000 item vectors with four nonzero values between -1 and 1—and then summing the vectors for all words present in each context. Some evidence suggests that

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raw co-occurrence, used by Jones et al., may perform better than dimensionally reduced representations, used by Hoffman et al., in approximating human semantic similarity judgments (Recchia & Jones, 2009). Other research suggests that dimensional reduction with SVD may provide exceptionally good approximations of human semantic similarity judgments as good or better than raw co-occurrence (Bullinaria & Levy, 2007, 2012), albeit the best performance with SVD models involves modifications that were not made by Hoffman et al. (2013; i.e., reducing the contribution of or eliminating the first several principal components).

The comparative reliability of the contextual representations used to create Hoffman et al.'s SemD is supported by the fact that the authors directly tested whether their word vectors reflected a useful approximation of true semantic relationships, whereas Jones et al. supplied only a second-order approximation of such a test. Hoffman et al. (2013) tested their word vectors against a synonym selection task with a probe word and three choices. These word vectors are the product of the same SVD calculation that derives context vectors and their ability to represent true relationships should therefore reflect the ability of context vectors to do the same. Hoffman et al. found that the correct choice in the synonym selection task showed the highest cosine with the probe 82% of the time, somewhat close to performance of native English speakers (95%). Using the highest cosine as a decision rule, their model tended to make errors on the same trials as human participants. Thus, there is reason to believe that Hoffman's SemD represents realistic semantic relationships. Jones et al. (2012) showed that their model better correlated with WordNet semantic similarities than did LSA values, but the difference between the correlations was small ($r = .172$ vs. $r = .158$) and the exact relationship between WordNet meaning similarities and human semantic similarity judgments is difficult to assess (Maki et al., 2004). Future studies could adjudicate the value of Hoffman SemD compared with Jones SemD by testing the ability of both measures to predict human performance.

Semantic Selection and SemD

SemD has previously shown opposing facilitatory and inhibitory effects across different tasks (Hoffman & Woollams, 2015; Pexman et al., 2017; Plummer et al., 2014; Sidhu et al., 2016; Yap & Pexman, 2016), similar to other semantic richness variables such as ambiguity or number of features (Hino et al., 2006; Jager et al., 2015; Pexman et al., 2008; Piercey & Joordens, 2000; Yap et al., 2011). Inhibitory effects of semantic richness variables, including SemD, are often thought to be caused by problems selecting or distinguishing a specific semantic representation, a task which becomes more difficult when more semantic information is activated (Hino et al., 2006; Mirman & Magnuson, 2008; Pexman et al., 2008; Rabovsky et al., 2016; Steyvers & Malmberg, 2003; Yap et al., 2011). The results of the current study may be consistent with this claim, as the only task that showed an inhibitory effect of SemD in healthy older adults, concreteness decisions to concrete words, had the potential for requiring semantic selection. However, by accepting this claim one must infer that semantic selection may only take place for some words within a given task—a puzzling conclusion. That is, if inhibitory SemD effects index the presence of semantic selection requirements, then it would seem that only concrete and not abstract words require selection of a specific semantic representation during concreteness decisions. It seems more likely that the task would guide which features are accessed, given their relevance to its goals, and not that word properties would change the decision-making process within a task.

An alternative interpretation of the results for concreteness decisions may be given by analogy to another set of results—those of Yap and Pexman (2016) for syntactic (noun/verb) decisions, where SemD showed an inhibitory effect in deciding that a word was a noun. As with concreteness decisions, it is not clear that a specific semantic representation must be selected to perform this task. In this way, syntactic decisions stand out among other tasks that have shown inhibitory SemD effects. However, SemD need not invoke semantic selection to have an inhibitory effect in this task. Because high SemD words are less likely to be nouns and more likely to be verbs—for example, in the ELP data set, mean SemD is higher for verbs (1.68) than for nouns (1.5)—one need only detect a word's SemD to be biased toward a certain response. The same is true for concreteness decisions, where detecting a word's SemD alone could bias decisions, given that high SemD words are less likely to be concrete and more likely to be abstract (see Hoffman et al., 2013, Figure 2; Table S1 in the online supplemental materials).

It is clear from these examples that SemD may create inhibitory effects without the task requiring semantic selection. This is not to say that semantic selection may not be involved in other cases. For example, settling on a single meaning of a high SemD word may be required in synonym judgment or semantic relatedness judgments and create inhibitory SemD effects. But the inhibitory SemD effects in syntactic decisions and concreteness decisions need not invoke semantic selection to exist, and therefore one cannot determine the presence of semantic selection demands by an inhibitory SemD effect alone.

SemD, Frequency Effects, and Semantic Control

As stated above, SemD effects in previous research have been claimed to impact the size of frequency effects when left uncontrolled. Hoffman et al. (2013) appealed to semantic control and the positive correlation between frequency and SemD to explain the fact that controlling for inhibitory SemD effects revealed otherwise unobservable frequency effects in synonym judgment performance of healthy adults and aphasic patients with multimodal semantic deficits. Their explanation has the potential to explain many absent or, occasionally, reversed frequency effects that have been observed in the aphasic patient literature, which often accompany the presence of a semantic deficit (for example, Butterworth et al., 1984; Crutch & Warrington, 2005; Hanley et al., 2002; Hoffman, Jefferies et al., 2011; Jefferies & Lambon Ralph, 2006; Marshall et al., 2001; Nickels & Howard, 1995; Thompson et al., 2018; Warrington & Cipolotti, 1996; Warrington & Shallice, 1979). Notably, only Hoffman et al. (2013; Hoffman, Rogers, et al., 2011) have provided evidence that SemD might impact apparent frequency effects in aphasic patients, and these two studies present the same evidence from a single group of aphasic patients.

Our findings provide evidence that SemD is, in fact, unlikely to explain previously unobserved frequency effects. Although we found that SemD effects may change the apparent size of frequency effects when left uncontrolled, the impact of controlling

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SemD on frequency effects was usually mild—generally changing the frequency effect by 6% to 23%. Such mild changes were seen regardless of the presence of aphasia or the presence of a multimodal semantic deficit. Indeed, significant, facilitatory frequency effects were found in all tasks but one regardless of whether SemD was controlled—in healthy participants and aphasic patients—and regardless of whether the SemD effect was facilitatory or inhibitory. These results suggest that SemD effects do not have a strong enough influence on task performance to nullify apparent effects of frequency, even in patients with multimodal semantic deficits.

Our picture naming results are especially relevant to this discussion, because picture naming is one common task in which frequency effects have been shown to be absent in patients with multimodal semantic deficits (e.g., Jefferies & Lambon Ralph, 2006). In picture naming, both healthy participants and aphasic patients, regardless of the presence of a multimodal semantic deficit, showed significant, substantial facilitatory frequency effects regardless of whether SemD was controlled. Furthermore, we found no strong evidence for the inhibitory effects of SemD that would be required in picture naming to decrease the apparent size of the frequency effect. We found some evidence that effects of Jones SemD were different between patients with and without multimodal semantic deficits, but the size and direction of the effects for each patient group were not clear from further analyses, as SemD effects in the individual patient groups were not statistically significant. Given our large sample of patients with multimodal semantic deficits ($n = 110$) and the large sample of items in the task ($n = 166$), we should have had the power to detect any reasonably sized effects of SemD. Thus, if any inhibitory SemD effect exists in picture naming for patients with multimodal semantic deficits, it must be small, and it would therefore be even less likely to strongly impact the apparent size of frequency effects when SemD is left uncontrolled. Interestingly, Hoffman SemD, the measure derived by the authors who generated the hypothesis about SemD suppressing the apparent size of frequency effects, did not show any hint of inhibitory SemD effect in picture naming in these patients.

Another concern in picture naming is that healthy adults showed only facilitatory SemD effects. If an inhibitory effect were to exist only in patients, it would require that patients need semantic control in situations where healthy participants do not need it. Although this is theoretically possible, no evidence exists to support such a conclusion. The evidence provided in previous studies relies on manipulations in which semantic control deficits should exaggerate difficulties that an intact semantic control mechanism handles—for example, making associations between semantically distant words, overcoming misleading cues about the meaning of a word, or finding the synonym of a word in the presence of a related but nonsynonymic word (Noonan et al., 2010; Thompson et al., 2018). The only other inhibitory effects of SemD that have been observed in patients were also observed in healthy older adults (Hoffman et al., 2013). These facts, together with our results, suggest that SemD effects are not inhibitory in picture naming, even in patients with multimodal semantic deficits. If this is true, then absent frequency effects in picture naming in previous studies (e.g., Jefferies & Lambon Ralph, 2006; Thompson et al., 2018) are unlikely to be related to semantic control. In the absence of further evidence that controlling SemD reveals otherwise unobservable frequency effects in tasks such as picture naming in patients with multimodal semantic deficits, our results suggest that SemD does not explain absent frequency effects.

Beyond the impact of SemD on frequency effects, there are several reasons to be cautious about the claims of Hoffman et al. (2013) regarding the relationship of semantic control to SemD effects. First, results from healthy adults in concreteness decisions to concrete words suggest that inhibitory SemD effects can occur without the task necessarily requiring semantic control. The pattern of SemD effects in the concreteness decisions of the CSDP seem better explained by a semantic richness effect that biases decisions. Other previously observed inhibitory SemD effects may also have explanations beyond semantic control. For instance, the synonym judgment task from Hoffman et al. (2013); Hoffman, Rogers et al., 2011 is likely to recruit working memory abilities. In the task, participants choose which of three words is the synonym of a probe word. Working memory may be recruited to assess and maintain the similarity of each choice to the probe word to choose the most highly similar option, and the inhibitory effect of SemD may relate to increased working memory load for high SemD items. That is, if SemD reflects spreading activation to contextually related semantic information, then comparing multiple words could involve holding a relatively large amount of semantic information in short-term memory (STM) for high SemD words, giving rise to an inhibitory SemD effect. Working memory could also explain reversed frequency effects observed in the delayed repetition performance of the two semantically impaired patients from Hoffman, Jefferies, et al. (2011). The authors appealed to SemD as a potential explanation for these effects, citing the fact that high SemD in high frequency words may have stressed semantic control processes. However, given that the authors did not manipulate or analyze effects of SemD, it is just as likely that the high SemD words stressed a working memory mechanism, causing a disadvantage for high frequency words in their delayed repetition task.

A larger issue is that the true mechanism underlying the aphasic patients' multimodal semantic deficits is not clear from the literature. Before one can conclude that semantic control is required to resolve competition created by SemD in patients, one must establish whether semantic control deficits exist. The controlled semantic cognition framework (Lambon Ralph et al., 2017) claims that certain patients have a semantic control deficit based primarily on behavioral differences observed between aphasic patients with multimodal semantic deficits, who are argued to have semantic control deficits, and semantic dementia patients, who are argued to have damage to conceptual representations (e.g., Jefferies & Lambon Ralph, 2006; Noonan et al., 2013). However, recent research investigating these behavioral differences shows that many of the purported differences between semantic dementia and comprehension-impaired aphasic patients do not stand up to scrutiny, which calls into question whether conceptual representations and the mechanism used to access them can be damaged independently (Chapman & Martin, 2017, Chapman et al., 2020). Furthermore, variable brain areas are damaged in patients classified as having semantic control deficits, encompassing frontal, temporal, and parietal lobes (Jefferies & Lambon Ralph, 2006; Thompson et al., 2015; Thompson et al., 2018). Because damage leading to patients' semantic deficits may be so widespread, one may easily

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imagine that the deficits result from damage to multiple underlying cognitive mechanisms.

The Interaction of Frequency and Semantic Diversity

In many existing language models, word frequency is implemented as the strength of connections from lexical representations to other representations (Coltheart et al., 2001; Dahan et al., 2001a; Dell, 1989; McClelland & Rumelhart, 1981; Plaut et al., 1996). We extrapolated from this theory of word frequency that if SemD reflects the breadth of semantic information associated with a lexical representation, as claimed by Hoffman et al. (2013; Hoffman, Rogers, et al., 2011), then word frequency may exaggerate a task's SemD effects, resulting in an interaction of the two variables. We found some evidence that this may be the case. Single word reading and lexical decision tasks showed the expected interaction, with beneficial SemD effects increasing with increased frequency. Given that we did not find an interaction in all cases where tasks showed frequency and SemD effects, our evidence is not resoundingly strong. However, given that the databases showing significant interactions had by far the largest samples—the smallest of them, the BLP, had nearly twice as many observations as CSDP concrete and abstract combined—it is possible that picture naming and concreteness decision were simply underpowered for detecting the interactions. Future studies may carefully control frequency, SemD, and other lexical measures to investigate whether such an interaction may be detected in picture naming or concreteness decisions and therefore whether the proposed interaction of frequency and SemD occurs. In the following sections, we discuss the potential for further investigating whether SemD influences the spread of activation in the semantic system and whether frequency scales the strength of spreading activation.

SemD and Spreading Activation

No evidence currently exists concerning the influence of SemD on spreading activation, but related evidence may inform our expectations. Semantic priming studies have provided good evidence that activation spreads in the semantic system (Meyer & Schvaneveldt, 1971, 1976; Moss et al., 1995). Such studies have shown that one may prime not only words with overlapping semantic features but also semantically associated concepts (see Hutchison, 2003) or multiple meanings of ambiguous words (Onifer & Swinney, 1981; Seidenberg et al., 1982; Swinney, 1979). If SemD corresponds to the amount of contextually related information that is associated with a word, then these studies suggest that activation may spread to a network of associated meaning representations proportional to a word's SemD. One study found that LSA semantic similarity between prime and target words did not predict priming effects in lexical decision or single word reading (Hutchison et al., 2008). This result may suggest that SemD will not affect priming, but the predictive value of this result is limited, given that SemD represents similarities between the contexts in which a word appears rather than words themselves. Future studies could explore the role of SemD in spreading activation by investigating the influence of prime and target SemD on priming effects. If SemD indexes spreading activation, then one would predict greater priming for higher prime and target SemD, as the amount of activated overlapping semantic information between prime and target should increase as SemD increases.

Frequency and the Strength of Spreading Activation

Experimental evidence for the influence of frequency on semantic activation is limited, but the semantic priming literature provides a clue. Hutchison et al. (2008) investigated semantic priming at the item-level in a large group of older and younger healthy adults ($n = 203$), including a detailed investigation of the influence of prime words on priming effects. The authors found, when collapsing across lexical decision and single word reading tasks, that higher frequency primes increased priming effects at short SOAs, where automatic (nonstrategic) priming is more likely to occur. These results strongly suggest an influence of frequency on the strength of spreading activation.

Future experiments with semantic priming could provide further evidence for this influence of frequency. Similar to our hypothesis in the current study, one could predict that word frequency will interact with forward association strength between a semantic prime and target although similar to the predicted interaction between frequency and SemD in the current study, an interaction with forward association strength may be a more powerful test of the influence of frequency. That is, forward association strength positively relates to the size of semantic priming effects at the item level, and it is typically assumed to index spreading activation in the semantic system (Hutchison et al., 2008). In contrast, no evidence currently exists to support the hypothesis that SemD is related to spreading activation. Furthermore, forward association strength is likely to index typical, strong associative semantic links, given that it is based on free association norms (see Nelson et al., 1998). In contrast, one may suspect that SemD, if it represents spreading activation, represents either predominately weakly associated semantic information or a conglomeration of strongly and weakly associated semantic information to a target word, given that most of the words in the contexts that are used to calculate SemD will be only peripherally associated with the target word. Future studies examining the interaction between frequency and forward association strength could provide strong evidence on whether frequency scales the activation spread from word representations to semantic representations.

Conclusions

Although much prior work has investigated the influence of word frequency and semantic relatedness (i.e., semantic priming) on word processing, relatively little work has been carried out on the role of words' semantic diversity. Only recently has it been possible to generate quantitative measures of the degree of relatedness of meaning across different contexts that allow one more precisely to assess contextual diversity in a manner that is separate from frequency, and recent research has begun to reveal that measures of semantic richness such as semantic diversity show complex and important influences on word processing. The present research contributes to this literature by demonstrating that word frequency and semantic diversity show distinct effects. Whereas frequency effects are nearly always facilitatory, effects of semantic diversity are task dependent and may be facilitatory or inhibitory—although it is clear that inhibitory effects need not be driven by semantic selection demands. Furthermore, although semantic diversity effects influence the apparent size of frequency effects when left uncontrolled, semantic diversity does not provide a sufficient explanation for absent or reversed frequency effects seen in semantically impaired patients in the literature. Future research will provide evidence on the mechanism of semantic diversity effects across different tasks, the value of one semantic diversity measure over another, and the influence of frequency and semantic diversity on spreading activation in the semantic system.

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Appendix A

Correlations of Lexical Measures and Dependent Variables by Task

Table A1
ELP Word Reading Variable Correlations (n = 16,804)

Variable	Errors	Frequency	SemD
log RT	0.53**	−0.54**	−0.20**
Errors		−0.33**	−0.14**
Frequency			0.36**

Note. ELP = English Lexicon Project.
** $p < .01$.

Table A2
ELP Lexical Decision Variable Correlations (n = 16,804)

Variable	Errors	Frequency	SemD
log RT	0.47**	−0.66**	−0.23**
Errors		−0.38**	−0.21**
Frequency			0.36**

Note. ELP = English Lexicon Project.
** $p < .01$.

(*Appendices continue*)

Table A3

BLP Lexical Decision Variable Correlations (n = 9,513)

Variable	Errors	Frequency	SemD
log RT	0.66**	−0.67**	−0.32**
Errors		−0.41**	−0.24**
Frequency			0.42**

Note. BLP = British Lexicon Project.
** $p < .01$.

Table A4

IPNP Object Naming Variable Correlations (n = 423)

Variable	Errors	Frequency	SemD
log RT	0.68**	−0.37**	−0.21**
Errors		−0.21**	−0.08
Frequency			0.45**

Note. IPNP = International Picture Naming Project.
** $p < .01$.

Table A5

CSDP Concreteness Decision (Abstract) Variable Correlations (n = 3,736)

Variable	Errors	Frequency	SemD
log RT	0.52**	−0.28**	−0.27**
Errors		−0.02	−0.23**
Frequency			0.36**

Note. CSDP = Calgary Semantic Decision Project.
** $p < .01$.

Table A6

CSDP Concreteness Decision (Concrete) Variable Correlations (n = 2,831)

Variable	Errors	Frequency	SemD
log RT	0.70**	−0.35**	−0.03^
Errors		−0.17**	0.09**
Frequency			0.40**

Note. CSDP = Calgary Semantic Decision Project.
^ $p < .10$. ** $p < .01$.

Table A7

MAPPD Control PNT Variable Correlations (n = 166)

Variable	Frequency	SemD
Errors	−0.17^	−0.16^
Frequency		0.54**

Note. MAPPD = Moss Aphasia Psycholinguistics Project Database; PNT = Philadelphia Naming Test.
^ $p < .10$. ** $p < .01$.

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(*Appendices continue*)

Table A8

MAPPD Semantic Patient PNT Variable Correlations (n = 166)

Variable	Frequency	SemD
Errors	−0.51**	−0.28**
Frequency		0.54**

Note. MAPPD = Moss Aphasia Psycholinguistics Project Database; PNT = Philadelphia Naming Test.
** $p < .01$.

Table A9

MAPPD Nonsemantic Patient PNT Variable Correlations (n = 166)

Variable	Frequency	SemD
Errors	−0.47**	−0.24**
Frequency		0.54**

Note. MAPPD = Moss Aphasia Psycholinguistics Project Database; PNT = Philadelphia Naming Test.
** $p < .01$.

Table A10

MAPPD Semantic Patient PRT Variable Correlations (n = 166)

Variable	Frequency	SemD
Errors	−0.50**	−0.28**
Frequency		0.54**

Note. MAPPD = Moss Aphasia Psycholinguistics Project Database; PRT = Philadelphia Repetition Task.
** $p < .01$.

Table A11

MAPPD Nonsemantic Patient PRT Variable Correlations (n = 166)

Variable	Frequency	SemD
Errors	−0.37**	−0.14^
Frequency		0.54**

Note. MAPPD = Moss Aphasia Psycholinguistics Project Database; PRT = Philadelphia Repetition Task.
^ $p < .10$. ** $p < .01$.

Appendix B

Results From Models With Only Content Words

Table B1

Standardized Coefficients From Error Mixed Models With Only Content Words

Database	Test	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × Freq	Conc.	Length	Ortho N.	Phon N.
ELP	Word reading	468909	16,388	460	−0.606***	0.938***	−0.133***	−0.033	−0.062***	−0.216***	−0.301***	0.058	0.335***
ELP	Lexical decision	558349	16,388	818	−0.854***	0.394***	−0.128***	0.128^	−0.009	−0.137***	−0.735***	0.404***	−0.014
BLP	Lexical decision	356946	9,155	78	−1.085***	1.448***	−0.248***	0.529***	−0.035^	−0.241***	−0.603***	0.188***	−0.027
MAPPD	Obj. naming	—	—	—	—	—	—	—	—	—	—	—	—
IPNP	Obj. naming	—	—	—	—	—	—	—	—	—	—	—	—
CSDP	Conc. decision (abs.)	115269	3,695	312	−0.001	0.068	−0.337***	−0.236	−0.028	1.884***	−0.324***	−0.050	0.107*
CSDP	Conc. decision (conc.)	88,155	2,825	312	−0.281***	−0.328^	0.091***	0.477***	0.021	−2.378***	0.121***	−0.221***	−0.081

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. All main effects are from models with no higher order terms.
^ $p < .10$. * $p < .05$. *** $p < .001$.

(*Appendices continue*)

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Table B2

Standardized Coefficients From Log RT Mixed Models With Only Content Words

Database	Test	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × Freq	Conc.	Length	Ortho N.	Phon N.
ELP	Word reading	436976	16,803	460	−0.038***	0.059***	−0.012***	0.005	0	−0.014***	0.022***	0.009***	0.023***
ELP	Lexical decision	499927	16,388	818	−0.067***	0.060***	−0.012***	0.013*	−0.003***	−0.014***	0.019***	0.021***	0.023***
BLP	Lexical decision	323515	9,155	78	−0.067***	0.064***	−0.013***	0.020***	−0.002^	−0.015***	−0.004***	0.009***	0.002
IPNP	Object naming	17,986	420	50	−0.082***	0.237*	−0.026***	−0.055	0.004	−0.042***	0.044^	−0.042	−0.012
CSDP	Conc. decision (abs.)	99,730	3,695	312	−0.023***	0.002	−0.021***	−0.007	0.002	0.098***	0.001	−0.016***	0.022***
CSDP	Conc. decision (conc.)	75,102	2,825	312	−0.046***	−0.036*	0.001	0.032*	0.003	−0.198***	0.033***	−0.026***	0

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. All main effects are from models with no higher order terms.

^ $p < .10$. * $p < .05$. *** $p < .001$.

Appendix C

Results From Models Controlling Age of Acquisition

Table C1

Standardized Coefficients From Error Mixed Models Controlling AoA

Database	Test	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × Freq	Conc.	Length	Ortho N.	Phon N.	AoA
ELP	Word reading	364574	12,743	460	−0.288***	1.309***	−0.053***	−0.071	−0.049*	−0.027	−0.241***	0.013	0.184***	0.623***
ELP	Lexical decision	434089	12,743	818	−0.567***	0.984***	−0.042***	0.209*	−0.009	0.017	−0.699***	0.386***	−0.147***	0.600***
BLP	Lexical decision	299268	7,676	78	−0.738***	1.800***	−0.180***	0.351***	−0.013	−0.124***	−0.542***	0.142***	−0.080*	0.537***
MAPPD	Obj. naming	3,320	166	20	0.398	−2.040	−0.216	3.025^	−0.025	0.004	0.448	−0.318	—	0.960***
IPNP	Obj. naming	21,550	420	50	−0.187	1.633	−0.048	−0.281	−0.002	−0.159^	0.405	−0.482^	−0.026	0.548***
CSDP	Conc. decision (abs.)	86,212	2,764	312	0.031	0.276^	−0.306***	−0.071	−0.068^	1.756***	−0.411***	0.070	0.065	0.128***
CSDP	Conc. decision (conc.)	72,693	2,329	312	−0.168***	0.070	0.141***	0.558***	0.009	−2.139***	0.167***	−0.316***	−0.096	0.389***

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. All main effects are from models with no higher order terms.

^ $p < .10$. * $p < .05$. *** $p < .001$.

Table C2

Standardized Coefficients From log RT Mixed Models Controlling AoA

Database	Test	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × Freq	Conc.	Length	Ortho N.	Phon N.	AoA
ELP	Word reading	353897	12,743	460	−0.020***	0.079***	−0.007***	−0.001	0	−0.002*	0.022***	0.012***	0.016***	0.043***
ELP	Lexical decision	424609	12,743	818	−0.046***	0.088***	−0.006***	0.008	−0.003***	−0.005***	0.021***	0.016***	0.013***	0.038***
BLP	Lexical decision	293949	7,676	78	−0.045***	0.084***	−0.009***	0.011^	−0.001	−0.007***	0.005***	0.002	0	0.026***
IPNP	Object naming	20,777	420	50	−0.041***	0.169	−0.020*	−0.063	0.003	−0.031***	0.025	−0.028	−0.014	0.075***
CSDP	Conc. decision (abs.)	85,302	2,764	312	−0.016***	0.051***	−0.014***	0.004	−0.001	0.097***	0.003	−0.012***	0.015***	0.024***
CSDP	Conc. decision (conc.)	71,787	2,329	312	−0.029***	−0.010	0.006*	0.045***	0.003	−0.168***	0.027***	−0.026***	−0.001	0.043***

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. All main effects are from models with no higher order terms.

^ $p < .10$. * $p < .05$. *** $p < .001$.

(*Appendices continue*)

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Appendix D

Results From Models With Jones SemD in Place of Hoffman SemD

Table D1

Standardized Coefficients From Error Mixed Models With Jones SemD

Database	Test	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × Freq	Conc.	Length	Ortho N.	Phon N.
ELP	Word reading	635513	22,214	460	−0.532***	0.664***	−0.132***	−0.947***	0.015	−0.216***	−0.310***	0.069*	0.304***
ELP	Lexical decision	756791	22,214	818	−0.660***	0.836***	−0.361***	−0.445***	−0.133***	−0.129***	−0.843***	0.419***	0.027
BLP	Lexical decision	456990	11,720	78	−0.730***	1.386***	−0.838***	−0.360	−0.084^	−0.140***	−0.690***	0.308***	−0.034
MAPPD	Obj. naming	3,360	168	20	−0.339	2.954	0.051	4.671	−0.394	−0.211	0.926	−0.579	—
IPNP	Obj. naming	23,600	460	50	−0.436*	1.774	−0.248	2.097	−0.090	−0.193*	0.462^	−0.523^	−0.019
CSDP	Conc. decision (abs.)	141133	4,524	312	0.178***	0.621*	−0.441***	0.506^	−0.167***	1.986***	−0.420***	0.002	0.128***
CSDP	Conc. decision (conc.)	143840	4,612	312	−0.257***	−0.053	0.123***	0.725*	−0.140*	−2.376***	0.074*	−0.246***	0.001

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. All main effects are from models with no higher order terms.

^ $p < .10$. * $p < .05$. *** $p < .001$.

Table D2

Standardized Coefficients From Error Mixed Models With Jones SemD

Database	Test	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × Freq	Conc.	Length	Ortho N.	Phon N.
ELP	Word reading	617478	22,212	460	−0.030***	0.068***	−0.030***	0.033***	−0.002***	−0.012***	0.016***	0.016***	0.026***
ELP	Lexical decision	745870	22,214	818	−0.047***	0.076***	−0.038***	−0.033***	−0.003***	−0.014***	0.021***	0.019***	0.020***
BLP	Lexical decision	449108	11,720	78	−0.043***	0.082***	−0.042***	−0.025*	−0.004***	−0.009***	0.006***	0.003*	0.001
IPNP	Object naming	22,713	460	50	−0.077***	0.326*	−0.038^	−0.056	−0.007	−0.039***	0.040^	−0.042	−0.012
CSDP	Conc. decision (abs.)	139609	4,524	312	−0.001	0.025*	−0.043***	−0.020	0.003	0.1***	0.005*	−0.020***	0.023***
CSDP	Conc. decision (conc.)	142104	4,612	312	−0.037***	−0.039*	−0.004	−0.002	0.008***	−0.199***	0.020***	−0.015***	0.004

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects. All main effects are from models with no higher order terms.

^ $p < .10$. * $p < .05$. *** $p < .001$.

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Appendix E

Variance Explained and Bayesian Information Criterion Across Task Models

Table E1
Marginal Variance Explained in Task Models

SemD Measure	DV	Database	Task	Covariates Only	Covariates + Freq	Covariates + SemD	Covariates + Freq + SemD	Covariates + Freq + SemD + Interaction	Freq Over Covariates	SemD Over Covariates	Freq Unique Variance	SemD Unique Variance	Interaction Unique Variance	Freq/SemD Shared Variance	Unique Freq Advantage Over Unique SemD
Hoffman	errors	ELP	Word reading	0.0128	0.0326	0.0186	0.0333	0.0327	0.0197	0.0058	0.0147	0.0007	−0.0006	0.0050	0.0139
Hoffman	errors	ELP	Lexical decision	0.0052	0.0397	0.0144	0.0403	0.0396	0.0345	0.0092	0.0259	0.0006	−0.0006	0.0050	0.0253
Hoffman	errors	BLP	Lexical decision	0.0064	0.0607	0.0256	0.0635	0.0617	0.0543	0.0192	0.0379	0.0028	−0.0019	0.0164	0.0351
Hoffman	errors	IPNP	Object naming	0.0046	0.0151	0.0072	0.0154	0.0164	0.0105	0.0026	0.0082	0.0003	0.0010	0.0023	0.0079
Hoffman	errors	CSDP	Conc. decision (abs.)	0.0229	0.0235	0.0277	0.0277	0.0278	0.0006	0.0048	0.0000	0.0042	0.0001	0.0006	−0.0042
Hoffman	errors	CSDP	Conc. decision (conc.)	0.0545	0.0576	0.0545	0.0577	0.0578	0.0031	0.0000	0.0032	0.0001	0.0001	−0.0001	0.0031
Hoffman	log RT	ELP	Word reading	0.0760	0.0925	0.0830	0.0935	0.0940	0.0164	0.0070	0.0105	0.0010	0.0005	0.0060	0.0095
Hoffman	log RT	ELP	Lexical decision	0.0723	0.1009	0.0815	0.1016	0.1018	0.0286	0.0092	0.0201	0.0007	0.0002	0.0085	0.0195
Hoffman	log RT	BLP	Lexical decision	0.0247	0.0701	0.0410	0.0712	0.0718	0.0454	0.0163	0.0302	0.0011	0.0006	0.0152	0.0291
Hoffman	log RT	IPNP	Object naming	0.0270	0.0775	0.0468	0.0825	0.0839	0.0506	0.0198	0.0358	0.0050	0.0014	0.0148	0.0308
Hoffman	log RT	CSDP	Conc. decision (abs.)	0.0205	0.0256	0.0247	0.0275	0.0275	0.0052	0.0043	0.0028	0.0019	0.0000	0.0024	0.0009
Hoffman	log RT	CSDP	Conc. decision (conc.)	0.0616	0.0734	0.0632	0.0734	0.0734	0.0118	0.0016	0.0102	0.0000	0.0001	0.0016	0.0102
Jones	errors	ELP	Word reading	0.0101	0.0243	0.0189	0.0244	0.0241	0.0142	0.0087	0.0055	0.0000	−0.0002	0.0087	0.0055
Jones	errors	ELP	Lexical decision	0.0058	0.0336	0.0270	0.0344	0.0350	0.0278	0.0212	0.0074	0.0008	0.0006	0.0204	0.0066
Jones	errors	BLP	Lexical decision	0.0090	0.0618	0.0558	0.0651	0.0636	0.0528	0.0469	0.0092	0.0033	−0.0015	0.0436	0.0059
Jones	errors	IPNP	Object naming	0.0025	0.0127	0.0115	0.0130	0.0145	0.0102	0.0090	0.0015	0.0003	0.0015	0.0087	0.0012
Jones	errors	CSDP	Conc. decision (abs.)	0.0177	0.0185	0.0203	0.0207	0.0207	0.0008	0.0027	0.0004	0.0022	0.0000	0.0004	−0.0019
Jones	errors	CSDP	Conc. decision (conc.)	0.0359	0.0371	0.0362	0.0372	0.0375	0.0011	0.0003	0.0010	0.0001	0.0003	0.0002	0.0008
Jones	log RT	ELP	Word reading	0.0847	0.1025	0.1019	0.1044	0.1046	0.0178	0.0173	0.0024	0.0019	0.0002	0.0154	0.0127
Jones	log RT	ELP	Lexical decision	0.0825	0.1157	0.1132	0.1183	0.1182	0.0331	0.0306	0.0052	0.0026	−0.0001	0.0280	0.0025
Jones	log RT	BLP	Lexical decision	0.0348	0.0879	0.0854	0.0926	0.0923	0.0531	0.0506	0.0072	0.0047	−0.0002	0.0459	0.0025
Jones	log RT	IPNP	Object naming	0.0269	0.0903	0.0792	0.0910	0.0922	0.0634	0.0522	0.0119	0.0007	0.0012	0.0515	0.0112
Jones	log RT	CSDP	Conc. decision (abs.)	0.0214	0.0279	0.0322	0.0322	0.0322	0.0066	0.0108	0.0000	0.0042	0.0000	0.0066	−0.0042
Jones	log RT	CSDP	Conc. decision (conc.)	0.0534	0.0638	0.0600	0.0638	0.0640	0.0104	0.0066	0.0038	0.0000	0.0001	0.0066	0.0038

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project.

(*Appendices continue*)

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Table E2

Bayesian Information Criteria (BIC) in Task Models

SemD Measure	DV	Database	Task	Covariates Only	Covariates + Freq	Covariates + SemD	Covariates + Freq + SemD	Covariates + Freq + SemD + Interaction	Freq Over Covariates	SemD Over Covariates	Freq Unique Variance	SemD Unique Variance	Interaction Unique Variance	Freq/SemD Shared Variance	Unique Freq Advantage Over Unique SemD
Hoffman	errors	ELP	Word reading	150981	149227	150398	149159	149163	1753***	583***	1239***	68***	−4**	−10	1171
Hoffman	errors	ELP	Lexical decision	280308	275442	279033	275338	275309	4866***	1275***	3695***	104***	29***	1171	3591
Hoffman	errors	BLP	Lexical decision	164401	160941	163231	160772	160664	3460***	1170***	2459***	169***	109***	1001	2290
Hoffman	errors	IPNP	Object naming	14933	14920	14937	14929	14936	13***	−4*	8***	−9	−7	5	17
Hoffman	errors	CSDP	Conc. decision (abs.)	77933	77921	77735	77747	77755	12***	198***	−12	174***	−8^	24	−186
Hoffman	errors	CSDP	Conc. decision (conc.)	59668	59596	59679	59597	59607	72***	−11	82***	−1**	−10	−10	83
Hoffman	log RT	ELP	Word reading	−35269	−38366	−36510	−38568	−38681	3097***	1241***	2058***	202***	113***	1039	1856
Hoffman	log RT	ELP	Lexical decision	146734	140533	144997	140364	140284	6201***	1738***	4633***	169***	80***	1039	4464
Hoffman	log RT	BLP	Lexical decision	23984	18929	22470	18762	18628	5055***	1514***	3708***	167***	134***	1347	3541
Hoffman	log RT	IPNP	Object naming	−173	−235	−189	−233	−227	63***	17***	44***	−2**	−6^	19	46
Hoffman	log RT	CSDP	Conc. decision (abs.)	39047	38788	38825	38686	38697	260***	222***	139***	101***	−10	121	38
Hoffman	log RT	CSDP	Conc. decision (conc.)	25333	24997	25305	25008	25017	336***	28***	297***	−11	−10	39	308
Jones	errors	ELP	Word reading	221088	218806	219492	218786	218798	2282***	1596***	706***	20***	−12	1576	686
Jones	errors	ELP	Lexical decision	430475	423613	424945	423239	423231	6862***	5530***	1706***	374***	8***	5156	1332
Jones	errors	BLP	Lexical decision	249455	244282	244354	243498	243438	5174***	5101***	856***	784***	60***	5156	72
Jones	errors	IPNP	Object naming	16835	16810	16814	16819	16822	25***	21***	−5*	−9	−2**	30	4
Jones	errors	CSDP	Conc. decision (abs.)	97728	97688	97557	97539	97548	40***	172***	18***	149***	−9	30	−131
Jones	errors	CSDP	Conc. decision (conc.)	92237	92187	92236	92185	92177	49***	0***	51***	2***	9***	−2	49
Jones	log RT	ELP	Word reading	−35332	−35451	−35332	−35909	−36003	3953***	3834***	576***	457***	94***	3377	2480
Jones	log RT	ELP	Lexical decision	212812	204404	204978	203465	203432	8408***	7834***	1513***	939***	33***	6895	574
Jones	log RT	BLP	Lexical decision	51012	44483	44703	43554	43482	6529***	6309***	1149***	929***	73***	5380	220
Jones	log RT	IPNP	Object naming	332	243	258	250	254	90***	74***	8***	−7	−4*	82 81	15
Jones	log RT	CSDP	Conc. decision (abs.)	47013	46628	46335	46346	46357	384***	677***	−11	282***	−11	395	−293
Jones	log RT	CSDP	Conc. decision (conc.)	39802	39347	39529	39358	39364	455***	273***	171***	−11	−6*	284	182

Note. ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project.
^ $p < .10$. * $p < .05$. ** $p < .01$. *** $p < .001$.

(*Appendices continue*)

Appendix F

Results From Models With Log BNC Frequency in Place of SUBTLEX Zipf Frequency in the BLP

Table F1

Standardized Coefficients From Mixed Model Results for BLP Lexical Decision With Log BNC Frequency

DV	Model	Obs.	Words	Ss	Freq	Freq sq	SemD	SemD sq	SemD × freq	Conc.	Length	Ortho N.	Phon N.	AoA
error	Hoffman SemD	372450	9552	78	−0.804***	1.168***	−0.270***	1.292***	−0.119***	−0.404***	−0.554***	0.196***	0.029	—
error	Hoffman (content)	358478	9194	78	−0.903***	1.457***	−0.281***	1.281***	−0.148***	−0.388***	−0.503***	0.146***	0.034	—
error	Hoffman (-AoA)	299268	7676	78	−0.524***	1.080***	−0.170***	0.826***	−0.054*	−0.153***	−0.488***	0.113**	−0.050	0.708***
error	Jones SemD	372450	9552	78	−0.468***	0.672***	−0.919***	0.557^	0.102*	−0.269***	−0.520***	0.156***	−0.061*	—
log RT	Hoffman SemD	337585	9552	78	−0.049***	0.060***	−0.013***	0.077***	−0.006***	−0.023***	−0.001	0.009***	0.006***	—
log RT	Hoffman (content)	324666	9194	78	−0.054***	0.072***	−0.013***	0.075***	−0.008***	−0.023***	0.002	0.006***	0.006***	—
log RT	Hoffman (-AoA)	293918	7676	78	−0.032***	0.050***	−0.006***	0.038***	−0.002^	−0.008***	0.008***	< .001	0.001	0.037***
log RT	Jones SemD	365874	9552	78	−0.029***	0.034***	−0.049***	0.009	0.003	−0.015***	0.010***	0.001	< .001	—

Note. — = variable not included in model; Freq = frequency; SemD = semantic diversity; Freq sq = frequency squared; SemD sq = semantic diversity squared; Conc = concreteness; Ortho N = orthographic neighborhood; Phon N = phonological neighborhood; Obs = observations; Ss = subjects; BLP = British Lexicon Project; BNC= British National Corpus. All main effects are from models with no higher order terms.
^ $p < .10$. * $p < .05$. ** $p < .01$. *** $p < .001$.

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