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How do word frequency and semantic diversity affect selection of representations in word processing?

by

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ABSTRACT

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The frequency at which words are encountered has long been considered an important factor in language processing, with higher frequency speeding word comprehension and production. That is, many theories claim that word representations are stronger for words encountered more often. However, some recent work has claimed that, rather than word frequency, the factor determining the strength of the representation of words (and accounting for previous effects of word frequency) is the word’s semantic diversity (SemD) – i.e., the variety of contexts in which a word is found (Adelman et al., 2006; Jones et al., 2012). Other recent approaches have suggested that SemD may play a more nuanced role in language processing—helping in certain situations and harming in others. That is, when a specific word meaning must be accessed without sufficient context, greater SemD may lead to more effortful processing, sometimes even minimizing or reversing typical frequency effects (Hoffman et al., 2011, 2013). More effortful processing would occur because one has to distinguish a single meaning from among all of the contextually-associated meanings to which a word may be potentially related. A mechanism that distinguishes a target meaning from among potential meanings would be an important one in language processing generally, but the presence of such a mechanism and its relationship to SemD have not been deeply explored. This dissertation explores the relationship and influence of word frequency and SemD in language processing, including whether SemD
explains typical word frequency effects and whether SemD creates a need to distinguish from among competing contextual meanings. Part one explores effects and interactions of word frequency and SemD across a variety of large mega-study databases of language processing tasks. Part two attempts to manipulate the mechanism that resolves competition between word meanings to examine its impact on effects of SemD and language processing more generally. Results indicate that both frequency and SemD are important qualities affecting word processing, but little evidence is found for the role of a meaning selection mechanism that responds to SemD. The impact of these results on current theories of language processing is discussed.
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# Nomenclature

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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CD</td>
<td>Contextual Diversity</td>
</tr>
<tr>
<td>SemD</td>
<td>Semantic Diversity</td>
</tr>
<tr>
<td>CSC</td>
<td>Controlled Semantic Cognition</td>
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Chapter 1

Introduction

Since the 1950’s, psycholinguistic research has suggested that the relative 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). The results have suggested that frequency is an important factor in lexical processing that facilitates retrieval. For instance, in the classic logogen model, a word’s frequency determined its threshold for recognition, with higher frequency resulting in lower thresholds (Morton, 1969). More recent models have assumed that frequency plays other important linguistic roles, such as in strengthening the connections between representations at different levels (e.g., Plaut, McClelland, Seidenberg, & Patterson 1996) or strengthening the resting activation of word nodes (Dell, 1988; McClelland & Rumelhart, 1981).

Recent research has suggested that another factor related to frequency plays an important role in lexical access—its contextual diversity (CD), or the number of different contexts in which
a word is found (Adelman, Brown, & Quesada, 2006), often operationalized as the number of
documents or films in which a word appears. Studies in several languages have found that CD
explains 1-4% 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 near
zero (Adelman, Brown, & Quesada, 2006; Cai & Brysbaert, 2010; Dimitropoulou, Duñabeitia,
Because of these results, several studies have claimed that classic effects of frequency are
actually effects of CD and that frequency does not independently contribute to lexical processing

The hypothesized importance of CD derives from the tenets of rational models of
memory (e.g., Anderson & Milson, 1989), which claim the strength of a word’s representation
should be proportional to the likelihood that it will be needed in future situations. Adelman et al.
claim that a word that appears in a greater number of contexts will be more readily available
from the lexicon, as it is more likely to be needed in any given situation. 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 (Brysbaert & New, 2009; Hsiao & Nation, 2018; Hoffman,
Rogers, & Lambon Ralph, 2011). One may also 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, Cohn, West, & Aiken, 2003).

Even though CD shows facilitative effects in studies of single word processing and
reading and frequency effects tend to be absent when CD is controlled (Chen et al., 2017; Perea,
Soares, & Comesaña, 2013; Plummer, Perea, & Rayner, 2014), some studies suggest that CD and
frequency show independent effects. Vergara-Martinez, Comesaña, and Perea (2017) showed independent electrophysiological effects of frequency and CD, and Steyvers & Malmberg (2003) showed independent effects of frequency and contextual variability (a measure nearly identical to CD) in recognition memory for word lists. Both of these studies may suffer from overly selective and small samples, but they nevertheless bring into question whether CD effects may really explain frequency effects or whether they are separate phenomena. Whichever situation holds true for CD, its very high correlation with frequency remains a barrier to understanding the true influence of contextual variation on language processing.

More recent research has derived a few distinct measures termed semantic diversity (SemD) measures, which, unlike CD, explicitly quantify the semantic relationships between the contexts in which a word appears (Hoffman et al., 2011; Jones, Johns, & Recchia, 2012). Such measures should better reflect the diversity of contexts in which a word appears because a word might show up in a many documents, but many of those documents instantiate highly similar semantic contexts. Thus, these measures, which go beyond counting documents to take into account the semantic relationships among context, are preferable to CD on theoretical grounds from the perspectives of rational models of memory and lexical processing. That is, their quantification of semantic relationships gives stronger reason to believe that something qualitatively different than frequency is being measured, allowing one to assess whether this factor has an impact on whether a word is likely to be needed and how words are selected.

Two prominent measures of SemD have provided evidence for effects of contextual variation related to semantic distinctiveness of contexts (Jones et al., 2012; Hoffman et al., 2011). The SemD measure of Jones and colleagues (Johns, Dye, & Jones, 2014, 2016; Jones et al., 2012) is a continuous measure that is larger for words that have occurred in more
semantically distinct contexts and smaller for words that have occurred in more semantically redundant contexts. This measure was created to test rational models of memory with a measure of contextual variation that accounted for the semantic content of the contexts being compared. This measure accounted for a larger proportion of variance in lexical decision and word reading in megastudy data sets than did either frequency or CD (Jones et al., 2012), a finding replicated in a sample of monolingual and bilingual adults and in a smaller set of words (Johns, Sheppard, Jones, & Taler, 2016). Similar to results from studies of CD, these studies show little to no frequency effect after accounting for CD and SemD—though CD effects sometimes remain significant, suggesting independent effects of SemD and CD. Like CD, however, the SemD measure of Jones et al. correlates strongly with frequency ($r > .80$), and thus, the lack of an independent effect of frequency is likely solely due to its large overlap with both measures. As noted earlier, it is unwarranted to conclude that the overlapping variance in a multiple regression is due to the variable with the larger unique contribution (Cohen, Cohn, West, & Aiken, 2003).

The SemD measure of Hoffman et al. (2011) also takes into account the degree to which a word occurs in more unique or distinct contexts. This measure, like Jones et al.’s measure of SemD, assumes that there is continuous variation in the meaning of words, rather than a distinct set of senses. Unlike the Jones measure, Hoffman et al. used latent semantic analysis (Landauer & Dumais, 1997) to derive vectors for the contexts in which a word occurs, rather than raw co-occurrence between pairs of words in different contexts (as in Jones et al. 2012). They took the average of the cosine distances between all pairs of contexts in which a word occurred, log transformed it, and reversed its sign. Averaging insured that words that occur frequently in highly similar contexts had smaller SemD values. This SemD measure is more clearly distinguished from frequency, correlating to a much smaller degree ($r \sim .50$) than does Jones et
al.’s SemD, presumably due to the use of latent semantic analysis rather than frequency of co-occurrence in determining similarity of contexts. Effects of Hoffman et al.’s SemD measure independent of frequency have been shown in lexical decision, semantic relatedness decisions to word pairs, concreteness decisions, word reading, past tense verb generation, syntactic classification of verbs, and in the lexical decision and word reading of children (Hoffman & Woollams, 2015; Hsiao & Nation, 2018; Pexman, Heard, Lloyd, & Yap, 2017; Sidhu, Heard, & Pexman, 2016; Yap & Pexman, 2016).

Interestingly, unlike high word frequency, which is nearly always beneficial (see Balota, Law, & Zevin, 2000), high SemD as measured by Hoffman et al. is sometimes beneficial (i.e., in lexical decision, word reading, concreteness decisions, past tense verb generation) and sometimes detrimental (i.e., in semantic relatedness decisions, syntactic classifications). 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, which have been shown as beneficial in tasks where specific experiences need not be distinguished, such as lexical decision, but detrimental in tasks where a single experience must be identified (Hino, Pexman, & Lupker, 2006; Mirman & Magnuson, 2008; Pexman, Hargreaves, Siakaluk, Bodner, & Pope, 2008; Rabovsky, Schad, & Rahman, 2016; Steyvers & Malmberg, 2003; Yap, Tan, Pexman, & Hargreaves, 2011).

Relatedly, Hoffman and colleagues claim that the direction of SemD effects depends on the degree to which a specific semantic representation is accessed (Hoffman & Woollams, 2015; Hoffman, Lambon Ralph, & Rogers, 2013; Hoffman, Rogers, & Lambon Ralph, 2011). When a task does not constrain the contextual 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, etc.—as well as semantic attributes of different senses of the word—e.g., “the detective will dog your footsteps” (Hoffman, Rogers, & Lambon Ralph, 2011, p. 2434)—and features of different contexts in which you’ve encountered a dog—at home, the park, your cousin’s house, etc. The array of co-activated information, the authors claim, may be useful in tasks such as lexical decision because any degree of semantic activation helps to support the decision that an observed letter string is a word; on the other hand, they claim that an abundance of activated information causes difficulty in tasks such as semantic relatedness decision because one must distinguish relevant from irrelevant activated information (Hoffman & Woollams, 2015; Hoffman, Lambon Ralph, & Rogers, 2013; Hoffman, Rogers, & Lambon Ralph, 2011). For instance, when deciding whether *thirst* and *drought* are related, one must attend to any information that is held in common between the two words and ignore other information. Similar claims about opposing effects of contextually related semantic information have been made about effects of contextual dispersion, a measure similar to SemD (Logan, 1988; Pexman, Hargreaves, Siakaluk, Bodner, & Pope, 2008). These opposing effects of SemD suggest that detrimental effects of SemD should relate to the degree that a task requires access to specific semantic information.

In situations in which one must select appropriate aspects of meaning from many irrelevant aspects, evidence suggests that cognitive control mechanisms come into play to make this selection (e.g., Schnur, Schwartz, Brecher, & Hodgson, 2006; Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997). Crucial to the Hoffman et al.’s account of detrimental SemD effects is the claim that the resolution of competition among activated semantic information is performed by a cognitive control mechanism known as semantic control, one of two major components of
the semantic system according to the Controlled Semantic Cognition framework (Lambon Ralph, Jefferies, Patterson, & Rogers, 2017). This mechanism is claimed to be necessary, for example, in situations such as focusing on the correct aspects of a piano when one is trying to play music as opposed to when one wants to move it across a room (Jefferies & Lambon Ralph, 2006; Saffran, 2000). Semantic control 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 in stroke patients with multi-modal semantic deficits (Hoffman et al., 2011). Some studies have claimed that such patients (referred to as individuals with “semantic aphasia”) 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). Because frequency and SemD are correlated, and because activation may spread from target words to associated information and multiple meanings, higher frequency words may tend to activate a wider array of semantic information than low frequency words. This large set of activated representations may cause difficulty for semantic aphasia patients in distinguishing the correct semantic representation from among associated information. Such difficulty would predominate for high frequency words relative to low frequency words because high frequency words tend to have higher SemD, which may slow response times (and increase error rates) and thereby eliminate the typical frequency effect in tasks in which it is necessary to focus on a particular meaning – for example, in choosing a synonym to match a given word (Hoffman, Rogers, & Lambon Ralph, 2011).

The claim that absent frequency effects in semantic aphasia are caused by the competition created by high SemD is supported by findings from a study in which semantic aphasia patients were tested on a synonym selection task. In this task, semantic aphasia patients
failed to show a typical word frequency effect when accuracy was predicted by frequency alone, but when SemD was included as a predictor in the model, a typical word frequency effect was revealed, as was a harmful effect of high SemD (Hoffman et al., 2011). Using the same task, Hoffman, Lambon Ralph, and Rogers (2013) found the same lexical effects in older adults—a suppressive effect of SemD on the size of the frequency effect and a detrimental effect of high SemD. This result suggests a more general effect of SemD on word processing, possibly generated by the semantic control demands of high SemD words (Hoffman et al., 2013).

This dissertation was motivated by the anomalously absent and reversed word frequency effects in “semantic aphasia” patients and claims that followed from this research—i.e., that SemD plays an important role in language processing, suppressing effects of frequency in tasks requiring semantic access, and that competition generated by SemD is resolved by a cognitive control mechanism. Because these effects were based on the formulation of SemD by Hoffman et al. (2013), this is the primary measure I investigated in the current study. In this dissertation, I explore the role of SemD in language processing through the relationship of SemD and word frequency, the modulation of SemD effects by semantic requirements, and the relationship of SemD effects to cognitive control manipulations. The dissertation has two main foci:

1) Research has suggested that word frequency effects are absent in some aphasic patients due to competition in the semantic system created by high SemD words. However, to create an absent frequency effect, this high SemD competition must principally affect high frequency words, with low frequency, high SemD words not being affected. This interaction between frequency and SemD has not been explored by previous studies but would show that SemD creates competition in lexical processing. Thus, in the first part of
my dissertation, I explore the relationship between SemD and word frequency effects in a variety of language processing tasks via data from large, public databases.

2) Theoretical insights gained from impaired populations should ultimately have implications for healthy cognitive systems. As this applies to the current project, the claimed relationship between cognitive control and effects of SemD should be observed not only in semantic aphasia patients, but also in healthy adults. Finding evidence that the phenomena observed in semantic aphasia patients may be replicated in healthy participants by manipulating cognitive control demands could help to adjudicate theories of cognitive processing, primarily those concerning semantic control. Furthermore, evidence of a relationship between cognitive control and SemD may help to elucidate the mechanisms by which SemD has its effects. Thus, in the second part of my dissertation I experimentally manipulate cognitive control processes during word processing in healthy undergraduates in an attempt to replicate purported effects of semantic diversity seen in aphasic patients and gain insight into whether semantic diversity creates selection demands mediated by a control mechanism.
The Role of Semantic Diversity in Word Processing and its Relation to Word Frequency: Evidence from Large Language Processing Databases

Proponents of the CSC framework have claimed that, in semantic tasks, word frequency effects are absent in some aphasic patients and reduced in healthy older adults due to competition in the semantic system created by high SemD words (Hoffman et al., 2013; Hoffman et al., 2011). However, for the frequency effect to be eliminated, this high SemD competition must affect high frequency words more than low frequency. That is, if high SemD words with both low and high frequency were equally affected by competition, the typical frequency effect would remain because performance for both high and low frequency words would be diminished. It is possible that a lesser SemD effect for low frequency words occurred because, on average, the SemD of the low frequency items was lower than that of the high frequency items (which is consistent with the correlation between frequency and SemD). Nonetheless, it is possible that high SemD would have a greater effect for high than low frequency words even when the correlation between frequency and SemD was controlled for. That is, one might predict that competing semantically related contexts would be more highly activated for higher frequency
words, requiring greater cognitive control and reducing the frequency effect for high SemD words compared to low SemD words. If an interaction is observed, it would suggest that effects of contextual variation do not explain frequency effects but may be independent of and interact with frequency effects.

Although a large literature exists on semantic selection mechanisms (e.g., Gold & Buckner, 2002; Thompson-Schill et al., 1997; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001), there are only a few studies examining the degree to which SemD affects semantic selection (Hoffman et al., 2013; Hoffman et al., 2011; Hsiao & Nation, 2018). Consequently, there is little evidence that high SemD creates concept selection pressures and diminishes typical word frequency effects. Hsiao and Nation (2018) investigated the interaction of word frequency and SemD in single word reading and lexical decision as part of a study on whether high SemD relates to improved reading ability in children. They found no interaction between frequency and SemD. However, their measure of SemD, a) was 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) ($r \sim .50$). That study is therefore difficult to generalize to typical adult behavior. Thus, it remains unclear whether and how SemD and frequency effects interact in adult populations.

The current study investigated the independence of frequency and SemD effects and the Controlled Semantic Cognition framework’s predictions regarding competition-inducing effects of high SemD in language processing using publicly available psycholinguistic data. In recent years, many megastudies have used analyses of these databases as investigative tools to address hypotheses regarding cognitive and psycholinguistic mechanisms, such as those currently at issue. My 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 semantic cognitive deficits; thus, I examined databases with multiple tasks and participant types. The tasks included word repetition, single word reading, lexical decision, concreteness decisions, and picture naming; and participants included young and old healthy subjects as well as stroke patients with aphasia.

I focused on the measure of SemD proposed by Hoffman and colleagues (Hoffman et al., 2013) because: 1) it uses the semantic relatedness of different contexts in its computation, which seems theoretically justified, and 2) prior studies show that this measure relates to the performance of healthy older adults and individuals with aphasia in terms of explaining the size of their frequency effects (Hoffman et al., 2013; Hoffman et al., 2011). Although I focused on this measure of SemD, I also explored the extent to which the use of different measures of SemD and CD (Adelman et al., 2006; Jones, Dye, & Johns, 2014, 2016) affected the pattern of results.

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

First, 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 larger effects of SemD than frequency should be observed when both are included as predictors of task performance.

Second, if the strength of connections between target words and associated meanings depends on frequency, then the strength of activated contextual information, and the size of effects of SemD on performance should depend on word frequency. According to proponents of the CSC framework, co-activated semantic information creates difficulty due to the need for competition resolution, and high frequency words are those primarily affected by this competition (Hoffman et al., 2011). Thus, this theory would predict greater competition amongst
meanings as frequency increases, and detrimental effects of SemD (as in semantic relatedness judgements) should depend on word frequency. Thus, I predict an interaction between word frequency and SemD effects, with a larger detrimental effect of SemD as frequency increases. Conversely, I predict that as SemD increases, the size of the frequency effect will diminish.

Third, the strength of this interaction—i.e., the degree to which word frequency effects are diminished for high SemD words—should depend on the semantic requirements of the task. That is, tasks that require participants to process the meaning of stimuli should show this interaction, while tasks that do not require semantic selection (or require less semantic selection) should show no interaction or even an interaction in the opposite direction, with greater benefits of SemD as frequency increases. That is, if tasks demands are such that greater activation of a range of semantic representations aids performance (for instance, in lexical decision), then the greater activation that may arise with higher frequency would lead to larger beneficial effects. This prediction also applies to the main effect of SemD, which should be less negative or even positive for tasks requiring access to specific semantic representations and more beneficial for tasks that do not.

Fourth, the strength of the frequency–SemD interaction should depend on the presence of a semantic control deficit among aphasic patients. That is, aphasic patients who meet the criteria for having a semantic control deficit should show stronger interactions—and stronger effects of SemD—in semantic processing tasks than do aphasic patients who do not meet these criteria, given that semantic control ability should underlie the resolution of semantic competition that is predicted to create the interaction.
Fifth, if selection among competing semantic representations is resolved by a cognitive control mechanism and SemD creates such competition, then individual differences in executive task performance among healthy individuals should interact with effects of SemD (and its interaction with frequency) after controlling for the influence of word frequency. That is, participants with better executive function should show smaller detrimental effects of SemD than do participants with poorer executive function.

### 2.1. Methods

#### 2.1.1. Participants and Stimuli

Data were retrieved from six public databases for 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, Lacey, Rastle, & Brysbaert, 2012); concreteness decision (i.e., concrete/abstract) data from the Calgary Semantic Decision Project (CSDP; Pexman et al., 2017); picture naming data from the International Picture Naming Project (IPNP; Szekely et al., 2004); object picture naming and word repetition data from the Moss Aphasia Psycholinguistics Project Database (MAPPD; Mirman et al., 2010); and lexical decision and single word reading data from the Semantic Priming Project (SPP; Hutchison et al., 2013). Participant and stimuli sample sizes by study are shown in Table 2.1 – Participant information across studies. Stimulus frequency (Brysbaert & New, 2009) and SemD (Hoffman et al., 2013, or Jones et al., 2012) characteristics are listed in Table 2.2 – Word stimuli characteristics across studies (all words).
Both tasks from the MAPPD were analyzed primarily because they are word processing tasks, but also had the potential to show effects as semantic tasks. Picture naming is well-established as a task that requires semantic processing, as it is affected by many semantic variables, including imageability, concreteness, and interference from semantically related words (Alario et al., 2004; Bates, Burani, D’Amico, & Barca, 2001; Damian, Vigliocco, & Levelt, 2001). Single word repetition has also been associated with semantic processing, as aphasic patients with various deficits show effects of concreteness and imageability on accuracy of repetition and concreteness affects the type of errors they make (Hanley & Kay, 1997; Hanley, Kay, & Edward, 2002; Saffran & Martin, 1997). Also, patients with deep dysphasia show a striking contribution of semantics, as they make semantic errors in repetition (Berkowitz, Kohen, & Martin, 2011; Katz & Goodglass 1990). This previous research suggests that lexical effects in aphasic patients with and without semantic deficits may differ in both picture naming and word repetition.

Regarding the relative degree of semantic processing required across tasks, I predicted that CSDP concreteness decision would require more semantic processing than would lexical decision in the ELP and BLP, given the strong effects of semantic variables seen in the literature in concreteness decision (and other semantic classification tasks; Pexman, Heard, Lloyd, & Yap, 2017; Taikh, Hargreaves, Yap, & Pexman, 2015; Rabovsky et al. 2016; Yap et al., 2011) compared to lexical decision (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Pexman et al., 2008; Yap et al., 2011). Concreteness decision and lexical decision were chosen for comparison because of the large number of overlapping stimuli used across tasks, which provided a robust sample in which to test task differences. Word reading tasks contained similarly large samples to lexical decision. However, I refrained from making a specific
prediction about the relative degree of semantic processing involved in word reading because the
degree to which semantic processing is obligatory in this task is much less clear than in the cases
of lexical decision and concreteness decision. It is clear that semantic variables may affect single
word reading (e.g., Yap et al., 2011), but the degree to which semantic processing is obligatory
in reading is debatable given the several potential cognitive routes available for translating
orthography into speech in models of reading aloud (e.g., Coltheart, 2006; Coltheart, Rastle,
Perry, Langdon, & Ziegler, 2001; Seidenberg & McClelland, 1989). In addition, previous
behavior studies show conflicting evidence on whether the contribution of semantics is larger in
word reading or lexical decision—some studies show a larger contribution for word naming
(Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004), others show the reverse or no
difference (Sidhu, Heard, & Pexman, 2016; Yap et al., 2011).
<table>
<thead>
<tr>
<th>ID</th>
<th>Study</th>
<th>Task</th>
<th>Participants</th>
<th>Total Words</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ELP</td>
<td>Lexical decision</td>
<td>816</td>
<td>16,804</td>
</tr>
<tr>
<td>2</td>
<td>ELP</td>
<td>Single word reading</td>
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<td>16,804</td>
</tr>
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<td>BLP</td>
<td>Lexical decision</td>
<td>78</td>
<td>9,513</td>
</tr>
<tr>
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<td>CSDP</td>
<td>Concreteness decision</td>
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<td>6,566</td>
</tr>
<tr>
<td>5</td>
<td>IPNP</td>
<td>Picture naming (objects)</td>
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</tr>
<tr>
<td>6</td>
<td>IPNP</td>
<td>Picture naming (actions)</td>
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<tr>
<td>7</td>
<td>MAPPD</td>
<td>Picture naming (PNT)</td>
<td>20, 36, 110*</td>
<td>166</td>
</tr>
<tr>
<td>8</td>
<td>MAPPD</td>
<td>Word repetition (PRT)</td>
<td>38, 111*</td>
<td>166</td>
</tr>
<tr>
<td>9</td>
<td>SPP</td>
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<td>512</td>
<td>1,530</td>
</tr>
<tr>
<td>10</td>
<td>SPP</td>
<td>Single word reading</td>
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<td>1,538</td>
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</tbody>
</table>

ELP = English Lexicon Project; BLP = British Lexicon Project; CSDP = Calgary Semantic Decision Project; IPNP = International Picture Naming Project; MAPPD = Moss Aphasia Psycholinguistics Project Database; SPP = Semantic Priming Project; PNT = Philadelphia Naming Test; PRT = Philadelphia Repetition Task; *MAPPD PNT participants are (older adults; non-semantic; and semantic patients), PRT participants are only aphasic patients (non-semantic; and semantic patients).

Table 2.1 – Participant information across studies.
<table>
<thead>
<tr>
<th>Measure</th>
<th>Log SUBTLEX</th>
<th>SemD</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>2</td>
<td>16804</td>
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<td>6566</td>
<td>1.88</td>
</tr>
<tr>
<td>5</td>
<td>412</td>
<td>2.85</td>
</tr>
<tr>
<td>6</td>
<td>202</td>
<td>3.11</td>
</tr>
<tr>
<td>7</td>
<td>166</td>
<td>3.02</td>
</tr>
<tr>
<td>8</td>
<td>166</td>
<td>3.02</td>
</tr>
<tr>
<td>9</td>
<td>1530</td>
<td>3.28</td>
</tr>
<tr>
<td>10</td>
<td>1538</td>
<td>3.28</td>
</tr>
</tbody>
</table>

For Task ID referents, see Table 2.1 – Participant information across studies.

**Table 2.2** – *Word stimuli characteristics across studies (all words).*
All participants were healthy, younger adults (< 45 yrs), except for participants from the MAPPD database, who were either older control participants or chronic stroke patients with aphasia. Aphasic patients were classified as having a multi-modal semantic deficit if they performed worse (scores > 2 standard deviations lower) than older controls on two non-verbal 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 “non-semantic” patients. Participant groups in different tasks within the same database were non-overlapping (e.g., ELP lexical decision & word reading) except for MAPPD, where 107 semantic and 36 non-semantic patients were tested on both Philadelphia Repetition Task (Dell, Martin, & Schwartz, 2007) and Philadelphia Naming Task (Roach, Schwartz, Martin, Grewel, & Brecher, 1996).

2.1.2. Analyses

Various measures, tasks, and datasets required specific treatment for analysis. In all RT analyses, only correct trials were analyzed. For each lexical decision study (i.e., ELP, BLP, & SPP), only word trials were analyzed. In the IPNP dataset, two RT measures were available: the mean RT across all valid naming responses and the mean RT across the single, dominant response. Only the former measure was analyzed, as this measure should reflect the general semantic processing associated with an appropriate word rather than the selection of a specific target the experimenter had in mind. Additionally, I analyzed the IPNP accuracy measure that includes all valid responses as correct.
In the SPP, I analyzed only a subset of the original dataset. In the SPP’s tasks, each target word was preceded by a prime word that could be either related or unrelated to the target. Related primes could be the first associate or another associate from the relevant word association norms (Nelson, McEvoy, & Schreiber, 1999). Unrelated trials were originally created so that both the first associate and other associate used in a related trial could be used as primes for an unrelated word, resulting in two unrelated trials per target. Because effects of priming were not the interest of the current study, only trials with unrelated prime words were analyzed. RTs and errors for each word were averaged across the two trials with unrelated primes.

Additionally, the stimulus onset asynchrony (SOA) between the prime and target in the SPP could be either 200 ms or 1200 ms. To minimize the influence of strategic processing related to probes in the long SOA condition (Hutchison, Neely, & Johnson, 2001), I analyzed only 200 ms SOA trials.

Finally, databases with large numbers of words included many function words in addition to content words. To examine the potential influence of the extremely high frequency and high semantic diversity of function words, I performed two separate versions of each analysis: one including all words and one including only words predominantly used as nouns or verbs according to the US SUBTLEX database (Brysbaert & New, 2009). Separate analyses were not performed for IPNP naming tasks or MAPPD object naming, as the items in these tasks elicited content words.

RT outliers were determined in a two-step process. First, responses faster than 200 ms were excluded. Second, any RT 2.5 SDs above or below the mean RT by participant and task block (where indicated in the data) was considered an outlier. Outlier trimming was carried out by block to reduce the influence of fatigue and practice on outlier detection. To reduce the
influence of individual differences in overall speed and age, and to make model coefficients more comparable across tasks, all RTs were standardized by participant by block (zRTs). No RT data were available for word repetition and object picture naming tasks from the MAPPD database and thus only accuracy data were available for analysis.

Subject-level data were analyzed with linear and generalized linear mixed effect models using the lme4 package (Bates, Mächler, Bolker, & Walker, 2014) in R v3.4.2 (R Core Team). Fixed effects included log SUBTLEX word frequency, SemD, the interaction between frequency and SemD, plus a number of psycholinguistic variables known to affect word processing, consisting of word length in letters (Balota et al., 2007), orthographic neighborhood (OLD20; Yarkoni, Balota, & Yap, 2008), phonological neighborhood (PLD20; Suarez, Tan, Yap, & Goh, 2011), and concreteness (Brysbaert, Warriner, & Kuperman, 2014). Some tasks did not require the explicit use of orthography (i.e., object and action picture naming and repetition) or phonology per se (i.e., lexical decision and concreteness decision). However, some evidence indicates a role for orthography in spoken word production (e.g., Rastle et al., 2011). Thus, orthographic and phonological neighborhoods were controlled across all tasks. Moreover, doing so insured that a uniform analysis could be performed across tasks and differences in results could not be tied to differences in control variables. Random intercepts were estimated for participants and items. Because some data sets were prohibitively small to estimate random slopes without convergence issues, and so that identical models could be run on all datasets, no random slopes were estimated. I estimated $p$-values using the Satterthwaite approximation for degrees of freedom from the R package lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017). All predictor variables were standardized prior to modeling. Main effects were acquired from models excluding the two-way interaction terms. For patient comparisons in the MAPPD
database, models included patient group—semantic or non-semantic—as a predictor, along with interactions of group with frequency, SemD, and their interaction. Two-way interactions were obtained from models without a three-way interaction term.

In MAPPD patients, analyses were performed across patient groups, including group as a control variable and including interactions of group with frequency, SemD, and the frequency x SemD interaction to investigate differences between groups. I also investigated in MAPPD patients whether severity of semantic deficit predicted the size of frequency and semantic diversity effects, and their interaction. To do so, a principal component score was derived for each patient using principal component analysis of the PPT, CCT, and synonymy triplets scores, with the score on the first principal component taken to reflect semantic impairment severity. Given the strong relationship observed between these tasks ($r = .60 - .69, p < .01$), this component should reflect the degree of overall semantic deficit for each patient better than individual tasks. Additional mixed models were then run with patient semantic impairment severity as a predictor in place of group (semantic vs. non-semantic), along with interactions of severity with frequency, SemD, and their interaction.

To address whether semantic requirements determined the size of SemD effects, models were run comparing concreteness decision and lexical decision. Frequency, SemD, and frequency x SemD interaction effects in errors and zRTs of ELP and BLP lexical decision tasks were compared to the corresponding effects in CSDP concreteness decision. This was done by analyzing only those words that were present across both tasks and by including as a factor in the model task and its interactions with frequency, SemD, and the frequency-SemD interaction.
To address the relationship between competition resolution and executive processing, additional models were run on SPP single word reading and lexical decision including an executive function (EF) factor as a predictor with frequency and SemD, as well as interactions of the EF factor with frequency, SemD, and the frequency x SemD interaction. Two-way interactions were obtained from models without a three-way interaction term. The EF factor in these analyses was a principal component derived from the three EF tasks employed by the SPP: anti-saccade, operation span, and verbal Stroop (see Hutchison, 2007). Factor scores on the EF principal component were computed by Hutchison et al. (2013) for the lexical decision task. I computed the EF principal component for the single word reading task. For these models, the EF component was included as a fixed effect, as were its interactions with frequency, SemD, and their interaction.

2.2. Results

A summary of errors and RTs across all words in the included studies are listed in Table 2.3 – Participant errors across studies (function and content words). and Table 2.4 – Participant RTs across studies (function and content words). Results for analyses containing only content words showed some differences from analyses containing content and function words. These differences will be discussed below in the context of the various effects in models with content and function words. Table 2.5 – Error Mixed Model Results. and Table 2.6 – zRT Mixed Model Results. contain model coefficients and significance of each model of healthy participant performance in errors and RTs.
### Table 2.3 – Participant errors across studies (function and content words).

<table>
<thead>
<tr>
<th>Database</th>
<th>Task</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>Skew</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELP</td>
<td>Word Reading</td>
<td>16804</td>
<td>0.03</td>
<td>0.07</td>
<td>3.38</td>
<td>0.00</td>
<td>0.73</td>
</tr>
<tr>
<td>SPP</td>
<td>Word Reading</td>
<td>1538</td>
<td>0.01</td>
<td>0.03</td>
<td>4.20</td>
<td>0.00</td>
<td>0.33</td>
</tr>
<tr>
<td>ELP</td>
<td>Lexical Decision</td>
<td>16804</td>
<td>0.08</td>
<td>0.11</td>
<td>2.36</td>
<td>0.00</td>
<td>0.88</td>
</tr>
<tr>
<td>BLP</td>
<td>Lexical Decision</td>
<td>9513</td>
<td>0.08</td>
<td>0.12</td>
<td>2.64</td>
<td>0.00</td>
<td>0.90</td>
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<tr>
<td>SPP</td>
<td>Lexical Decision</td>
<td>1530</td>
<td>0.05</td>
<td>0.06</td>
<td>4.01</td>
<td>0.00</td>
<td>0.67</td>
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<tr>
<td>MAPPD (controls)</td>
<td>Object Naming</td>
<td>166</td>
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<td>0.00</td>
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<tr>
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<td>Object Naming</td>
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<td>Action Naming</td>
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<td>CSDP</td>
<td>Conc. decision</td>
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<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>MAPPD (semantic pts)</td>
<td>Word Repetition</td>
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<td>0.16</td>
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<td>1.76</td>
<td>0.02</td>
<td>0.65</td>
</tr>
<tr>
<td>MAPPD (non-semantic pts)</td>
<td>Word Repetition</td>
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<td>0.08</td>
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<td>MAPPD (semantic pts)</td>
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<td>MAPPD (non-semantic pts)</td>
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<td>0.13</td>
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<td>0.00</td>
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</table>

### Table 2.4 – Participant RTs across studies (function and content words).

<table>
<thead>
<tr>
<th>Database</th>
<th>Task</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>Skew</th>
<th>Min</th>
<th>Max</th>
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<tr>
<td>ELP</td>
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<td>Word Reading</td>
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<td>Lexical Decision</td>
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<td>Object Naming</td>
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<td>-.091</td>
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***p < .001, **p < .01, *p < .05, ^p < .10. All main effects are from models with no interaction term.

Table 2.5 – Error Mixed Model Results.
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<th>SemD</th>
<th>Conc.</th>
<th>Length</th>
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<th>Phon N.</th>
<th>Obs.</th>
<th>Words</th>
<th>Ss</th>
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</thead>
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<td>-.055***</td>
<td>.032***</td>
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<td>.028***</td>
<td>.087***</td>
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<td>-.004</td>
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<td>.007</td>
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<td>Lexical Decision</td>
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<td>-.049***</td>
<td>.034***</td>
<td>-.059***</td>
<td>-.026***</td>
<td>.039***</td>
<td>-.001</td>
<td>341433</td>
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<tr>
<td>SPP</td>
<td>Lexical Decision</td>
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<td>-.019*</td>
<td>.050***</td>
<td>-.054***</td>
<td>.034**</td>
<td>.017</td>
<td>.029*</td>
<td>97220</td>
<td>1530</td>
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<tr>
<td>IPNP</td>
<td>Object Naming</td>
<td>-.263***</td>
<td>-.072*</td>
<td>.025</td>
<td>-.139***</td>
<td>.085</td>
<td>-.102</td>
<td>-.034</td>
<td>20056</td>
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<tr>
<td>IPNP</td>
<td>Action Naming</td>
<td>-.136**</td>
<td>.037</td>
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<td>-.226***</td>
<td>.140*</td>
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<td>-.080</td>
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<td>CSDP</td>
<td>Conc. Decision</td>
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<td>-.068***</td>
<td>.021*</td>
<td>-.149***</td>
<td>.035*</td>
<td>-.098***</td>
<td>.048*</td>
<td>40561</td>
<td>1573</td>
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</table>

***p < .001, **p < .01, *p < .05, ^p < .10. All main effects are from models with no interaction term.

Table 2.6 – zRT Mixed Model Results.
2.2.1. Effects of word frequency and SemD

Main effects of word frequency independent of SemD were observed in all tasks in both error rates and zRTs \((p < .05)\), both including and excluding function words, except in MAPPD controls’ picture naming errors, where the effect was non-significant. Significant frequency effects uniformly reflected faster and more accurate performance for high frequency than low frequency items. These results suggest that word frequency plays a role in all single word processing tasks and in naming pictures of objects and actions, consistent with previous research, and that these frequency effects could not be attributed to variation in SemD.

Main effects of SemD were significant \((p < .05)\) in the errors of ELP word reading and lexical decision, BLP lexical decision, and CSDP concreteness decisions and in the zRTs of all tasks but SPP word reading and IPNP action naming. In analyses excluding function words, the same pattern of significant SemD coefficients was found. Like frequency effects, significant SemD effects uniformly reflected faster and more accurate performance for high SemD than low SemD items. These results suggest that SemD, like frequency, plays a beneficial role in many single word processing tasks and in naming pictures of objects that is independent of frequency.

SemD results here are inconsistent with previous findings showing that semantic richness is detrimental for tasks involving access to specific semantic representations (Hino et al., 2006; Hoffman & Woollams, 2015; Mirman & Magnuson, 2008; Rabovsky et al., 2016; Steyvers and Malmberg, 2003; Yap et al., 2011), given that I obtained beneficial effects for concreteness decisions in RTs and errors and for object naming in RTs. Especially relevant are the results of Yap et al. (2011), which showed that detrimental effects of semantic richness (i.e. number of senses) in concreteness decision. Differences in my results compared to those of Yap et al.
may be due to the larger number of words in my analysis (1573 vs. 505), the variables in my regressions, or the semantic richness measure I employed. I included in my analyses, and Yap et al. did not include, the more subjective variable of concreteness. It is possible that some of the shared variance between concreteness and SemD ($r = .49$ in the CSDP word set) shifted what would be the typical, detrimental effect of SemD. However, when concreteness was left out of the analysis, the SemD effect was non-significant ($\beta = .015, p = .13$), likely due to the interaction between frequency and SemD (still significant; $\beta = .033, p < .001$), discussed below. Another possibility is that the semantic richness measure used here, SemD, is qualitatively different from the variable that showed detrimental effects for Yap et al., number of senses. SemD necessarily represents the diversity of contextually-related information for all different senses of a word without weighing the influence of each different sense. Because of this, the influence of a word’s number of senses is diluted within SemD. It is likely that SemD and number of senses have separable effects on language processing, given the difference of the SemD effect in the current study with the semantic richness effect of a word’s number of senses in Yap et al. (2011). Future studies could be useful for teasing apart exactly how and where these differences arise in processing.

Detrimental effects of semantic richness had also been observed previously in picture naming. Rabovsky et al. (2016) found that participants were slower and less accurate to name pictures representing concepts with a higher degree of intercorrelation among semantic features; by contrast, the same study found that a concept’s number of features facilitated picture naming in RTs and accuracy. Both parameters were drawn from the norms of McRae, Cree, Seidenberg, & McNorgan (2005). Rabovsky et al. (2016) claimed that number of semantic features should enhance activation at the conceptual level, increasing activation flow to the correct lexical
representation and thus facilitating naming, whereas intercorrelation of semantic features would activate competing lexical representations, overriding conceptual facilitation with lexical inhibitory influence.

My results suggest that high SemD could correspond to a high number of semantic features or low SemD could correspond to a high intercorrelation of features in Rabovsky et al.’s study. The former possibility could occur if nouns with more features (e.g., cow, bike, plate, trousers) are more likely to be present in a wider variety of context than nouns with fewer features (e.g., nightingale, colander, bucket, cloak) or because it is easier to name features of items that are associated with a wider variety of contexts. Likewise, the latter possibility could occur if the contexts in which low SemD words occur—contexts which contain larger sets of overlapping words than do the contexts of high SemD words—tend to contain words evoking intercorrelated features of those words more often than do the contexts in which high SemD words. In this case, low SemD would lead to worse performance because of a negative correlation between SemD and intercorrelated features. Repetition of these contextually-related words would necessarily occur more often for low SemD than high SemD words. I tested each of these possibilities by correlating SemD with number of features and with intercorrelational feature density\(^1\) in the McRae et al. (2005) norms and found that the semipartial correlation (after controlling frequency and orthographic neighborhood, as done by Rabovsky et al.) of SemD and number of features was negative—rather than positive—and not significant, \(r'(438) = -0.08, p = .11\), but the semipartial correlation of SemD and intercorrelational density was negative and

\[^1\] After Rabovsky et al. (2016), we used the square root of McRae et al.’s intercorrelational density measure. Rabovsky et al. did this transformation to avoid the influence of outliers.
significant, $r(438) = -.09, p < .05$. It is clear from these analyses that high SemD does not correspond to a concept’s having a high number of listable semantic features (as measured by the McRae norms), given the small negative correlation observed. If anything, it appears that high SemD have a weak tendency to have fewer listable semantic features. However, these results provide evidence that low SemD weakly corresponds to high intercorrelational density. This constitutes evidence that the direction of the SemD effect observed in IPNP object naming is due to words with intercorrelated semantic features appearing more often in the context of low SemD words. The trend is very weak, but this correlation suggests that intercorrelated features could partially explain SemD effects.

Tasks that require participants to use specific aspects of an item’s meaning and that provide fewer constraints on the meaning of the item may be more likely to show competition due to SemD according to the Controlled Semantic Cognition framework. When the size of significant frequency and SemD coefficients are compared, frequency shows a much larger independent effect than SemD on errors and zRTs, except in concreteness decision errors. This result is inconsistent with the claim that effects of frequency in these tasks may be explained by SemD. However, effects of SemD may be different here than in previous studies, where different measures of SemD were used (Adelman et al., 2006; Jones et al., 2012). This possibility is investigated in the next section.

2.2.1.1. Relation of word frequency and SemD effects.

Contrary to previous results, which showed little to no effect of word frequency after accounting for semantic or contextual diversity (Adelman et al., 2006; Jones et al., 2012), I found that word frequency effects were consistently larger than SemD effects in zRTs and errors
(except in CSDP concreteness decisions). To investigate why my results differed from previous results, I attempted to approximate the analyses carried out in these previous studies, comparing the results for different SemD measure. I analyzed zRTs from lexical decision and single word reading tasks from the English Lexicon Project, as RTs from these tasks were analyzed by Adelman et al. (2006) and Jones et al. (2012). These studies, and the current study, used different subsets of words from the ELP, but given that they were all very large samples (roughly 14,000-40,000 words), differences in our analyses are unlikely to be due to use of different words. To approximate the analyses of Adelman et al. (2006), I used mixed models to analyze these tasks using SUBTLEX word frequency and SUBTLEX CD (Brysbaert & New, 2009), the SemD of Hoffman et al. (2013), or the SemD of Johns, Dye, and Jones (2014, 2016; hereafter Jones SemD), controlling for word length in letters, orthographic neighborhood size, number of syllables, and initial phoneme (in single word reading analyses). To approximate the analyses of Jones et al. (2012), I included only SUBTLEX word frequency, SUBTLEX CD, and either Hoffman SemD or Jones SemD. Note that the analyses of Jones et al. were carried out on three different corpora and used frequency, CD, and SemD measures derived from each corpus. To simplify my analyses, I used only SUBTLEX CD, which should capture the same theoretical construct.

2.2.1.2. Analyses after Adelman et al. (2006).

The results of the mixed model analysis of ELP word reading and lexical decision based on Adelman et al. (2006) are shown in Table 2.7 – Mixed models after Adelman et al. (2006). Consistent with the results of Adelman et al. (2006), CD showed a large beneficial effect compared to a smaller, detrimental effect of word frequency in both word reading and lexical decision when both are included in the model. Neither of the other diversity measures showed a
larger effect than word frequency in both tasks, though Jones SemD showed a larger effect than frequency in lexical decision. These results suggest that the Hoffman et al. measure of SemD above taps into a substantially different construct from the CD of Adelman et al., (2006)—a fact corroborated by the low correlation between SUBTLEX CD and the SemD measure of Hoffman et al. in both ELP data sets (both r’s = .39).
<table>
<thead>
<tr>
<th>Diversity measure</th>
<th>Database</th>
<th>Test</th>
<th>Freq</th>
<th>Diversity</th>
<th>Length</th>
<th>Ortho N.</th>
<th>N. Syll</th>
<th>Obs.</th>
<th>Word</th>
<th>Ss</th>
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<td>-.382***</td>
<td>-.067***</td>
<td>.173***</td>
<td>.186***</td>
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<td>33965</td>
<td>460</td>
</tr>
<tr>
<td>Hoffman SemD</td>
<td>ELP</td>
<td>Word Reading</td>
<td>-.172***</td>
<td>-.023***</td>
<td>-.029***</td>
<td>.131***</td>
<td>.152***</td>
<td>658766</td>
<td>24678</td>
<td>460</td>
</tr>
<tr>
<td>Jones SemD</td>
<td>ELP</td>
<td>Word Reading</td>
<td>-.130***</td>
<td>-.100***</td>
<td>-.066***</td>
<td>.160***</td>
<td>.181***</td>
<td>888360</td>
<td>33965</td>
<td>460</td>
</tr>
<tr>
<td>SUBTLEX CD</td>
<td>ELP</td>
<td>Lexical Decision</td>
<td>.220***</td>
<td>-.484***</td>
<td>-.047***</td>
<td>.167***</td>
<td>.120***</td>
<td>968233</td>
<td>33958</td>
<td>818</td>
</tr>
<tr>
<td>Hoffman SemD</td>
<td>ELP</td>
<td>Lexical Decision</td>
<td>-.223***</td>
<td>-.015***</td>
<td>-.030***</td>
<td>.139***</td>
<td>.118***</td>
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</tr>
<tr>
<td>Jones SemD</td>
<td>ELP</td>
<td>Lexical Decision</td>
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<td>-.116***</td>
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<td>.114***</td>
<td>968233</td>
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</tr>
</tbody>
</table>

***p < .001, **p < .01, *p < .05, ^p < .10.

Table 2.7 – Mixed models after Adelman et al. (2006).

<table>
<thead>
<tr>
<th>SemD Measure</th>
<th>Database</th>
<th>Test</th>
<th>Freq</th>
<th>SemD</th>
<th>CD</th>
<th>Obs.</th>
<th>Word</th>
<th>Ss</th>
</tr>
</thead>
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<td>-.170***</td>
<td>-.136***</td>
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<td>33978</td>
<td>460</td>
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<td>ELP</td>
<td>Word Reading</td>
<td>.004</td>
<td>.001</td>
<td>-.284***</td>
<td>658819</td>
<td>24680</td>
<td>460</td>
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<td>Lexical Decision</td>
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<td>-.167***</td>
<td>-.261***</td>
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<tr>
<td>Hoffman SemD</td>
<td>ELP</td>
<td>Lexical Decision</td>
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<td>.020***</td>
<td>-.449***</td>
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</table>

***p < .001, **p < .01, *p < .05, ^p < .10.

Table 2.8 – Mixed models after Jones et al. (2012)
2.2.1.3. Analyses after Jones et al. (2012).

Results from the mixed model analysis of ELP word reading and lexical decision after Jones et al. (2012) are shown in Table 2.8 – Mixed models after Jones et al. (2012). Consistent with the results of Jones et al. (2012), which showed that, after accounting for the other variables, Jones SemD accounted for more variance than did the others in both lexical decision and word reading, the mixed model for word reading showed that the coefficient for Jones SemD was larger than those for CD and frequency. Inconsistent with Jones et al. (2012), lexical decision showed a larger coefficient for CD than Jones SemD. This inconsistency is likely due to my using a different measure of CD than did Jones et al. and not due to my method of analysis, as a standard multiple linear regression showed the same pattern of coefficients as did the mixed model.

When SemD was used in place of Jones SemD, CD showed the largest effect in both word reading and lexical decision. In these models, SemD showed either no effect (lexical decision) or a small, detrimental effect (word reading). These results show that Hoffman and Jones SemD have different impacts on processing and are likely tapping different constructs. This conclusion is corroborated by the low correlation between Hoffman et al.’s SemD measure and Jones SemD ($r = .44$). In fact, Hoffman et al.’s SemD measure appears to differ more from both CD and Jones SemD than either of the latter measures differs from the other ($r = .83$).

In addition to showing clear differences between Hoffman et al.’s SemD measure and Jones SemD, the results of these analyses show that when CD is included Hoffman’s SemD shows either null or positive (detrimental) effects rather than the very prevalent negative (beneficial) effects seen in the larger analyses above. This is likely an artifact due to a shift in the
boundary along the frequency dimension where the effect of SemD shifts from negative to positive due to the inclusion of CD. This may happen because CD and SemD overlap in why they create a benefit in processing. Because SemD is especially beneficial for low frequency words, the unique portion of SemD after accounting for CD may on average show a negative (detrimental) effect. As discussed below, SemD shows opposite effects on the two sides of the frequency dimension in ELP word reading and lexical decision—negative effects for low frequency words and positive effects for high frequency words. For the inclusion of CD to have changed the main effect of SemD (i.e., the effect of SemD at mean frequency), this inclusion must have shifted the boundary of where the SemD effect shifts from negative to positive.

### 2.2.2. Interactions of Word Frequency and SemD.

Significant interactions between SemD and word frequency ($p < .05$) were observed across nearly all tasks in both errors and zRTs of healthy participants. Exceptions were for the most part from picture naming measures (errors in MAPPD controls’ picture naming; errors and zRTs of IPNP action naming; zRTs of IPNP object naming) though errors of CSDP concreteness decision also failed to show the interaction. In analyses excluding function words, the pattern of significant interactions was the same, except that the interaction in ELP word reading errors was no longer significant. The primary issue I was investigating was whether beneficial effects of high frequency would diminish as SemD increased, as might be predicted by Hoffman et al. (2011). The first relevant fact for this matter is that all interaction coefficients were positive, indicating that as SemD increased, the frequency effect coefficient became more positive. Because the main effect of frequency reflected better performance as frequency increased (with a negative slope reflecting decreased errors and zRTs), this positive coefficient indicates less
benefit of high frequency relative to low frequency as SemD increased. To further explore the observed significant interactions, I plotted predicted zRTs (Figure 2.1 – **Plots of significant zRT interactions across databases (plotting method from Dawson, 2014)**). All graphs indicate decreased frequency effects for high SemD words and decreased benefit of high SemD for high frequency words.) or errors (Figure 2.2 – **Plots of significant error interactions across databases (plotting method from Dawson, 2014)**). All graphs indicate decreased frequency effects for high SemD words and decreased benefit of high SemD for high frequency words.) from coefficients in mixed effects models based on the method of Dawson (2014), treating one standard deviation above and below the mean as high and low marks of each variable.²

² In addition to these plots, I also plotted median split frequency and SemD effects in the residuals from mixed models excluding frequency, SemD, and their interaction. These plots can be found in the Appendix.
Figure 2.1 – Plots of significant zRT interactions across databases (plotting method from Dawson, 2014). All graphs indicate decreased frequency effects for high SemD words and decreased benefit of high SemD for high frequency words.
Figure 2.2 – Plots of significant error interactions across databases (plotting method from Dawson, 2014). All graphs indicate decreased frequency effects for high SemD words and decreased benefit of high SemD for high frequency words.
2.2.2.1. Effects of semantic diversity across word frequency.

As evident in Figures 2.1 and 2.2, the frequency x SemD interaction showed surprising results with regard to effects of SemD across the frequency values. At lower frequency values, high SemD was always beneficial, but as frequency increased, high SemD showed no advantage over low SemD. In SPP word reading and lexical decision, one can observe that high SemD was actually detrimental for high frequency words. Given that the graphs above are limited to predicting frequency one standard deviation above the mean, it is clear that SemD’s crossover to having a detrimental effect occurs for higher frequency words in the other interactions as well, albeit only at higher frequencies than in the SPP tasks. Detrimental effects of high SemD were predicted by Hoffman and Woollams (2015) to occur only for highly semantic tasks, with beneficial effects for less semantic tasks; however, it appears that beneficial and detrimental effects of high SemD are both common, but beneficial effects are the general case and detrimental effects are restricted to items with the highest frequencies.

2.2.2.2. Effects of word frequency across semantic diversity.

In all significant interactions, for zRTs and errors, I observed the same phenomenon with regard to frequency effects: as SemD increases, frequency effects decrease. Looking at the interaction from the perspective of frequency effects, the frequency effect is smaller for high than low SemD. That is, as frequency gets higher, SemD effects get exaggerated, causing greater competition which counteract the benefit of target frequency.

It is possible that frequency effects decreased as SemD increased due to a floor effect on RTs and errors—that is, the difference in processing high and low frequency items would
necessarily shrink if only high diversity, low frequency items had room for improvement because high diversity, high frequency items were being processed nearly as well as possible. An argument against this claim could be made by SPP word reading and SPP lexical decision, where high frequency, low SemD words—not high frequency, low SemD words—show the best performance in RTs and errors. However, these cases do not preclude the possibility of floor effects in other databases and tasks. One way to investigate whether the observed interactions are robust and not due to floor effects is to explore whether they remain significant when items with the highest frequencies are removed. Thus, for each data set, items with the highest quarter of frequency values were removed and the data were re-analyzed.

Analyses of zRTs in the range-restricted data sets showed that significant interactions persisted in all tasks. Analyses of errors in the range-restricted data sets showed that significant interactions persisted in all tasks but ELP word reading and IPNP object naming. In tasks where the significant interaction did not persist, the interaction coefficients stayed roughly the same, suggesting that the change in significance resulted from lower power. The fact that frequency x SemD interactions tended to be maintained after items with the top quarter of frequency values are removed suggests that floor effects are not the cause of the observed interactions.

2.2.3. Effects of semantic task requirements on the frequency x SemD interaction

Another prediction was that the degree to which a task required semantic processing would influence the direction and size of the SemD main effect and the size of the interaction between SemD and word frequency. That is, as the level of obligatory semantic processing in a task increased, the interaction and main effect coefficients would become more positive, reflecting a stronger detriment to performance for high SemD. To test this hypothesis, I
examined whether CSDP concreteness decision coefficients were more positive than the corresponding coefficients in lexical decision from the ELP and BLP. To compare effects of SemD and its interaction with frequency across tasks, I needed to restrict the analyzed data set so that only words that overlapped between databases were included. This was done for each pairing of the CSDP concreteness decision with a lexical decision task. I then analyzed the datasets together, including a main effect of task and interactions of task with frequency, SemD, and the frequency x SemD interaction. As an additional check on whether the tasks required different degrees of semantic processing, I also included an interaction between task and concreteness in these analyses. The results of these are shown in Table 2.9 – Overlap Analyses of Concreteness Decision and Lexical Decision.
### Table 2.9 – Overlap Analyses of Concreteness Decision and Lexical Decision.

<table>
<thead>
<tr>
<th>Effect</th>
<th>CSDP &amp; ELP zRTs</th>
<th>CSDP &amp; BLP zRTs</th>
<th>CSDP &amp; ELP errors</th>
<th>CSDP &amp; BLP errors</th>
</tr>
</thead>
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<td>.597**</td>
<td>.736***</td>
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<tr>
<td>Freq</td>
<td>-.163***</td>
<td>-.155***</td>
<td>-.339***</td>
<td>-.274***</td>
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</tr>
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<td>Conc.</td>
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<td>-.596***</td>
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<td>Ortho N.</td>
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<td>.197*</td>
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<td>Phon N.</td>
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***p < .001, **p < .01, *p < .05, ^p < .10. Lexical decision was used as the baseline in all models. All main effects are from models with no interaction term containing the given variable. Two-way interactions are from models without a three-way interaction.

These analyses show several interesting interactions with task and several interestingly absent interactions. No analysis showed a significant interaction of task with the frequency x SemD interaction, suggesting that the mechanism driving the relationship between frequency and SemD is not increasingly taxed when a task’s semantic demands increase. Comparing ELP lexical decision to CSDP concreteness decision, the beneficial effect of SemD strengthened in zRTs. These results are contrary to the claims of Hoffman and Woollams (2015), which stated that SemD should have a detrimental effect in more semantic tasks and a beneficial effect in less
semantic tasks. One may argue that the concreteness decision task may not have increased semantic demands compared to lexical decision. However, significant task x concreteness interactions in nearly all comparisons provide evidence that semantic demands are greater in the concreteness decision task, showing an increasing benefit of concreteness from lexical decision to concreteness decision. Consistent with other literature showing stronger frequency effects in lexical decisions than more semantic tasks (Balota & Chumbley, 1984; Chumbley & Balota, 1984; Jescheniak & Levelt, 1994), I observed significant task x frequency interactions in all comparisons, which showed that frequency effects decreased from lexical decision to concreteness decision.

2.2.4. Effects of frequency and SemD in semantic and non-semantic patients in the MAPPD database

In exploring the relationship of frequency and SemD in patient results in the MAPPD database, I first modeled effects of frequency and other lexical covariates excluding SemD, as done in previous research (Hoffman, Rogers, & Lambon Ralph, 2011; Hoffman et al., 2013). Unlike patients with multi-modal semantic deficits in previous studies tested on a synonym task, patients in the MAPPD database showed strong frequency effects before SemD was introduced into the model in both picture naming and word repetition (see Table 2.10 – MAPPD Patient Mixed Model Results. columns labeled no SemD). In picture naming, these frequency effects did not differ based on the presence of a multi-modal semantic deficit, as indicated by the lack of a significant frequency x group interaction. Such an interaction was present in word repetition, but it indicated that frequency effects were stronger in semantic than non-semantic patients. When SemD was introduced into the model, frequency effects numerically increased, but the addition
of SemD did not statistically improve the model fit for object naming, $\chi^2(\text{df}=1)=.20$, $p = .66$, or word repetition, $\chi^2(\text{df}=1)=.19$, $p = .66$.

Neither MAPPD picture naming or MAPPD word repetition showed a main effect of SemD across patient groups, nor was there an interaction of group and SemD. These results, in contrast to predictions from Hoffman et al. (2011) and Hoffman et al. (2013) show no evidence for a detrimental effect of high SemD in word repetition or picture naming, either across patients or in either group individually.
As in healthy participants, I observed an interaction between frequency and SemD across patient groups, both in word repetition and picture naming (see Figure 2.3 – **Plots of significant error interactions across patients in the MAPPD** (plotting method from Dawson, 2014). Both graphs indicate decreased frequency effects for high SemD words and decreased benefit of high SemD for high frequency words, as were observed in healthy participants.). These interactions took the same form as those described above in healthy participants’ performance—frequency effects decreased as SemD increased, and benefits of SemD for low frequency words

<table>
<thead>
<tr>
<th>Test</th>
<th>Controls</th>
<th>All Patients</th>
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<th>All Patients</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Obj Naming</td>
<td>Obj Naming</td>
<td>Obj Naming</td>
<td>Repetition</td>
<td>Repetition</td>
</tr>
<tr>
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<td>1.49***</td>
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<td>.463^</td>
</tr>
<tr>
<td>Freq</td>
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<td>-.355***</td>
<td>-.374***</td>
<td>-.303***</td>
<td>-.323***</td>
</tr>
<tr>
<td>SemD</td>
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<td>-.029</td>
<td>-</td>
<td>-.028</td>
<td></td>
</tr>
<tr>
<td>SemD x Freq</td>
<td>.142</td>
<td></td>
<td>.122***</td>
<td></td>
<td>.081*</td>
</tr>
<tr>
<td>Group x Freq</td>
<td>-</td>
<td>-.024</td>
<td>.014</td>
<td>-.152**</td>
<td>-.093</td>
</tr>
<tr>
<td>Group x SemD</td>
<td>-</td>
<td></td>
<td>-.043</td>
<td>-</td>
<td>-.101</td>
</tr>
<tr>
<td>Group x SemD x Freq</td>
<td>-</td>
<td></td>
<td>.020</td>
<td>-</td>
<td>.045</td>
</tr>
<tr>
<td>Concreteness</td>
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<td>-.199***</td>
<td>-.197***</td>
<td>-.114*</td>
<td>-.113*</td>
</tr>
<tr>
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<td>.170</td>
<td>.173</td>
<td>-.055</td>
<td>-.051</td>
</tr>
<tr>
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<td>-.217</td>
<td>-.243</td>
<td>.180</td>
<td>.151</td>
</tr>
<tr>
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<td>.490***</td>
<td>.508***</td>
<td>.291*</td>
<td>.311*</td>
</tr>
<tr>
<td>Observations</td>
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<td>24528</td>
<td>24236</td>
<td>25032</td>
<td>24734</td>
</tr>
<tr>
<td>Word</td>
<td>166</td>
<td>168</td>
<td>166</td>
<td>168</td>
<td>166</td>
</tr>
<tr>
<td>Ss</td>
<td>20</td>
<td>146</td>
<td>146</td>
<td>149</td>
<td>149</td>
</tr>
</tbody>
</table>

***p < .001, **p < .01, *p < .05, ^p < .10. Non-semantic patients were used as the baseline group. All main effects are from models with no interaction term. Two-way interactions are from models with no three-way interaction term.

Table 2.10 – MAPPD Patient Mixed Model Results.
changed to detriments of SemD for higher frequency words. The interaction appeared to be stronger in picture naming than word repetition, with stronger frequency effects for both high and low SemD words in picture naming, likely due to the higher overall percentage of errors in that task. These interactions both showed that SemD switched from having a beneficial to having a detrimental effect at lower frequency values than where this switch was observed in healthy participants. Most importantly, the frequency x SemD interaction did not differ between groups in word repetition or picture naming, as indicated by the non-significant three-way interaction term. This result indicates, contrary to predictions, that the interaction of frequency and SemD was not stronger in patients with multi-modal semantic deficits than those without in either task. It is notable that frequency effects in this interaction never reversed, though such a reversal might have been predicted based on some studies of semantic control patients (Almaghyuli et al., 2012; Hoffman, Jefferies, & Lambon Ralph, 2011).
Figure 2.3 – Plots of significant error interactions across patients in the MAPPD (plotting method from Dawson, 2014). Both graphs indicate decreased frequency effects for high SemD words and decreased benefit of high SemD for high frequency words, as were observed in healthy participants.

Because absent frequency effects have been associated with the presence of multi-modal semantic deficits in the literature (Hoffman, Jefferies, & Lambon Ralph, 2011; Hoffman, Rogers, & Lambon Ralph, 2011), I also explored the relationship between MAPPD patients’ level of semantic impairment and lexical effects with a continuous variable. I created a multi-modal
semantic impairment factor from the first principal component of the correlations between three semantic tasks: two non-verbal (Camel and Cactus & Pyramid and Palm Trees tests) and one verbal (synonym triplets). Higher scores on this component indicated more severe semantic impairments. The semantic severity factor was included as a control variable in a generalized linear mixed effects model, and I additionally included the interaction between the semantic severity factor and my variables of interest: frequency, SemD, and the frequency x SemD interaction. The results of these analyses are shown in Table 2.11 – MAPPD Effects of Severity.
<table>
<thead>
<tr>
<th></th>
<th>All Patients</th>
<th>All Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group</strong></td>
<td>Obj Naming</td>
<td>Repetition</td>
</tr>
<tr>
<td><strong>Test</strong></td>
<td>All Patients</td>
<td>All Patients</td>
</tr>
<tr>
<td><strong>Severity</strong></td>
<td>.940***</td>
<td>.272*</td>
</tr>
<tr>
<td><strong>Freq</strong></td>
<td>-.374***</td>
<td>-.323***</td>
</tr>
<tr>
<td><strong>SemD</strong></td>
<td>.029</td>
<td>.028</td>
</tr>
<tr>
<td><strong>SemD x Freq</strong></td>
<td>.124***</td>
<td>.082*</td>
</tr>
<tr>
<td><strong>Severity x Freq</strong></td>
<td>.064**</td>
<td>.017</td>
</tr>
<tr>
<td><strong>Severity x SemD</strong></td>
<td>-.047*</td>
<td>-.035</td>
</tr>
<tr>
<td><strong>Severity x SemD x Freq</strong></td>
<td>-.015</td>
<td>.037*</td>
</tr>
<tr>
<td><strong>Concreteness</strong></td>
<td>-.197***</td>
<td>-.113*</td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td>.174</td>
<td>-.051</td>
</tr>
<tr>
<td><strong>Ortho N</strong></td>
<td>-.243</td>
<td>.151</td>
</tr>
<tr>
<td><strong>Phon N</strong></td>
<td>.508***</td>
<td>.311*</td>
</tr>
<tr>
<td><strong>Obs</strong></td>
<td>24236</td>
<td>24734</td>
</tr>
<tr>
<td><strong>Word</strong></td>
<td>166</td>
<td>166</td>
</tr>
<tr>
<td><strong>Ss</strong></td>
<td>146</td>
<td>149</td>
</tr>
</tbody>
</table>

***p < .001, **p < .01, *p < .05, ^p < .10. All main effects are from models with no interaction term. Two-way interactions are from models with no three-way interaction term.

Table 2.11 – MAPPD Effects of Severity.

Based on the literature, I predicted that as semantic impairments worsened, SemD effects would become increasingly detrimental and this would cause frequency effects to decrease. Because of the results from my analyses above, I additionally predicted that the interaction between frequency and SemD, if mediated by semantic control, would strengthen as semantic impairments worsened.

The results did not support predictions based on the studies of Hoffman et al. (2011) and the Controlled Semantic Cognition framework. In object naming, frequency effects did decrease...
with increasing semantic impairment; however, these decreased frequency effects accompanied an increasing benefit of high SemD with increasing semantic impairment. In word repetition, I observed a three-way interaction between severity, frequency, and semantic diversity. However, as shown by Figure 2.4 – **Predicted probability of error across levels of semantic impairment and frequency (Freq) for significant three-way interaction in MAPPD word repetition (plotting method from Dawson, 2014).** Predicted error probabilities are for -1 and +1 standard deviation from the mean on each variable., this interaction did not follow predictions: patients with high and low semantic impairment showed a similar detriment of high SemD for high frequency words, but as semantic severity increased, patients showed an increased benefit of high SemD for low frequency words. This result provides no evidence that patients with more severe semantic impairments show stronger effects of competition due to SemD.
Figure 2.4 – Predicted probability of error across levels of semantic impairment and frequency (Freq) for significant three-way interaction in MAPPD word repetition (plotting method from Dawson, 2014). Predicted error probabilities are for -1 and +1 standard deviation from the mean on each variable.

Altogether, the MAPPD patient results indicate that defining a semantic access deficit by the presence of a multi-modal semantic deficit does not lead to the correct predictions: word frequency effects are not uncovered or increased by controlling for SemD, either in patients with multi-modal semantic deficit or those without; and neither the presence of a multi-modal semantic deficit nor a more severe semantic deficit strengthens detrimental effects of SemD or
strengthen its interaction with word frequency, both of which effects are claimed to be driven by semantic control demands.

### 2.2.5. Relation of executive functions to lexical measures in the SPP.

To explore whether detrimental effects of SemD were related to an executive mechanism, I used linear or generalized linear mixed effects models to predict zRTs or errors with SemD, word frequency, and an executive factor for both lexical decision and word reading for healthy adults in the SPP. The executive factor was the first principal component derived from the correlations between the Stroop effect in RTs and errors, the antisaccade effect, and the operation span of each participant. The primary concern in these models was whether the executive measure would interact with lexical properties. I originally predicted that the executive factor would interact with SemD, consistent with high SemD causing semantic selection problems, particularly for those low on executive function abilities. Given that high SemD only seems to have this effect for HF words (per the interactions between frequency and SemD discussed above), the original prediction was revised: an interaction should occur between the executive factor and the SemD x word frequency interaction. Models included main effects of frequency, SemD, and the executive factor, as well as all possible interactions between the three variables.
<table>
<thead>
<tr>
<th>Model</th>
<th>Freq</th>
<th>SemD</th>
<th>EF</th>
<th>Freq x SemD</th>
<th>Freq x EF</th>
<th>SemD x EF</th>
<th>Freq x SemD x EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Word Reading zRT</td>
<td>-.139***</td>
<td>.027***</td>
<td>-.001</td>
<td>.024***</td>
<td>-.006^</td>
<td>.007^</td>
<td>.001</td>
</tr>
<tr>
<td>Word Reading errors</td>
<td>-.357***</td>
<td>-.012</td>
<td>-.190**</td>
<td>.088*</td>
<td>.081*</td>
<td>-.037</td>
<td>.001</td>
</tr>
<tr>
<td>Lexical Decision zRTs</td>
<td>-.201***</td>
<td>.014*</td>
<td>0.001</td>
<td>.051***</td>
<td>.005</td>
<td>-.0003</td>
<td>.003</td>
</tr>
<tr>
<td>Lexical Decision errors</td>
<td>-.489***</td>
<td>-.014</td>
<td>-.087*</td>
<td>.214***</td>
<td>-.017</td>
<td>.021</td>
<td>.035**</td>
</tr>
</tbody>
</table>

***p < .001, p < .01, *p < .05, ^p < .10

Table 2.12 – SPP Executive Function Models.
Results of the SPP word reading and lexical decision log RT model comparisons are shown in Table 2.12 – SPP Executive Function Models. All zRT and error models showed interactions between frequency and SemD consistent with the analyses described above. In addition, both word reading and lexical decision errors showed main effects of the executive factor, which indicated that higher EF led to fewer errors. Word reading zRTs showed interactions between the executive factor and both frequency and SemD that fell just short of significance ($p < .10$). Word reading errors, however, showed a significant ($p < .05$) interaction between the executive factor and frequency. This interaction showed that frequency effects were smaller for participants with high EF compared to those with low EF ability, primarily due to high SemD participants showing a lower probability of error for low frequency words (see Figure 2.5 – Predicted probability of error across levels of executive function (EF) and frequency (Freq) for significant two-way interaction in SPP word reading (plotting method from Dawson, 2014). Predicted error probabilities are for -1 and +1 standard deviation from the mean on each variable.).
Figure 2.5 – Predicted probability of error across levels of executive function (EF) and frequency (Freq) for significant two-way interaction in SPP word reading (plotting method from Dawson, 2014). Predicted error probabilities are for -1 and +1 standard deviation from the mean on each variable.

Lexical decision zRTs showed no interactions with the executive factor, but lexical decision errors showed a three-way interaction of frequency, SemD, and the executive factor. This interaction showed that as executive ability increased, the interaction between frequency and SemD was more extreme due to participants with high EF showing a larger benefit of high SemD for low frequency words (see Figure 2.6 – Predicted probability of error across levels
of executive function (EF), SemD, and frequency (Freq) for significant three-way interaction in SPP lexical decision (plotting method from Dawson, 2014). Predicted error probabilities are for -1 and +1 standard deviation from the mean on each variable, difference between solid lines and dotted lines). Given that previous research predicted that semantic control should help to resolve competition created by SemD (Hoffman et al., 2013) and given that the frequency x SemD interactions described above suggest high frequency words are where such competition may be taking place, one would have expected the advantage of individuals with higher EF ability to appear as a smaller advantage for low SemD, high frequency words over high SemD, high frequency words. Because this was not the case, I have found no evidence that effects of SemD are mediated by an executive mechanism. If SemD does create semantic competition for high frequency words, its resolution may be executed by a domain-specific mechanism rather than a domain-general mechanism.
Figure 2.6 – Predicted probability of error across levels of executive function (EF), SemD, and frequency (Freq) for significant three-way interaction in SPP lexical decision (plotting method from Dawson, 2014). Predicted error probabilities are for -1 and +1 standard deviation from the mean on each variable.

2.3. Discussion

In this study, I explored effects of a lexical variable, semantic diversity (SemD), that appeared to have intriguing but understudied effects based on the literature. Research with aphasic patients, healthy older adults, and younger adults has shown that SemD, the variety of
contexts in which a word appears, is a variable that creates difficulty in performing semantic tasks (Hoffman & Woollams, 2015; Hoffman et al. 2011, 2013) and a benefit in performing other, less semantic tasks (Hoffman & Woollams, 2015; Hsiao & Nation, 2018). Most intriguing, however, are studies showing that SemD appears to modulate typical word frequency effects in healthy older adults and patients with semantic comprehension deficits, as inclusion of this variable uncovers an otherwise unobservable frequency effect in synonym judgments (Hoffman, et al., 2011, 2013). The authors of these studies claim that SemD suppresses the frequency effect because high SemD words, which also tend to have high frequency, require the use of an executive semantic control mechanism to resolve competition between activated, contextually-related semantic representations, whereas low SemD words do not require such a mechanism. Use of semantic control, they claim, slows processing in healthy individuals and causes errors in comprehension-impaired aphasic patients, whose semantic control is impaired. Because of this slowing or impairment, the typical advantage for high frequency words is reduced and can only be observed if SemD is controlled. This result 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—and create a null frequency effect only for high SemD words, where the selection difficulty would be strongest. Such an interaction between frequency and SemD had not been previously investigated in healthy adult language processing.

I explored this interaction in existing databases of healthy adult language processing and aphasic patient language processing across six tasks: single word reading, word repetition, lexical decision, concreteness decision, object naming, and action naming. In five of these tasks, in healthy adults and aphasic patients, I observed the predicted interaction, with typical word
frequency effects decreasing as SemD increased, and many tasks showed beneficial main effects of SemD independent of frequency effects. However, despite predictions from the literature, I found no evidence that effects of SemD—or their interaction with word frequency—were underpinned by an executive semantic control mechanism. Furthermore, I found that the beneficial or detrimental effects of SemD did not differ across task, regardless of the tasks’ semantic requirements, but were observable across all tasks. This complex relationship between frequency and SemD suggests an important relationship between an influential psycholinguistic variable, word frequency, and a less well-studied semantic variable, SemD, in models of language processing.

2.3.1. Are frequency effects just semantic diversity effects?

Several previous studies have shown that some version of SemD may explain typical word frequency effects better than a simple word count (Adelman et al., 2006; Brysbaert & New, 2009; Cai & Brysbaert, 2010; Dimitropoulou et al., 2010; Jones et al., 2012; Soares et al., 2015). These studies have shown that measures of document count—a proxy for contextual variability—or SemD explain all or most of the variance accounted for by word frequency in typical lexical decision or single word reading experiments. To investigate whether SemD completely explains word frequency effects, I explored the relative contribution of frequency and SemD to each task that I analyzed. Contrary to the findings of these previous studies, however, I found that frequency effects were consistently larger than the observed SemD effects. I reasoned that the SemD measure I chose to use, that of Hoffman et al. (2013), may have caused these differences, so I attempted to replicate the previous findings of two major studies (Adelman et al., 2006; Jones et al., 2012) using tasks, analyses, and data approximating their own, and
compared effects of their diversity measures with Hoffman et al.’s SemD. I was generally able to replicate previous findings, and my comparisons showed clear differences in the effects of previous diversity measures and the measure I used. These results suggested that Hoffman et al.’s SemD is tapping a different construct than does contextual diversity (CD) or Jones et al. (2012)’s SemD.

If each measure is tapping a different construct, is one measure preferable over the others? I argue that the SemD measures of Hoffman et al. (2013) and of Jones et al. (2012) are preferable to Adelman et al. (2006)’s CD, given that both explicitly characterize the semantic content of the contexts in which words appear. Because it does not take into account the similarity of the content of different contexts, CD appears to not accomplish its theoretical goal of measuring contextual variation. In addition, its extremely strong correlation with frequency suggests that it is unlikely to measure much beyond the construct captured by frequency. The SemD measures of Hoffman et al. (2013) and Jones et al. (2012), by contrast, capture the content of contextual variation and correlate less strongly with frequency than does CD.

Comparing these two measures of SemD is more difficult, given that they have been used to pursue different theoretical goals and therefore their effects have often been explored in different sets of tasks. The SemD of Hoffman et al. was derived to capture the theory that a word’s meaning may vary continuously based on the contexts in which it is found and has been explored in many studies as a measure of semantic richness or semantic ambiguity (e.g., Hoffman & Woollams, 2015; Hoffman et al., 2011, 2013; Yap et al., 2016); 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. (2006)’s CD and has been explored more often in relation to
artificial and natural language learning (e.g., Jones et al., 2012; Johns, Dye, & Jones, 2016). As these measures pertain to the current study, Hoffman et al.’s SemD has been studied more deeply relative to its effects across different tasks, which, as discussed in the introduction, are sometimes beneficial and sometimes detrimental. It remains an empirical question whether the SemD of Jones et al. would show the same detrimental effects in tasks such as synonym judgment or word pair semantic association judgments. One clue that we may expect differences between the SemD of Jones et al. and Hoffman et al. across tasks is that Jones et al.’s SemD interacted with CD in ELP lexical decision such that SemD showed no effect for low CD words and a beneficial effect for high CD words (Jones et al., 2012). Because CD correlates so strongly with frequency, we can take this interaction as inconsistent with the interactions of Hoffman et al.’s SemD and frequency in the analyses of the data from the ELP, where I found a beneficial effect of SemD at low frequency and a detriment of SemD at the highest frequencies. These differences in the results of the two measures must ultimately spring from differences in their calculation.

The SemD 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) created their contexts with the methods of 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 vector that is predictive of the contexts from which it was derived and should measure the higher order similarity structure among the words. Jones et al. (2012) created their contexts by first creating sparse ternary vectors to represent each possible word—2000 item vectors with four non-zero values between -1 and 1—and then summing the vectors for all words present in each context. The process of SVD in latent semantic analysis is explicitly meant to capture higher-order semantic relationships (Landauer & Dumais, 1997), and it is not clear whether these relationships are adequately captured by co-occurrence of word vectors that were created from whole cloth. Some evidence suggests that raw co-occurrence may perform as well or better than dimensionally-reduced representations (e.g., Bullinaria & Levy, 2007; Recchia & Jones, 2009), but it is impossible to say whether such is the case for the SemD measures at hand without directly comparing the performance of their word vectors against human semantic similarity judgments.

The comparative reliability of the contextual representations used to create Hoffman et al.’s SemD is supported by the fact that they 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.’s 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. (2013) tested their word vectors against a synonym judgment task with a probe word and three choices. They found that the correct choice showed the highest cosine with the probe 82% of the time, close to performance of native English speakers (95%), and tended to make errors on the same trials as
human participants. Thus, there is reason to believe that the context vectors of Hoffman et al., which are derived from the same matrix as the word vectors, represent realistic semantic relationships. It is not clear whether the same is true of the word and context representations of Jones et al.—whether such is the case remains an empirical question. Jones et al. (2012) showed that their model better correlated with WordNet semantic similarities than did LSA values, but the difference between the two 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, McKinley, & Thompson, 2004).

### 2.3.2. SemD effects are not mediated by semantic control

My hypothesis that SemD may interact with word frequency was motivated by studies claiming that an executive semantic control mechanism resolves competition among activated representations that is created by high SemD (Hoffman et al., 2011, 2013). In my analyses, I found an interaction between frequency and SemD in nearly all tasks I investigated, but my results did not suggest that this interaction, nor the main effect of SemD, is driven by the resolution of semantic competition. Whereas competition might be indicated by an increasing detriment of high SemD as word frequency increases, the observed interactions revealed that SemD had a beneficial effect at lower word frequency and a detrimental effect at higher word frequency. If the competition potentially evident at high word frequencies reflected semantic competition, then tasks more strongly obligating the use of semantic representations should have shown stronger interactions; however, the presence of increased semantic task demands did not increase the detrimental impact of SemD effects, either alone or in conjunction with word frequency effects. Furthermore, if semantic control mediated the frequency x SemD interaction,
patients with semantic control deficits should have shown stronger detrimental effects of SemD than patients without such deficits; however, patients meeting the criteria for a semantic control deficit showed no difference in SemD effects from patients without such deficits. Finally, detrimental effects of SemD effects at higher levels of word frequency were not found to be related to healthy individuals’ EF abilities. All of these results contradict the hypothesis of the Controlled Semantic Cognition (CSC) framework given by Hoffman et al. (2011, 2013) that detrimental effects of SemD take place at the level of semantic representations and are resolved by an executive semantic control mechanism.

SemD was predicted to be resolved by an executive semantic mechanism primarily because comprehension-impaired stroke patients who showed detrimental effects of SemD were considered to have a semantic control deficit. However, the true mechanism of these patients’ semantic deficits is not clear from the literature. The CSC framework (Lambon Ralph et al., 2017) claims that certain patients have a semantic control deficit primarily because of behavioral differences observed between comprehension-impaired stroke patients, argued to have semantic control deficits, and semantic dementia patients, argued to have damage to conceptual representations (e.g., Jefferies & Lambon Ralph, 2006; Noonan, Jefferies, Ehsan, Garrard, & Lambon Ralph, 2013). However, recent research investigating many of 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 & Martin, submitted). 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., 2018;
Thompson, Robson, Lambon Ralph, & Jefferies, 2015). Because of this widespread damage, one may easily imagine that patients’ semantic deficits may have multiple underlying cognitive mechanisms.

In the current study, when I divided aphasic patients into those with and without multi-modal semantic deficits based on the inclusion criteria for having a semantic control deficit used in the literature (e.g., Thompson et al., 2018), none of the literature’s predictions were satisfied. These results show clearly that classifying a semantic control deficit based on a multi-modal semantic deficit makes incorrect predictions. If semantic control/semantic access may be damaged independent of conceptual representations, more criteria are necessary to define it than the presence of a multi-modal semantic deficit. However, even if one could identify some portion of the MAPPD database as having a semantic control, it is not clear that one should expect patients to show these exaggerated effects, as I did not find that effects of SemD in healthy participants varied with increasing semantic task demands.

One must also ask, given that I analyzed a semantic task in aphasic patients, why my results did not follow the pattern of Hoffman et al. (2011). One obvious difference between my analyses is that the MAPPD sample is many times larger than that of Hoffman et al. (2011). It is possible that the findings of Hoffman et al. were spurious, given that their sample included only thirteen patients. This interpretation appears less likely given that the same pattern was observed in a sample of healthy older adults, though without any other independent replication of these effects it is possible that both effects were spurious due to small sample sizes. Another clear difference between our analyses was in the tasks employed: I analyzed results from picture naming and word repetition tasks, whereas Hoffman et al. employed a synonym judgment task.
There are multiple reasons to believe that Hoffman et al.’s synonym judgment task may show different effects than the tasks employed in the current study. First, synonym judgment is more likely to recruit working memory abilities than are picture naming and word repetition. In their synonym judgment task, participants are asked to choose from among three words which is the synonym of a probe word. Working memory may be recruited to compare each choice to the probe word. The detrimental effect of SemD may relate to this working memory load. If SemD effects reflect activation spreading to contextually related information, then comparing multiple words could involve holding multiple sets of meanings in memory, giving rise to a SemD effect when working memory ability is not controlled. Such effects would be further complicated if the frequency of each word influences the degree to which associated information is activated by a word (discussed below), as the frequency of each of the four visual words in the task would then influence processing. By contrast, word repetition and picture naming require processing only a single stimulus, and processing a single stimulus should be less taxing to working memory than processing three stimuli comparisons.

Second, semantic competition may be exaggerated in synonym judgment compared to picture naming or word repetition due to the level at which the task response is made. When naming a picture or repeating a word, meaning may be accessed, but the ultimate response must be verbal, so the relevant meaning must be translated into some form of lexical representation before the response is made. By contrast, the response in synonym judgment is based on which words are identified as having importantly similar semantic representations, a judgment which does not require using a semantic representation to access a lexical representation; instead, lexical representations are used to access semantic representations and judgments are made based on these representations. Because of the amplified importance of semantic information in making
this decision, it may be more likely for semantic interference due to SemD to occur in synonym judgment than in picture naming or word repetition, or semantic interference demands may simply be stronger in synonym judgment. However, this is not to say that semantically-induced competition can play no role in picture naming or word repetition. There is evidence that competition is induced by semantic information in picture naming—e.g., by semantically related words in picture-word interference tasks (e.g., Schriefers, Meyer, & Levelt, 1990) and in repetition of categorically-related pictures in blocked cyclic naming (Damian, Vigliocco, & Levelt, 2001). Word repetition, too, seems to involve accessing semantic representations, according to the aphasic patient literature (Berkowitz, Kohen, & Martin, 2011; Hanley & Kay, 1997; Hanley, Kay, & Edward, 2002; Katz & Goodglass 1990; Saffran & Martin, 1997), suggesting that semantic competition has potential to occur in single word repetition as well. Further research may help to clarify the levels at which SemD affects these tasks. It would be particularly revealing to understand whether and how the interaction of frequency and SemD is different in synonym judgment compared to those observed in picture naming and word repetition. A qualitatively similar interaction across the tasks, one like those shown in healthy individuals and patients in this study, would suggest that effects of SemD are due to the same mechanism across tasks.

2.3.3. Why do frequency and semantic diversity interact?

Despite incorrect predictions relative to the relationship between SemD and semantic control, the predicted interaction between frequency and SemD is robust. When SemD is defined by the relations between the semantic contexts in which words appear, as in the conception of Hoffman et al. (2011), it has an effect that differs from that of frequency and works in a complex
relationship with frequency. Frequency effects decrease as SemD increases, and high SemD is typically beneficial to processing but is detrimental for words with the highest frequencies.

Why might frequency and SemD interact in this manner? Studies of semantic priming have provided good evidence for spreading activation in the semantic system (Meyer & Schvaneveldt, 1971, 1976; Moss, Ostrin, Tyler, & Marslen-Wilson, 1995), and further studies have shown that one may prime semantically associated information (see Hutchison, 2003) or multiple meanings of ambiguous words (Swinney, 1979; Onifer & Swinney, 1981; Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982). 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 in size to a word’s SemD. Additionally, one study in the literature suggests that spreading activation to associated information is frequency-dependent: Hutchison, Balota, Cortese, and Watson (2008) found, when collapsing across lexical decision and naming tasks, that higher frequency primes increased priming effects at short SOAs. Thus, I propose that the dynamics of the frequency x SemD interactions observed in this chapter are due to a harmful effect of high frequency relative to low frequency on high SemD words.

I suggest that high frequency words cause relatively strong activation of contextually associated information, creating a competitive environment in which selection of the relevant target information is more difficult (i.e., slower and more errorful). My results suggest that this competition must take place at a non-semantic level of processing, given the fact that the frequency x SemD interaction was not modified by tasks’ semantic demands. Therefore, strong activation of semantically associated information must spread to lexical or phonological
representations. Because not only the target representation but also non-target representations are strongly activated, competition occurs, resulting in longer processing time and more potential for error in selection. By contrast, I propose that low frequency words cause relatively weak activation of associated semantic information that spreads to lexical or phonological representations. As with high frequency words, some activation from this associated semantic information spreads to non-target lexical or phonological representations and some to target representations; however, activation of non-target representations is weak enough not to create competition with the target. Furthermore, because of semantic overlap between the target and its contextually-related cohort, additional activation is spread from semantic representations to the target lexical, which supports target selection in a way that does not occur for words with lower SemD.

The opposing facilitative and inhibitory effects of SemD at different word frequency levels are reminiscent of the opposing effects observed for near and distant semantic neighbors in semantic category decisions (Mirman & Magnuson, 2008). In the current study, high SemD, low frequency words show facilitatory effects like words with many distant neighbors, and high SemD, high frequency words show inhibitory effects like words with many near neighbors. Mirman and Magnuson (2008) claimed that these effects occur based on attractor network dynamics at the semantic level of processing: near neighbors are competing attractors that slow settling to the correct representation, whereas distant neighbors create a gradient that facilitates settling to the correct attractor. This sort of attractor network might be applied to effects of SemD as well, provided that frequency may scale whether neighboring—here, contextually associated—information has distant (low frequency) or close (high frequency) neighbor effects.
Chapter 3

Investigating the Role of Cognitive Control in Semantic Diversity Effects on Word Processing

3.1. Introduction

The database analyses in Chapter 2 showed that SemD modulates word frequency effects in healthy participants in a consistent manner across many tasks, with a benefit for high SemD for low frequency words and a lesser benefit or even a disadvantage for high frequency words. However, the cognitive locus of the SemD effect and its interaction with frequency remain unclear from the available evidence. Recall that the original motivation for predicting a role of cognitive control in the influence of SemD came from evidence showing that patients with ostensible semantic control deficits displayed detrimental effects of SemD that appeared to mask typical frequency effects (Hoffman et al., 2011). Hoffman et al. posited that the patients’ damaged semantic control mechanism exaggerated the typical difficulty created by high SemD. They argued that this difficulty occurs because high SemD words activate a large array of associated contextual semantic information from which relevant information for the current task must be distinguished. The database analyses above reveal several problems with the hypotheses proposed by Hoffman et al.
First, my analyses of MAPPD aphasic patients with and without multi-modal semantic patients—the former of whom are thought to have semantic control deficits—revealed no differences in the effects of SemD in word repetition or picture naming. Because picture naming should involve processing of specific semantic representations, I hypothesized that this task at least, of the two, should show differences in SemD effects driven by semantic control deficits. The current study’s results showed that patients with and without multi-modal semantic deficits showed the same interaction between frequency and SemD in both picture naming and word repetition, implying either that those with semantic deficits did not have cognitive control deficits or cognitive control does not modulate the influence of SemD on word processing. In fact, previous work suggests that many of the phenomena claimed to distinguish “semantic control” patients from patients with deficits to semantic representations per se are not robust and do not hold up under scrutiny (Chapman & Martin, 2017, submitted). Thus, it is not clear that cognitive control should show any relationship with SemD effects, given that the findings from patients who originated that prediction may not actually have semantic control deficits.

Second, domain-general executive function showed no general relationship with detrimental effects of high SemD in my analyses of healthy participant performance in lexical decision and single word reading in the SPP (semantic priming project). A recent study showing similar effects of SemD on language processing in “semantic control” patients and healthy older adults suggested that the control mechanism proposed to underlie SemD effects should be used by healthy individuals as well as aphasic individuals (Hoffman et al., 2013). If cognitive control were related to competition resolution difficulties created by high SemD in healthy individuals, a relationship between executive control and SemD effects should have been observed—but it was
not. I therefore find no evidence that detrimental SemD effects are underpinned by an executive mechanism.

Despite these issues with previous theory, I may not have found a relationship between domain-general executive mechanisms and detrimental SemD effects because of the poor definition of “semantic control deficits” provided by the CSC literature. Such deficits could truly exist in patients, but the criterion of having a multi-modal semantic deficit may not be sufficient to delimit whether patients have semantic control problems. If this were the case, the MAPPD patients in the two groups may have been a mix of patients with and without semantic control deficits, diluting true differences in SemD effects. To test this possibility, one would need a clearer definition of what a semantic control deficit entails. However, the results of Chapman and Martin (submitted) suggest the boundaries of such a definition would be quite difficult to draw.

Nevertheless, it would be theoretically useful to have experimental evidence in lieu of circumstantial and correlational evidence for whether cognitive control relates to detrimental effects of SemD. A better test of whether cognitive control relates to detriments of SemD could be accomplished by manipulating cognitive control requirements experimentally. If detrimental SemD effects were exaggerated in semantic tasks by increasing cognitive control demands, one could infer that cognitive control was causally related to SemD effects. Several recent studies provide evidence for a manipulation of cognitive control that can be applied to psycholinguistic tasks. Results from these studies have implied that forcing participants to speed their processing of tasks may disrupt controlled processing (Balota, Burgess, Cortese, & Adams, 2002; Hodgson & Lambon Ralph, 2008; Kello & Plaut, 2000). These studies used a special form of speeded task
called a tempo task, in which participants make their responses in time with a counted tempo and after only brief exposure to the stimulus.

Balota et al. (2002) argued that a tempo task involving episodic recognition affected controlled recall processes as opposed to automatic familiarity processes. Their study investigated the mechanisms underlying episodic memory breakdown in older adults with and without Alzheimer’s dementia. Balota et al. had participants study lists of words before being given a recognition test in which they decided whether words had been previously seen. In a set of young adults, older adults, and mild dementia patients, Balota et al. found that hit rates for low frequency words decreased across the age and dementia spectrum, whereas there was no difference in hit rates across groups for high frequency words. False alarm rates rose slightly across the age and dementia spectrum for both high and low frequency words, with false alarm rates always higher for high frequency than low frequency words. Based on this pattern of results, the authors suggested that with increasing age and dementia, participants relied more on baseline familiarity to drive their responses. In a second experiment, Balota et al. performed a tempo version of the same episodic recognition task with either slow or fast tempos in young adults. With fast as opposed to slow tempos, young adults showed a similar reduction of hit rates for low frequency words as opposed to high frequency words as was seen with increasing age and dementia in the previous experiment. Balota et al. argued from these results that the tempo task mimicked aging to the extent that it forced young participants to rely more on word familiarity (an automatic process) rather than slow, controlled processing. They concluded that the tempo task impairs controlled recall processes but not familiarity-based mechanisms.
Hodgson and Lambon Ralph (2008) used a tempo picture naming task in an attempt to simulate the performance of semantic control patients in healthy control participants. Their results showed that, in tempo picture naming compared to standard picture naming, participants showed an increased prevalence of semantic errors and showed increased detriments of miscues. The authors argued this pattern of results mimicked the pattern seen in patients with impaired semantic control. Thus, as in Balota et al. (2002), the authors argued that the tempo task affects a controlled memory access mechanism.

Finally, Kello and Plaut (2000) investigated strategic control over response initiation in word reading using normal and tempo versions of a single word reading task. They showed that word frequency effects were attenuated in tempo compared to standard single word reading, consistent with the claim that tempo tasks tax mechanisms affecting word frequency effects. Kello and Plaut argued that tempo single word reading creates a compressed cognitive processing timeline in which participants must increase the degree to which their processing system responds to stimuli. Because of the compressed processing window, stimulus effects such as word frequency effects also become compressed in time, resulting in attenuated effects. This hypothesis was discussed in terms of “input gain” by analogy with a parameter that implements accelerated processing in a connectionist network. The input gain hypothesis states that participants can strategically change their sensitivity to incoming stimuli based on the time criterion of the tempo task; this sensitivity change results in faster RTs but increased errors due to either noise amplification or the fact that the relative timing of unit output trajectories is disturbed (Kello & Plaut, 2000, 2003). Whereas this hypothesis appears to simply explain speed-accuracy tradeoffs, Kello and Plaut (2000, 2003) demonstrated that increases in speed did not
always incur increases in errors, suggesting that this theory has explanatory power beyond a speed-accuracy tradeoff.

If the sensitivity parameter being adjusted according to Kello and Plaut (2000) relates to familiarity-based mechanisms and not recall-based mechanisms, then their proposal would be consistent with that of Balota et al. (2002). In a system with both familiarity-based and recall-based mechanisms, increasing the sensitivity of automatic, familiarity-based mechanisms might cause familiarity-based mechanisms to take precedence over controlled, recall-based mechanisms. This adjustment would cause more familiarity-based processing and potentially attenuate lexical effects via a compressed processing timeline, consistent with the proposals of Balota et al. (2002) and Kello and Plaut (2000). Importantly, the input gain hypothesis would predict reduced effects of SemD just as it predicts reduced effects of word frequency, as the SemD effect is simply another lexical effect dependent on time differences between conditions. Thus, the prediction of the input gain hypothesis about the source of shrinking word frequency effects and the direction of SemD effects in response to the tempo manipulation is at odds with the predictions of the Controlled Semantic Cognition (CSC) framework, in which detrimental effects of SemD (which are claimed to reduce word frequency effects) should result from controlled semantic retrieval processes and SemD effects should be exaggerated by less efficient use of these retrieval mechanism in tempo tasks.

These previous studies employing tempo tasks motivate the current study. First, they provide expectations regarding the impact of manipulating controlled processing on lexical effects. Balota et al. (2002) and Kello and Plaut (2000) showed that tempo tasks attenuate word frequency effects in single word reading and episodic recognition. Indeed, the input gain
hypothesis of Kello and Plaut (2000) predicts that any lexical effect—including word frequency effects and SemD effects—should be diminished by the tempo manipulation. Hodgson and Lambon Ralph (2008) suggested that performing tempo picture naming taxes controlled semantic mechanisms, which predicts that exaggerated effects of SemD should be seen in tempo tasks. Exaggerated SemD effects, consistent with the CSC framework’s hypothesis regarding semantic control, should also attenuate word frequency effects in semantic processing.

Second, these studies provide alternative theories on why lexical effects should change in a tempo task vs. a normal language processing task. The input gain hypothesis predicts that tempo tasks should decrease word frequency effects and SemD effects because participants adjust their sensitivity to incoming stimuli and compress their processing timeline, in turn compressing the size of lexical effects (Kello & Plaut, 2000, 2003). In contrast, Hodgson and Lambon Ralph (2008) claim that adding a tempo response criterion increases semantic control demands; in combination with the claim of Hoffman et al., (2011) that semantic control deficits increase detrimental effects of SemD, this claim predicts that—in tasks requiring selection of a specific semantic representation—a tempo criterion should increase detrimental SemD effects and decrease word frequency effects because tempo tasks limit the effective use of semantic control. Semantic control is relevant to SemD effects because it is claimed to be used when selecting among competing semantic representations, and the number of competing semantic representations activated is a function of SemD.

Thus, I carried out the following experiments, which compared the effects of SemD, word frequency, and their interaction in speeded (i.e., tempo) vs. unspeeded (standard) versions of four tasks that have previously shown interactions between word frequency and SemD (see
database analyses above): single word reading, lexical decision, concreteness decisions, and picture naming. With these experiments, I aimed to provide evidence regarding whether high SemD creates semantic competition that increases the demands of cognitive control processes in healthy adults. Predictions of the study may be grouped into two categories: 1) effects of the tempo manipulation on the size of individual lexical effects, and 2) the effect of SemD as a suppressor of word frequency effects.

1) The semantic control and input gain hypotheses make different predictions regarding the effects of the tempo manipulation. The semantic control hypothesis predicts that: unique detrimental effects of SemD (i.e., controlling for word frequency) will increase from standard to tempo task versions and the interaction between frequency and SemD will increase from standard to tempo task versions. These predictions are contingent upon the assumption that SemD creates increased semantic control demands in these tasks. The CSC hypothesis, as mentioned above, suggests that tasks requiring access to a specific semantic representation are the only ones that should show detrimental effects of SemD, as these increased demands are claimed to be the cause of decreasing word frequency effects in semantic aphasia patients (Hoffman et al., 2011; Hoffman et al., 2013). Therefore, all effects of the tempo manipulation listed above should be present only when the task requires accessing a specific

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3 The prediction regarding the frequency effect is less clear cut. If the tempo manipulation only affects cognitive control and if frequency effects are independent of cognitive control, then no effect on frequency should be observed. However, then it is unclear how the Hoffman et al. approach would account for the prior findings of Kello & Plaut (2000) and Balota et al. (2002)
semantic representation. I predicted that specific semantic representations are more likely to be consistently accessed in concreteness decisions and picture naming and less likely to be consistently accessed (if at all) in single word reading or lexical decision. The input gain hypothesis, by contrast, predicts that unique effects of both word frequency and SemD in RTs will decrease from standard to tempo versions of tasks with lexical input (i.e., all but picture naming), given the fact that the window of time in which these effects take place is necessarily compressed in the tempo relative to standard task versions. Because both effects should shrink, the interaction observed between frequency and SemD should also shrink. Note that these predictions apply only to RTs and not to errors, as the input gain hypothesis does not generate clear predictions about whether error rates should differ across word frequencies.

2) The semantic control hypothesis makes a prediction, and the input gain hypothesis makes no prediction, concerning the effect of SemD as a suppressor of word frequency effects. If the tempo manipulation disrupts semantic control for any task, then one should observe a suppressive effect of SemD on word frequency effects. That is, there should be a task version x frequency interaction when not controlling for SemD, but this interaction should not be present after SemD is controlled. The significant interaction should reflect a reduced frequency effect in the tempo task, and the reduction of the frequency effect should be lessened by controlling SemD. I expect a reduced word frequency effect in the tempo task because this task version is where Hodgson and Lambon Ralph (2008) predicts that healthy individuals should be more patient-like. However, rather than SemD acting as a suppressor, it could be that word frequency effects are also affected by cognitive control demands—even
independently of semantic requirements. Kello and Plaut (2000) provided evidence that word frequency effects may be attenuated in a task with little semantic requirement, single word reading. If adding a tempo criterion increases controlled processing demands, this result provides preliminary evidence that controlled processing affects word frequency effects independent of SemD, as there is little reason to believe semantic control is necessary in typical single word reading.

It is possible that the tempo manipulation will not disrupt semantic control for any task—even picture naming, which the task employed by Hodgson and Lambon Ralph (2008). Their arguments for a disruption of semantic control were based on the fact that semantic errors and errors from incorrect phonemic cues increased in healthy participants in the tempo relative to standard picture naming. However, these results may also have occurred because the language system did not have enough time to settle on the correct representation. Dell, Schwartz, Martin, Saffran, & Gagnon (1997) showed in a model of picture naming that early in processing semantic competitors are likely to be most strongly activated. If the system were not given enough time to settle in the tempo task before a response had to be made, semantic competitors may be strongly activated, and one need not posit a malfunctioning or overloaded control mechanism to account for increased semantic errors.

3.2. Methods

3.2.1. Stimuli

Stimuli from the four tasks were selected from the databases analyzed above. Single word reading and lexical decision stimuli come from the English Lexicon Project (Balota et al., 2007);
concreteness decision stimuli come from the Calgary Semantic Decision Project (Pexman et al., 2017); and picture naming stimuli come from the International Picture Naming Project (Szekely et al., 2004). Stimuli were chosen to meet several criteria. First, stimuli all had available SUBTLEX frequency and SemD values. Second, stimuli were between four and seven letters long, to limit word length effects that might occur from using very long words. Word length was also controlled in all analyses. Third, stimuli included only words dominantly used as nouns or adjectives, as verbs tend to have much higher SemD and I did not want the high SemD words to be dominated by a particular word class. Fourth, stimuli with the highest 1% of frequency values in a given word pool were not used, as those words seem to have an extreme impact on the interaction between frequency and SemD (see database analyses above). Fifth and finally, high frequency and low frequency words in single word reading and picture naming were matched in their initial phoneme to minimize the influence of phonemic differences on recorded response times by the microphone used for the task (e.g., Kessler & Treiman, 2002). These constraints limited the stimulus set sizes in picture naming and concreteness tasks, and the maximum possible number of stimuli were used in each of these tasks based on the constraints. Several additional items were eliminated from these two tasks based on low accuracy across participants (mean < 50%) in pilot testing. Descriptive statistics on the frequency, SemD, length, concreteness, phonological neighborhood density, and orthographic neighborhood density of each stimulus set are provided in Table 3.1 – Lexical attributes of task stimuli.
Table 3.1 – Lexical attributes of task stimuli.

### Task 3.1: Lexical attributes of task stimuli.

<table>
<thead>
<tr>
<th>Task</th>
<th>Set</th>
<th>n</th>
<th>Measure</th>
<th>Freq</th>
<th>SemD</th>
<th>Length</th>
<th>Conc</th>
<th>Orth N</th>
<th>Phon N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Word Reading</td>
<td>A</td>
<td>300</td>
<td>Mean</td>
<td>2.00</td>
<td>1.47</td>
<td>7.24</td>
<td>3.64</td>
<td>2.09</td>
<td>1.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SD</td>
<td>0.75</td>
<td>0.30</td>
<td>4.19</td>
<td>1.05</td>
<td>0.46</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>300</td>
<td>Mean</td>
<td>1.96</td>
<td>1.46</td>
<td>6.59</td>
<td>3.75</td>
<td>2.05</td>
<td>1.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SD</td>
<td>0.68</td>
<td>0.30</td>
<td>3.27</td>
<td>0.96</td>
<td>0.47</td>
<td>0.55</td>
</tr>
<tr>
<td>Lexical Decision</td>
<td>A</td>
<td>400</td>
<td>Mean</td>
<td>1.96</td>
<td>1.47</td>
<td>5.89</td>
<td>3.56</td>
<td>2.10</td>
<td>1.96</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SD</td>
<td>0.74</td>
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<td>0.52</td>
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<tr>
<td></td>
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<td>Mean</td>
<td>1.94</td>
<td>1.46</td>
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<td></td>
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<td>SD</td>
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<td>0.96</td>
<td>0.41</td>
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<tr>
<td>Concreteness Decision</td>
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<td>245</td>
<td>Mean</td>
<td>1.89</td>
<td>1.51</td>
<td>6.05</td>
<td>3.20</td>
<td>2.19</td>
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<td></td>
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<tr>
<td></td>
<td>B</td>
<td>245</td>
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<td>1.91</td>
<td>1.49</td>
<td>6.10</td>
<td>3.21</td>
<td>2.19</td>
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</tr>
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<td></td>
<td>SD</td>
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<td>0.32</td>
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<td>1.19</td>
<td>0.46</td>
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<tr>
<td>Picture Naming</td>
<td>A</td>
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<td>2.84</td>
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<tr>
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<td></td>
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<td>1.01</td>
<td>0.26</td>
<td>0.53</td>
<td>0.64</td>
</tr>
</tbody>
</table>

### 3.2.2. Procedure

For each version of the task, two different stimulus sets (A and B) were created so that standard and tempo task versions could be employed on the same day without repeating items. These stimulus sets included an equal number of stimuli in each frequency x SemD category (e.g., high frequency, high SemD words; low frequency, high SemD words, etc.) to make sure that a broad range of frequency and SemD values were present. For concreteness decision stimuli, each of these four categories had an equal number of abstract and concrete words. Separate sets of 20 practice stimuli were created as practice items for each of the two stimulus sets per task. Practice stimuli were not selected with the same constraints as experimental
stimuli. The two stimulus sets were counterbalanced to appear as standard or tempo stimuli across participants.

Standard tasks were always presented before tempo tasks so that a robust baseline RT for the task could be established. In tempo tasks, the pace of the tempo was always 150 ms faster than the baseline average RT for correct trials in the standard task. In single word reading and picture naming tasks, baselines were calculated manually, trimming RT outliers by 2.5 standard deviations. In lexical and concreteness decision tasks, baselines were calculated by the experiment execution program. It was unclear whether the 150 ms baseline shift would impact lexical effects to the same extent in each task; however, the purpose of the baseline shift was not necessarily to create a consistent 150 ms speeding of responses but to increase pressure on the participant to respond compared to the environment of the typical RT task with instructions to respond.

For each version of the task, participants received a block of 20 practice trials followed by four blocks of stimuli. Stimuli were randomized within blocks. Participants were given a chance to rest briefly between blocks. During practice sessions for lexical decision and concreteness decision, participants were given feedback on accuracy and RT. During experimental sessions for lexical decision and concreteness decision, participants received RT feedback only. In the tempo versions of these tasks, practice and experimental RT feedback showed the difference between the time of the participant’s response and the ideal moment of response to their tempo, in milliseconds (ms). This provided a useful measure for how participants could correct their response timing during the task, as negative RTs indicated that the response was too quick and positive RTs indicated that the response was too slow. In single
word reading and picture naming practice, participants were coached on how to speak at a volume audible for the microphone and on how to adjust their speed to the tempo. The experimenter also let participants know during the breaks of these tasks whether they should speed or slow their responses relative to the tempo.

In lexical decision and concreteness decision tasks, the procedure was as follows. Participants were presented with a fixation cross for 250 ms, followed by a 250 ms blank interval, followed by stimulus presentation (regular or tempo). If the stimulus was not named within 3000 ms, the word disappeared from the screen. Otherwise, after responding the participant was shown RT feedback for the current trial for 1000 ms. Feedback was followed by a 250 ms inter-trial interval.

In single word reading and picture naming, the procedure was as follows. Participants were presented with a fixation cross for 250 ms, followed by a 250 ms blank interval, followed by stimulus presentation. If the stimulus was not named within 3000 ms, the item disappeared from the screen. Trials were advanced by an experimenter, who coded whether the response was correct, incorrect, or a voice key error. A response was considered a voice key error if any sound that was not a whole word was made into the microphone after the stimulus was presented and before uttering a complete, correct response. Trials with voice key errors and errors were not included in RT analyses, but trials with voice key errors were included as correct in accuracy analyses. After the trial was advanced, there was a 1000 ms inter-stimulus interval.

Tempo versions of all tasks included the following procedure for stimulus presentation: after fixation, a set of five flanker stimuli were presented along with a beep; then, the flanker stimuli disappeared one at a time in rhythm with the participant-specific tempo (150 ms faster
than their average speed); as the fifth beep sounded, the target stimulus was presented between the last pair of flankers; participants were asked to time their response to where the sixth beep would occur, which was also when the last pair of flankers disappeared. The timing of the tempo was such that the time interval between the stimulus presentation and the response was 150 ms faster than the participant’s average response time in the standard task version. An illustration of this process (after Kello & Plaut, 2000) is provided in Figure 3.1.

Figure 3.1 – Diagram of the course of events in a tempo word reading task (after Kello & Plaut, 2000). The course events was identical in each task, save that the response for each task was different.
3.2.3. Analyses

Stimuli were selected so that half of all stimuli fell above and below the median log SUBTLEX frequency, and so that half of stimuli within each of these halves fell above and below the median SemD value. However, it was not possible to match SemD across frequency categories and frequency across SemD categories because of the strong positive correlation between frequency and SemD. Therefore, to control for the correlation of frequency and SemD, frequency and SemD effects were simultaneous predictors using linear mixed effects models. In all RT analyses, I trimmed all RTs less than 200 ms and greater than 2.5 SDs above or below the mean RT by condition for each participant. RTs from incorrect trials or trials with voice key errors were discarded. In addition, participants with mean accuracy below 60% were excluded from analyses on that task and items with accuracy below 50% across participants were excluded.

Mixed effects models and generalized mixed effects models were analyzed with the lme4 package (Bates, Mächler, Bolker, & Walker, 2015), including random intercepts for participants and items. Fixed effects included task version (standard or tempo), stimulus set (A or B), log SUBTLEX word frequency, SemD (Hoffman et al., 2013), as well as word length in letters, concreteness, phonological neighborhood, and orthographic neighborhood as control variables. Fixed interaction effects included frequency x SemD, task version x frequency, task version x SemD, and task version x frequency x SemD. Control variables were included because they tend to show significant effects in many tasks in the database analyses above and tend to be correlated with the frequency and SemD effects of interest. Effect significance was evaluated using the R package lmerTest (Kuznetsova, Brockhoff, & Christensen, 2014).
Different research questions motivated running different mixed-effects models. One hypothesis was that the tempo manipulation should create patient-like effects in healthy participants. That is, because the tempo manipulation is claimed to impair cognitive control and patients with purported cognitive control deficits showed reduced word frequency effects (Hoffman et al., 2011, 2013), I predicted that word frequency effects would be reduced in participants due to the tempo task; furthermore, because controlling for SemD in patients with purported cognitive control deficits increased frequency effects, I predicted that controlling SemD should reduce changes in the frequency effect due to tempo in participants. A model including all the above-mentioned factors but SemD and interactions containing SemD was used to analyze whether the uncontrolled effect of frequency diminished due to the tempo manipulation. Models including the main effect of SemD but no interactions with SemD were used to assess whether the frequency effect did not diminish due to the tempo manipulation when SemD was controlled. The difference expected between these models would be that the task version x frequency interaction would be significant only when SemD was not controlled.

Another hypothesis was that the tempo version of more semantic tasks should recruit semantic control or some related executive ability which should impact SemD effects and their interaction with frequency. Thus, I ran larger models including all of the factors listed above and the crucial interactions listed, focusing on whether task version interacted with SemD or with the interaction between frequency and SemD. These models also helped us assess the input gain hypothesis, which stated that with the smaller time window of processing allowed in the tempo task all lexical effects, including frequency and SemD effects, should shrink, regardless of task. The current study’ focus for this hypothesis was whether the interactions between task version and either frequency or SemD indicated that effects shrank due to the tempo manipulation.
3.3. Results

3.3.1. Overall performance and tempo effects of tempo manipulation

A summary of participant performance is shown in Table 3.2 – Task RTs and errors by task version. In each task at least one item in each task showed accuracy < 50% across participants and was removed from analyses. Two participants performed with accuracy < 60% in concreteness decision and were removed from further analyses.
Participants were fastest at word naming, followed by lexical decision, picture naming and concreteness. The tempo task version sped performance and increased errors in all tasks ($p$'s < .001; see Table 3.3 – Mixed model coefficients and significance (RTs). and Table 3.4 – Mixed model coefficients and significance (errors).). Concreteness decisions showed the most speeding, followed by lexical decision, word reading, and picture naming. The tempo manipulation increased errors most in lexical decision (10%), whereas effects were similar (1-4% increase) across the remaining tasks. Thus, in all tasks, the tempo manipulation appears to have had the desired effect of increasing the pressure to respond.

Interestingly, the current study’s tempo effects in single word naming were much smaller than those observed by Kello and Plaut (2000) in the same task. Whereas Kello and Plaut found a
roughly 100 ms tempo effect with a 150 ms shifted tempo, the current study’s tempo effect was only 25 ms. In fact, standard task RTs were much faster on average for Kello and Plaut (~450 ms) than observed in the current study’s standard task (517 ms). These differences are most likely due to differences in stimulus characteristics across the studies: Kello and Plaut used only monosyllabic words, whereas the current study’s words were predominately two-syllable words; Kello and Plaut presented their words in lowercase, the current study in capitals. Both of these factors are likely to have slowed RTs in the current study’s word naming task.

3.3.2. Effects of tempo on SemD and frequency effects in RTs.

The current study’s primary concern was whether the tempo manipulation would impact lexical effects—particularly SemD effects, which should grow in semantic tasks according to the CSC hypothesis and shrink in all tasks according to the input gain hypothesis. The input gain hypothesis predicts that frequency effects should shrink in the tempo task compared to the standard task whereas the CSC approach predicts that frequency effects should not change, provided that they are uninfluenced by cognitive control.
### Table 3.3 – Mixed model coefficients and significance (RTs).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Word Reading</th>
<th>Lexical Decision</th>
<th>Concreteness Decision</th>
<th>Picture Naming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Version</td>
<td>-23.88***</td>
<td>-40.64***</td>
<td>-88.31***</td>
<td>-24.53***</td>
</tr>
<tr>
<td>Frequency</td>
<td>-6.92***</td>
<td>-23.3***</td>
<td>-18.04***</td>
<td>-11.61^</td>
</tr>
<tr>
<td>SemD</td>
<td>-3.9***</td>
<td>-1.02</td>
<td>0.59</td>
<td>6.26</td>
</tr>
<tr>
<td>Freq x SemD</td>
<td>2.6*</td>
<td>-5.75*</td>
<td>3.48</td>
<td>-4.7</td>
</tr>
<tr>
<td>Version x Freq</td>
<td>1.84</td>
<td>22.6***</td>
<td>35.83***</td>
<td>-6.77</td>
</tr>
<tr>
<td>Version x SemD</td>
<td>1.83</td>
<td>-3.81</td>
<td>-7.86^</td>
<td>1.36</td>
</tr>
<tr>
<td>Version x Freq x SemD</td>
<td>-1.69</td>
<td>6.56^</td>
<td>-8.75**</td>
<td>-3.42</td>
</tr>
</tbody>
</table>

***p < .001, **p < .01, *p < .05, ^p < .10. Main effect coefficients are from models with no interactions. Two-way interaction coefficients are from models with no three-way interaction.

### Table 3.4 – Mixed model coefficients and significance (errors).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Word Reading</th>
<th>Lexical Decision</th>
<th>Concreteness Decision</th>
<th>Picture Naming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Version</td>
<td>0.9***</td>
<td>1.06***</td>
<td>0.53***</td>
<td>1.04***</td>
</tr>
<tr>
<td>Frequency</td>
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<td>-0.53***</td>
<td>-0.27***</td>
<td>-0.12</td>
</tr>
<tr>
<td>SemD</td>
<td>-0.12</td>
<td>-0.13^</td>
<td>-0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Freq x SemD</td>
<td>0.08</td>
<td>-0.02</td>
<td>0.06</td>
<td>0.14</td>
</tr>
<tr>
<td>Version x Freq</td>
<td>-0.18</td>
<td>0.21**</td>
<td>0.01</td>
<td>-0.2</td>
</tr>
<tr>
<td>Version x SemD</td>
<td>0.14</td>
<td>0.16*</td>
<td>0.06</td>
<td>0.31*</td>
</tr>
<tr>
<td>Version x Freq x SemD</td>
<td>0.04</td>
<td>-0.11</td>
<td>-0.06</td>
<td>0.16</td>
</tr>
</tbody>
</table>

***p < .001, **p < .01, *p < .05, ^p < .10. Main effect coefficients are from models with no interactions. Two-way interaction coefficients are from models with no three-way interaction.
RT analyses revealed no significant interactions between task version (tempo vs. standard) and SemD. A marginally significant interaction between task version and SemD was found in concreteness decision ($\beta = -7.86$, $SE = 4.7$, $t = 1.67$, $p = .09$). Analysis of the SemD effect in the separate task versions revealed a non-significant, positive (detrimental) effect of SemD in the standard version ($\beta = 1.82$, $SE = 3.54$, $t = 0.52$, $p = .61$) and a non-significant, negative (beneficial) effect of SemD in the tempo version ($\beta = -0.64$, $SE = 1.45$, $t = 0.44$, $p = .66$). Thus, the trend of this interaction occurs in the opposite direction of that predicted by the CSC hypothesis (i.e., an increasing detriment). The pattern appears more consistent with the input gain hypothesis, with the size of a negative effect of SemD decreasing from the standard to the tempo version, though interpretation is clouded by the fact that SemD effects were not close to significance in either version.

A significant three-way interaction between task version, frequency, and SemD was observed concreteness decision ($\beta = -8.75$, $SE = 3.45$, $t = 2.62$, $p = .01$) and a marginal interaction was observed in lexical decision ($\beta = 6.56$, $SE = 3.35$, $t = 1.96$, $p = .05$), but all other three-way interactions were non-significant. The three-way interactions were examined by investigating the interaction of frequency and SemD separately in the standard and tempo task versions and by examining RTs predicted by the mixed model at different levels of frequency and SemD. Predictions were generated by the R package “effects” (Fox, 2003).

In the standard concreteness decision task, the interaction of frequency and SemD was small, positive, and non-significant ($\beta = 4.95$, $SE = 3.51$, $t = 1.41$, $p = .16$), and in the tempo concreteness decision task the interaction of frequency and SemD was small, negative, and non-significant ($\beta = -1.42$, $SE = 1.43$, $t = 0.99$, $p = .32$). As seen in Figure 3.2 – Interaction of task
version, frequency, and SemD in concreteness decision. Each graph represents the predicted RT at different levels of SemD in each task version for a certain frequency value, indicated in the grey box at the top of the graph as the number of standard deviations away from mean frequency. SemD effects in the standard version grew more detrimental as frequency increased, but SemD effects in the tempo version grew more beneficial as frequency increased.
Each graph represents the predicted RT at different levels of SemD in each task version for a certain frequency value, indicated in the grey box at the top of the graph as the number of standard deviations away from mean frequency.

In the standard lexical decision task, the interaction of frequency and SemD was significant and negative ($\beta = -8.93$, SE = 3.53, $t = 2.53$, $p = .01$), whereas the interaction in the tempo task was non-significant and near zero ($\beta = -0.09$, SE = 2.3, $t = 0.04$, $p = .97$). As seen in Figure 3.3 – *Interaction of task version, frequency, and SemD in lexical decision*. Each graph represents the predicted RT at different levels of SemD in each task version for a certain frequency value, indicated in the grey box at the top of the graph as the number of standard deviations away from mean frequency. SemD effects in the standard version grew from being detrimental for low frequency words to beneficial for high frequency words, whereas SemD
effects in the tempo version grew from having no effect to having a beneficial effect as frequency increased.

![Graph showing interaction of task version, frequency, and SemD in lexical decision.](image)

**Figure 3.3 – Interaction of task version, frequency, and SemD in lexical decision.**

Each graph represents the predicted RT at different levels of SemD in each task version for a certain frequency value, indicated in the grey box at the top of the graph as the number of standard deviations away from mean frequency.

These interactions do not suggest a trend supporting the CSC hypothesis, which predicted a larger, positive interaction in the tempo tasks compared to the standard task rather than the smaller interaction observed in the tempo task. The marginal interaction observed in lexical decision is consistent with the input gain hypothesis, which predicted that the interaction effect would shrink toward zero, but the interaction observed in concreteness decision is more
problematic. Simple effects did not reveal a significant interaction in either task version, but if the direction of the interaction truly reverses, this result cannot be accommodated by the input gain hypothesis.

Significant interactions were observed between task version and word frequency in lexical decision ($\beta = 22.6$, SE = 2.9, $t = 7.93$, $p < .001$) and concreteness decision ($\beta = 35.83$, SE = 4.5, $t = 7.97$, $p < .001$), but not in single word reading ($\beta = 1.84$, SE = 1.24, $t = 1.54$, $p = .14$) or picture naming ($\beta = -6.77$, SE = 4.59, $t = 1.48$, $p = .14$). The significant interactions revealed reduced frequency effects in the tempo compared to the standard task versions (see Figure 3.4 – Interaction of task version and frequency in lexical decision RTs. and Figure 3.5 – Interaction of task version and frequency in concreteness decision RTs.). All frequency effects in word reading, lexical decision, and concreteness decision were significant across standard and tempo task versions ($p$’s $< .001$), and in picture naming the effect was marginally significant ($p < .10$). The results for word reading are not consistent with those of Kello and Plaut (2000), who found that tempo reduced frequency effects in word reading. However, this is likely due to the fact that I found a much smaller reduction in RTs on the tempo version of word reading than did Kello and Plaut (2000), giving a much smaller window in which to find such input gain effects.
Figure 3.4 – Interaction of task version and frequency in lexical decision RTs.
Figure 3.5 – Interaction of task version and frequency in concreteness decision RTs.

The current study’s RT results provide little evidence for the CSC hypothesis but provide some support for the input gain hypothesis. Regarding the CSC hypothesis, no task showed the predicted exaggeration of SemD detriments or the interaction of frequency and SemD due to the tempo manipulation. Regarding the input gain hypothesis, frequency effects shrank in lexical decision and concreteness decision, where there were large enough tempo effects for these decreases to be detected. SemD effects, on the other hand, did not shrink toward zero in any case, contrary to the predictions of the input gain hypothesis. However, given the small size of
SemD effects here and in the database analyses relative to frequency effects, it could be that the current study did not have enough power to find decreased SemD effects.

3.3.3. Effects of tempo on SemD and frequency effects in errors.

Error analyses revealed that the three-way interaction of version x frequency x SemD failed to reach significance for any of the tasks. This result is contrary to the predictions of the Controlled Semantic Cognition hypothesis, which holds that increasing the detriment of SemD (through disruption of executive control) should impact the size of word frequency effects.

Significant two-way interactions of task version and SemD were obtained in both lexical decision ($\beta = 0.16$, $SE = 0.07$, $t = 2.24$, $p = .03$) and picture naming ($\beta = 0.31$, $SE = 0.13$, $t = 2.34$, $p = .02$). As is evident in Figure 3.6 – Interaction of task version and SemD in lexical decision errors., there was a negative (beneficial) effect of SemD in both tasks versions of lexical decision, but the size of the effect was greater in the standard version ($\beta = -0.26$, $SE = 0.1$, $t = 2.59$, $p = .01$) than in the tempo version ($\beta = -0.08$, $SE = 0.07$, $t = 1.08$, $p = .28$). As shown in Figure 3.7 – Interaction of task version and SemD in picture naming errors., picture naming showed a slight beneficial effect of SemD in the standard task ($\beta = -0.1$, $SE = 0.17$, $t = 0.61$, $p = .54$) and a slight detrimental effect of SemD in the tempo task ($\beta = 0.15$, $SE = 0.14$, $t = 1.05$, $p = .29$). Both of these interactions indicate a decreased benefit of SemD in tempo conditions, which was most evident for high SemD items. In picture naming, the simple main effects analysis suggests a reversed effect of SemD in the tempo task, which is consistent with the prediction of the CSC hypothesis that tempo should increase the detriment of SemD on processing. However, the fact that tempo moves SemD effects in the same direction for these lexical decision and picture naming, which seem to require different levels of access to semantic
representations, is not consistent with the CSC hypothesis. Also, it is unclear why lexical
decision and picture naming were affected by the tempo manipulation but concreteness decision,
which also involves semantic processing, did not. Potential explanations are discussed below.
Figure 3.6 – Interaction of task version and SemD in lexical decision errors.
Only lexical decision showed a significant interaction of task version and frequency ($\beta = 0.21$, SE = 0.08, $t = 2.66$, $p = .01$) (see Figure 3.8 – Interaction of task version and frequency in lexical decision errors.). Analysis of the frequency effect in the separate task versions revealed significant benefits of frequency in both versions, with the benefit decreasing from standard ($\beta = -0.75$, SE = 0.1, $t = 7.55$, $p < .001$) to tempo versions ($\beta = -0.45$, SE = 0.07, $t = 6.58$, $p < .001$). This interaction, like the parallel interaction in RTs, revealed a decreasing benefit of frequency in the tempo task.

Figure 3.7 – Interaction of task version and SemD in picture naming errors.
Figure 3.8 – Interaction of task version and frequency in lexical decision errors.

The error results do not support the CSC hypothesis: picture naming showed a trend toward a growing detriment of SemD due to the tempo manipulation, but SemD effects in lexical decision went in the same direction, contrary to the prediction that lexical decision should not require access to a specific semantic representation. Furthermore, concreteness decision did not show the predicted increase in detrimental effects of SemD with the tempo manipulation.

The fact that the tempo manipulation decreased frequency effects in lexical decision independent of SemD is problematic for the CSC hypothesis, as it suggests that impairment of controlled processing can impact frequency effects independent of SemD. This result suggests
that patients who have control deficits might be expected to show reduced frequency effects regardless of the impact of SemD (Hoffman et al., 2011, 2013).

3.3.4. Does controlling SemD reveal stronger word frequency effects?

Because the tempo manipulation was intended to affect controlled processing, I also predicted based on the study of Hodgson and Lambon Ralph (2008) that the tempo task would create in healthy participants an absence (or reduction) of frequency effects like that reported for patients purported to have semantic control deficits. This should mean that the tempo task would reduce word frequency effects compared to the standard task before controlling for SemD, but after controlling for SemD frequency effects should look similar between the two tasks.

In RTs, before controlling for SemD, lexical decision and concreteness decision showed significant task version x word frequency interactions (p’s < .001), word naming showed a marginal interaction (p < .10), and picture naming showed no interaction. In errors, only lexical decision showed this interaction before controlling for SemD (p < .05). These significant interactions all show frequency effects that decrease from the standard to tempo task versions. However, contrary to the predictions of the CSC hypothesis, all of these interactions remained significant and nearly identical in size after controlling for SemD (see Table 3.5 – Task Version x Frequency Interactions in RTs and errors.). These results are not consistent with the predictions of the CSC literature. That is, Hodgson and Lambon Ralph (2008) claimed that the tempo manipulation should stress cognitive control, and Hoffman et al. (2011, 2013) claimed that cognitive control abilities mediate the relationship between word frequency and SemD effects, insofar as cognitive control is used to resolve competition created by high SemD. Because the impact of tempo on frequency effect remained virtually unchanged—and in no case
diminished—after controlling for SemD, it is clear that the predictions of the CSC literature relative to the tempo manipulation are incorrect.

If the tempo manipulation is truly a manipulation of cognitive control, then these results are problematic for the claims of Hoffman et al. (2011), as they suggest that the absent frequency effects reported for semantic aphasia patients may have been observed independent of the influence of SemD. The results of that study were the basis for believing that semantic control is called into play due to selection pressures created by SemD. The current study’s results provide reasons to believe that SemD may not be the source of these pressures. It is possible that the tempo task shrunk frequency effects not due to cognitive control demands but simply due to the deadline it imposed on processing—RT-based effects tend to shrink given a smaller time window in which to perform a task (e.g., Stanovich & Pachella, 1976). However, the results of Balota et al. (2002) and Hodgson and Lambon Ralph (2008) suggest that tempo manipulations may impact controlled processing, lending credence to the theory that cognitive control may impact frequency effects. Furthermore, analysis of the SPP in Chapter 2 showed evidence for this theory, indicating a relationship between frequency effects and executive function in word reading.
Table 3.5 – Task Version x Frequency Interactions in RTs and errors.

<table>
<thead>
<tr>
<th>Task</th>
<th>Without SemD</th>
<th>With SemD</th>
<th>Without SemD</th>
<th>With SemD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Word Reading</td>
<td>2.28^</td>
<td>2.2^</td>
<td>-0.153</td>
<td>-0.149</td>
</tr>
<tr>
<td>Lexical Decision</td>
<td>21.65***</td>
<td>21.84***</td>
<td>0.213**</td>
<td>0.219**</td>
</tr>
<tr>
<td>Concreteness Decision</td>
<td>21.6***</td>
<td>21.6***</td>
<td>0.027</td>
<td>0.027</td>
</tr>
<tr>
<td>Picture Naming</td>
<td>-6.41</td>
<td>-6.4</td>
<td>-0.075</td>
<td>-0.075</td>
</tr>
</tbody>
</table>

***p < .001, **p < .01, *p < .05, ^p < .10.

3.4. Discussion

In this study, I investigated the predictions of two hypotheses. First, the CSC hypothesis predicted that if the tempo manipulation taps an executive control mechanism, healthy participants should show performance like aphasic patients claimed to have semantic control deficits in the tempo version of tasks that require access to a specific semantic representation but not in other tasks. Accordingly, they were predicted to show increased detrimental effects of SemD, a strengthened interaction of frequency and SemD, and decreased frequency effects only when SemD was left uncontrolled. Second, the input gain hypothesis claimed that when a task is performed under speeded tempo conditions, the timeline of cognitive processing in that task would necessarily be compressed compared to the standard version of the task. This hypothesis predicts that, because the timeline of processing is compressed, any lexical effects observed in RTs that typically occur within a certain response time window would necessarily shrink when that response time window shrinks. In the current study, therefore, frequency and SemD effects were predicted to shrink in the tempo compared to the standard task version. The current study’s
results are problematic for the CSC hypothesis but provide some support for the input gain hypothesis. In the following discussion, I address how the results impact each theory.

3.4.1. Implications for the Controlled Semantic Cognition hypothesis

The current study’s results provide evidence against the CSC hypothesis that SemD creates competition in semantic tasks that is resolved by a cognitive control mechanism in healthy individuals. This claim was fundamentally based on the relationship between word frequency and SemD, as frequency effects were claimed to be diminished in semantic aphasia patients only because of high semantic control demands created by high SemD words (Hoffman et al., 2013; Hoffman et al., 2011). However, I found that manipulating cognitive control—in a way claimed by a previous study to tap semantic control (Hodgson & Lambon Ralph, 2008)—decreased frequency effects in healthy participants in several tasks independent of SemD. In fact, controlling SemD had little to no impact on how the tempo manipulation changed frequency effects. These results suggest that cognitive control impacted frequency effects in previous studies independently of SemD.

If this were the case, why did Hoffman, Rogers, Lambon Ralph (2011) observe frequency effects in semantic aphasia patients in a synonym judgment task only after controlling for SemD? This previous result was used to claim that patient deficits were related to effects of SemD. However, because healthy older adults show the same lexical effects as patients in RTs of the same task (Hoffman et al., 2013), it is not clear that patients’ lexical effects were necessarily related to their cognitive deficits. Theoretically, these observed effects would be apparent in errors in any case where errors were increased sufficiently and deficits did not directly impact the mechanisms underlying those effects. Furthermore, it is not clear that the patients in these
previous studies had deficits of semantic control, as recent work has suggested that establishing such a deficit independently of a semantic representation deficit is extremely difficult (Chapman & Martin, submitted).

The current study’s results show that tempo impacted SemD effects in both lexical decision and picture naming errors. These SemD effects move qualitatively in the same direction: increasing tempo decreases the benefit of high SemD. In the case of picture naming, a benefit of high SemD becomes a detriment of high SemD. Because these effects occur without a significant three-way interaction with frequency, it appears that the mechanism affected by the tempo manipulation is not the one underlying the frequency x SemD interaction observed in the database analyses reported in the first section and thus that the relationship between frequency and SemD is not mediated by an attentional or executive mechanism. This conclusion is inconsistent with the CSC hypothesis. The impact of the tempo manipulation on SemD effects also does not depend on whether a task requires access to a specific representation, as lexical decision showed a task version x SemD interaction and does not necessarily require access to a specific semantic representation. Previous studies have suggested that these minimal semantic requirements are the reason that benefits of high SemD are seen in lexical decision as opposed to detrimental SemD effects in a task requiring more specific semantic access, such as meaning relatedness comparison (Hoffman & Woollams, 2015). This result too is incompatible with the claims of the CSC hypothesis.

However, it remains likely, given that the tempo manipulation is claimed to be an attentional/executive one and that SemD effects were impacted by tempo in several tasks, that SemD effects are moderated by an attentional/executive mechanism. Because tempo affects high
SemD items more than low SemD items, it seems reasonable that the role of this attentional/executive mechanism is similar to the one posited for semantic control by the CSC hypothesis, albeit not dependent on accessing a specific semantic representation. That is, an attentional/executive mechanism may help to distinguish relevant from irrelevant semantic information related to a word, and this may be required more for high than low SemD items.

Results from the current experiment further suggest that the degree to which this mechanism is involved in resolving non-useful activation created by high SemD words is not affected by word frequency. Thus, the mechanism creating the robustly observed interactions in the database analyses above cannot be synonymous with the attention/executive mechanism manipulated here. This conclusion is consistent with the database results from the SPP (Semantic Priming Project), in which I observed an interaction between an executive component, word frequency, and SemD in lexical decision. That interaction indicated that executive function most affected processing of low SemD items, as opposed to the effects in the current study, which seem to affect high SemD items. The difference in effects of executive function in the SPP and tempo effects in the current study could also be due to the priming task recruiting different attentional/executive resources than do the tempo tasks.

If the tempo manipulation does not tap semantic control but only some more general executive or attentional processing, then several phenomena associated with semantic control must be related instead to more domain-general executive processes. Hodgson and Lambon Ralph (2008) claimed that tempo picture naming created similar phenomena in healthy participants to those found in semantic control patients: increased semantic errors and increased effects of detrimental phonemic cues. However, if these phenomena relate to more domain-general control processes, then they should not be associated with the more domain-specific
mechanism of semantic control. This conclusion would suggest that increased semantic errors and increased effects of detrimental phonemic cues, both of which may be related to domain general attention/executive mechanisms rather than a specifically semantic mechanism, should not be used to distinguish semantic control deficits from semantic representation deficits, as has been done in previous studies (Jefferies & Lambon Ralph, 2006; Jefferies, Patterson, & Lambon Ralph, 2008). The fact that these phenomena cannot be considered semantic is consistent with evidence that one may not clearly distinguish deficits of semantic representations and semantic access (Chapman and Martin, 2017, submitted).

One problem with concluding that the attentional/executive mechanism manipulated in the tempo tasks is generally useful in resolving competition from unnecessary semantic activation is that tempo did not interact with SemD in the concreteness decision task. On the surface, it is not clear why this should be the case, given that concreteness decision certainly involves semantic processing. Some studies have suggested that abstract and concrete words rely on different kinds of processing (Crutch & Warrington, 2005; Paivio, 1991) rather than relying to different degrees on a single mechanism (e.g., retrieval of sensory features), and other studies have shown that abstract and concrete words activate separable brain networks (Binder, Westbury, McKiernan, Possing, & Medler, 2005; Kounios & Holcomb, 1994). Thus, it is possible that differences in SemD effects across concrete and abstract words in the concreteness decision task nullified any impact tempo might have had on SemD effects. I investigated this possibility by modeling concreteness decision separately for concrete and abstract words, predicting that the task version x SemD interaction would differ across word concreteness. In RTs for concrete words, tempo decreased a detrimental effect of high SemD, whereas no interaction was found for abstract words. In errors for abstract words, tempo marginally
decreased a beneficial effect of high SemD, whereas no interaction was found for concrete words. While both RTs and errors showed one analysis without a significant interaction, the signs of the task version x SemD interactions were the same in both analyses for concrete words and both interactions for abstract words. Thus, for RTs and errors, tempo appeared to have opposing SemD effects for abstract and concrete words that likely masked the effect of tempo on SemD effects.

3.4.2. Implications for the input gain hypothesis

The current study’s results provide some support for the input gain hypothesis, though only two tasks, lexical decision and concreteness decision, showed large enough tempo effects to expect serious impacts of tempo on lexical variables. I found that both lexical decision and concreteness decision showed diminished word frequency effects due to the tempo manipulation. Problematically for the input gain hypothesis, SemD effects in lexical decision and concreteness decision were not impacted by the tempo manipulation. However, given the small, nonsignificant effects of SemD observed in these tasks and the fact that SemD effects were generally much smaller than frequency effects in the database analysis of section one, it is likely that the experiment did not have the power to detect the impact of the tempo manipulation on SemD effects.

Although Kello and Plaut (2000) found relatively large tempo effects in single word reading when their tempo was speeded 150 ms relative to baseline performance (~100 ms), the current study found only a much smaller tempo effect in the same task (25 ms). There are several possible reasons for this result: Kello and Plaut used only monosyllabic words, whereas the current study’s words were predominately two-syllable words; Kello and Plaut presented their
words in lowercase, the current study in capitals; Kello and Plaut used only 39 stimuli in each tempo condition, while the current study used 300 in the single tempo condition; and Kello and Plaut employed different tempos across blocks, whereas the current study used only a single tempo. It is unclear which of these differences may have caused the disparity in tempo effects and why it would have had such an effect.

The input gain hypothesis made no direct predictions about interactions between lexical attributes changing due to the tempo manipulation; however, it follows that if two lexical effects were to shrink due to the tempo manipulation that an interaction between them would also shrink. That is, if frequency effects typically shrink as SemD increases, then smaller frequency effects will have less room to shrink in the tempo task, creating a smaller interaction. The tempo manipulation impacted the interaction of frequency and SemD in concreteness decision, but the interaction appears to have reversed rather than simply shrinking. However, the simple effects do not show that the reversed effect is significant, leaving open the possibility that tempo merely shrank the interaction effect.

Considering the uncertainty of the observed SemD effects and interactions in concreteness decision, one should be cautious in the interpretation of these results. Nevertheless, they tentatively support the predictions of the input gain hypothesis—that is, that the tempo task reflects an increased sensitivity to the characteristics of incoming stimuli wherein decisions are made in a compressed time frame that compresses lexical effects. Because this study only included tempo and non-tempo conditions, it is impossible to rule out the possibility that shrinking frequency effects in RTs are the result of a speed-accuracy tradeoff (e.g., Pachella & Pew, 1968). As mentioned above, RT-based effects tend to shrink when the time window in
which they take place has shrunk. A speed-accuracy tradeoff may therefore explain the results as well as the input gain hypothesis without further evidence.

Unfortunately, it is impossible to interpret the error results in light of the input gain hypothesis, as it makes no predictions on error differences due to stimulus qualities such as frequency and SemD. To account for error effects, one must turn to alternative theories.

3.4.3. Alternative accounts

Existing language processing models may assist in understanding the observed tempo effects in the current study beyond the frames of the CSC hypothesis and the input gain hypothesis. One such model is a diffusion model, some versions of which have been used to analyze visual word recognition (Ratcliff, 1978; Ratcliff, Gomez, & McKoon, 2004). These models could account for the current study’s results in lexical decision and concreteness decision. Diffusion models account for reaction time and accuracy in tasks requiring a dichotomous decision by assuming an accumulation of noisy information over time that leads toward one of two decision criteria. In diffusion models, the mean rate at which information is accumulated is called “drift rate”, and this parameter has been shown across several studies to relate to frequency in visual word recognition, with higher drift rates for high frequency words (Ratcliff et al., 2004; Yap, Balota, Cortese, & Watson, 2006). Theoretically, drift rate should be affected by any lexical quality that informs the decision process (Ratcliff et al., 2004), which should include SemD. Another parameter of the model, boundary separation, represents the caution with which a decision is taken, with larger boundary separation indicating more caution. Because boundary separation is usually manipulated via speed-accuracy instructions (Matzke & Wagenmakers, 2009; Ratcliff et al., 2004), one may suppose that the tempo manipulation would
reflect a manipulation of boundary separation, with the tempo task requiring a smaller boundary separation in order to respond in time with the tempo.

Interestingly, a diffusion model would predict the shrinking lexical effects observed in the lexical decision and concreteness decision whether drift rate or boundary separation were manipulated. Reducing boundary separation or increasing drift rate would compress the RT distribution of, for example, high frequency and low frequency words and reduce the distance between them (see Ratcliff et al., 2004, Figure 2B). Likewise, increasing the drift rate would lead to a smaller difference in errors to high frequency and low frequency words. A diffusion model would also predict shrinking frequency effects in RTs and errors if boundary separation were decreased. In RTs, the same compression of RT distributions would occur as if the drift rate were increased. In errors, because the drift rate of high frequency words is hypothesized to be higher than that for low frequency words, high frequency words would be more likely than low frequency words to have accumulated evidence toward the correct response when boundary separation is reduced (as in the tempo task), leading to fewer errors for high than low frequency words.

The same predictions applied to frequency effects should also apply to high and low SemD, with high SemD likely increasing drift rate/decreasing boundary separation in lexical decision (leading to faster and more accurate responses) and decreasing drift rate/increasing boundary separation in concreteness decision (leading to slower and more errorful responses). Such predictions would be undermined, though, if the SemD effect in concreteness decision RTs truly reverses from a detrimental to a beneficial effect, as the simple main effects analyses suggested could be the case. Unfortunately, diffusion model accounts do not readily explain
tasks that do not involve a dichotomous choice—namely, single word reading and picture naming.

The predictions of diffusion models concerning the locus of the tempo effect are interestingly related to the input gain hypothesis. The input gain hypothesis, which claims that the tempo task is performed by increasing one’s sensitivity to incoming stimuli, would predict that tempo effects are related to increased drift rate in the diffusion model, as the input gain hypothesis suggests that tempo should cause quicker accumulation of information toward a decision—a phenomenon that should be captured by drift rate. The diffusion model shows a benefit over the input gain hypothesis in that it predicts—and the input gain hypothesis does not—that error rates will differ for words varying along certain lexical dimensions (e.g., frequency). Furthermore, diffusion models, as mentioned above, would predict that speed changes would be reflected in boundary separation, so future work could arbitrate between these two accounts of the tempo manipulation by investigating where effects of the tempo manipulation are reflected when its results are processed with a diffusion model.

Another model that could account for the current study’s results in lexical decision is the hybrid two-stage model of lexical decision performance (Balota & Chumbley, 1984; Balota & Spieler, 1999). This model claims that lexical decision may be performed with two types of information: a fast-acting familiarity-based signal, and a slower, attention-demanding signal for exploring aspects of the word (e.g., spelling) in memory. In this model, words and non-words are conceived as reflecting two underlying distributions along a familiarity-meaningfulness (FM) dimension. Because low frequency words are more likely to overlap with non-words on the FM
continuum, they are more likely to require the slow, attention-demanding process than are high frequency words, which are more likely to only require the fast, familiarity-based process.

While this model has not been discussed with reference to standard vs. speeded tasks, one may predict that speeded lexical decision would affect high and low frequency words differently in this model due to the disparity of slow processing requirements it posits for low vs. high frequency words. As participants are forced to speed their processing, the fast-familiarity based processing more common to high frequency words may sometimes lead to errors, but the slow search-based processing more common to low frequency words should be more compromised, leading to many more errors. Likewise, the fast familiarity process may have little room to speed further, but the slow search process may be sped up quite a bit, causing the tempo manipulation to decrease the frequency effect in RTs. Therefore, the current study’s frequency effect results in lexical decision are consistent with the two-stage model. For this model to apply to results for SemD, I would need to posit that high SemD words are more likely to require the slow, search-based process than low SemD words, as tempo appears to affect high SemD more than low SemD words in lexical decision. Such a proposal would be similar to the proposal that high SemD words require a higher degree of semantic control (Hoffman et al., 2011), although semantic control is typically associated with access to a specific semantic representation and it is not clear that this is required in lexical decision.

One way to empirically investigate whether the current results are consistent with the hybrid two-stage lexical decision model would be to use ex-Gaussian measures of response time distributions in standard and tempo lexical decision. The ex-Gaussian distribution is a convolution of a Gaussian and an exponential distribution that can be used to quantify RT
distributions beyond using only their means. Previous studies have associated the Gaussian portion (μ) of the RT distribution in lexical decision with the fast familiarity process of the two-stage theory and the exponential portion (τ) of the RT distribution with the slow search process (Balota & Spieler, 1999). If one were to find that the change in frequency effects from standard to tempo tasks was most associated with the τ parameter of the RT distribution, this would provide support for the two-stage model as an explanation of the current study’s results.

Interestingly, the τ parameter has also been associated with executive processing in previous studies (Shao, Roelofs, & Meyer, 2012) and with word frequency effects (Balota & Spieler, 1999; Yap et al., 2006; Yap, Balota, & Tan, 2013), consistent with the finding in the database analysis of the SPP in Chapter 2, where frequency effects in word naming and the word frequency x SemD interaction in lexical decision related to the executive component in word naming. Thus, finding that the effects of the tempo manipulation were related to τ parameter would support the notion that the tempo task is tapping some domain-general executive process.

Predictions regarding altered lexical effects due to speeded processing in language production—represented in this study by single word reading and picture naming—are not obviously built into prominent models of language production in that they do not provide motivation to expect a speeded task to affect different levels of a lexical variable differently. For example, the language production model of Levelt, Roelofs, and Meyer (1999) incorporates word frequency in the time to verify a selected phonological representation, but there is no clear reason why increasing the speed of processing should affect these verification times differently for words with different frequencies. The interactive two-step model of language production (Dell, Schwartz, Saffran, Martin, & Gagnon, 1997) does not implement frequency but may provide clear motivation for detrimental effects of SemD. That is, the model allows for
cascading, interactive activation that spreads from semantic to lexical information. If semantic activation spread from the target lexical representation back to contextually-related semantic information, this would in turn activate non-target lexical representations that might compete with the target for selection, slowing processing for higher SemD words. A similar kind of competition is thought to create aphasic patients’ speech errors when they are both semantically and phonologically related to the target (Schwartz, Dell, Martin, Gahl, & Sobel, 2006). However, this prediction of detrimental SemD effects is not borne out by the database analyses above, which showed beneficial effects of high SemD in both single word reading and object picture naming.

### 3.4.4. Limitations

One may argue that the tasks employed in the current study were not ideal for exploring effects of cognitive control because, unlike the synonym judgment task of Hoffman et al. (2011, 2013) or the meaning relatedness judgment task of Hoffman and Woollams (2015), the current study’s tasks did not necessarily require access to a specific semantic representation or were not likely to create high levels of competition in semantic selection. Previous studies claim that detrimental effects of SemD should arise from the need to access a specific semantic representation (Hoffman & Woollams, 2015; Hoffman et al., 2011, 2013) and thus may not have predicted that these tasks should have shown any relationship between cognitive control and SemD. That is, single word reading and lexical decision do not necessarily require accessing a specific semantic representation to perform the task; concreteness decision may require only recognition that physical features of a representation are activated rather than requiring selection of a specific representation from among activated information; and picture naming, while clearly
requiring access to a specific semantic representation, may not require semantic control to
distinguish relevant from irrelevant semantic information, given that the correct semantic
information should be consistently activated by the picture. Such criticisms could also be lodged
against the findings from Chapter 2, which used the same tasks.

These arguments against the tasks employed in the current study are not particularly
concerning for a few reasons. Foremost is the fact that relationships between cognitive control
and lexical effects in these tasks were found, both in the SPP in Chapter 2 and in relation to the
tempo manipulation in the current study. The executive factor in the SPP was associated with
frequency effects in word reading errors and with the frequency x SemD interaction in lexical
decision errors; tempo in the current study interacted with frequency effects in RTs and errors of
some tasks, SemD error effects in others, and the frequency x SemD effect of concreteness
decision RTs. One cannot argue that cognitive control is unlikely to be involved in these tasks,
given that evidence was found for its involvement. Another reason these tasks should be
considered as legitimate for exploring effects of cognitive control is that each of them showed
detrimental effects of high SemD in the analyses of Chapter 2—the very effects for which
cognitive control was argued to be responsible. While these detrimental effects of SemD tended
to only be found for items with higher frequency, one should still be able to detect any
relationship between cognitive control and these detrimental effects.

3.5. Conclusions

This study investigated whether controlled processing is necessary for resolving semantic
competition created by high SemD in semantic tasks and whether the manipulation of task tempo
impacts lexical effects due to controlled processing and/or due to a compressed processing window created by increasing one’s sensitivity to incoming stimuli. The results provide no evidence that controlled processing—at least the kind manipulated in this study—helps to resolve competition created by high SemD, but they do support the input gain hypothesis that lexical effects may be compressed in the tempo manipulation due to the compressed time frame in which processing occurs. Several of the current study’s results could also be explained by a diffusion model or the two-stage model of lexical decision, however shifting effects of SemD in picture naming are harder to accommodate with the available theories.
Summary, Conclusions, and Future Directions

3.6. Summary

In this dissertation, I investigated the role of semantic diversity (SemD) in language processing—specifically, whether SemD effects are separable from frequency effects, whether SemD creates competition among activated semantic representations, and whether SemD effects are mediated by executive/attentional mechanisms. In Chapter 2, I analyzed effects of SemD, word frequency and their interaction in a broad set of language tasks and in both healthy and aphasic populations. Nearly all models showed benefits of word frequency and SemD, with SemD effects being much weaker than word frequency effects. In healthy individuals, I observed a robust interaction between frequency and SemD in single word reading, lexical decision, concreteness decision, and object naming; in aphasic patients, the same interaction was found in object naming and word repetition tasks. All interactions indicated that high SemD was detrimental for high frequency words but beneficial for low frequency words. These interactions suggest that frequency and SemD have distinct effects and that SemD induces competition for high frequency words but not low frequency words. It is unlikely that this competition takes place at a semantic level of processing, as the size or direction of the interaction was not
influenced by task semantic requirements in healthy individuals and was not altered by the presence of a multi-modal semantic comprehension deficit in aphasic patients. Furthermore, the resolution of this competition is unlikely to relate to domain-general executive function, as individual differences in executive ability did not influence the size of the detrimental effects of SemD for high frequency words in the semantic priming project.

Chapter 3 further explored whether competitive effects of SemD were related to executive or attentional control by manipulating controlled processing in a set of language processing tasks with varying semantic demands. This experiment showed that reducing cognitive control in lexical decision and picture naming increases errors more for high SemD than low SemD items and, in concreteness decision RTs, changes a detriment of high SemD for high frequency items into a benefit. Like the results of Chapter 2’s database analyses, these results provide little support for the claim that the relationship between frequency and SemD—particularly the detrimental effects of SemD for high frequency words—are mediated by controlled processing. However, these results do support a relationship between controlled processing and SemD independent of word frequency, with reduced control tending to reduce benefits of high SemD.

In sum, these two investigations provide new insight into the influence of SemD on language processing. The complex relationship between SemD and frequency was previously unexplored, though it is consistent with studies showing that opposing effects of semantic richness may be present within a single task (Mirman & Magnuson, 2008; Rabovsky, Schad, & Rahman, 2016). Furthermore, my results provide additional evidence that high SemD may create competition in language processing, though this competition is unlikely to take place at the
semantic level and more likely to occur at the lexical or phonological level. My results also add to previous findings that opposing effects of SemD seem to occur generally across single word processing tasks. Furthermore, I have presented novel evidence that executive/attentional control is related to effects of SemD, though in an unexpected fashion—better executive/attentional control creates a larger advantage of high SemD for low frequency items.

3.7. Future Directions

Future research may clarify the source of the opposing effects of high SemD for high and low word frequency. Opposing effects were observed, but the precise cause of the effects is not obvious. I have proposed that frequency may scale activation of associated information—that high SemD is beneficial when the weak activation of associated information (i.e., from low frequency) is not sufficient to cause competition but supports the target representation and high SemD is detrimental when strong activation of associated information (i.e., from high frequency) causes non-target representations to strongly compete with the target representation. One useful tool for investigating whether this dynamic is feasible would be to examine what components are needed in a computational model to be able to generate such effects. Furthermore, computational models could provide proof of whether a single mechanism is sufficient to generate both effects or whether multiple mechanisms are required to explain SemD effects. Further investigations of semantic priming could provide converging evidence on whether higher prime frequency tends to create stronger priming than lower prime frequency. One might also hypothesize that higher SemD would lead to worse priming than lower SemD for related prime-target pairs, given that the activated target would have more competition for words with higher SemD.
Future research may also serve to clarify precisely how executive/attentional control may facilitate word processing. Computational modeling may also provide useful insights on this topic. It may be that a mechanism like the activation booster of the “dark side” speech production model may be used more or less effectively based on one’s available executive/attentional resources (Oppenheim, Dell, & Schwartz, 2010). If the mechanism that facilitates word processing is the same as the mechanism that resolves response conflict, one may hypothesize that it is a left frontal retrieval mechanism like that suggested by the work of Schnur, Thompson-Schill and colleagues across multiple studies (Harvey & Schnur, 2015; Schnur et al., 2009; Thompson-Schill et al., 1997). The left inferior frontal gyrus (LIFG) has been associated with semantic and lexical selection through tasks such as cyclic picture naming of semantically similar compared to semantically unrelated items (e.g., Schnur et al., 2009), and semantic tasks with high vs. low selection pressures (see Thompson-Schill et al., 1997).

Future work can also investigate the extent to which these effects can be seen in tasks requiring comprehension or production of more than a single word, such as sentence reading and sentence comprehension. For example, some studies have shown faster reading times for words with high contextual diversity (Plummer, Perea, & Rayner, 2014), and it may be that the interaction observed in the current study could be observed when words are read in the context of a larger passage—that SemD effects depend only on whether single words are being processed. However, given that sentences tend to constrain the contextual meaning of words, it is possible that SemD’s effects will vanish—activation may not spread to contextually related meaning information when the meaning of a semantically diverse word is contextually constrained.
Other behavioral executive/attentional manipulations could be carried out to confirm that such a mechanism is related to SemD effects. The difficulty manipulation of Armstrong and Plaut (2016) may qualify as an executive/attentional manipulation. They manipulated how word-like their nonwords were in a visual lexical decision task, both by manipulating their positional bigram frequency and by whether nonwords were pseudohomophones. Arguably, as nonwords become more word-like participants have to focus their attention more strongly on the task of discriminating nonwords from words. Thus, as nonwords become more word-like one would predict that attention would be strained and we would see effects similar to those observed in tempo lexical decision in Chapter 3: decreasing benefit of SemD in errors, and a decreased interaction between frequency and SemD in RTs.

3.8. Conclusion

While 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 to assess more precisely contextual diversity in a manner that is separate from frequency, and recent research has begun to reveal that measures of semantic richness such as contextual diversity show complex and important influences on word processing. The present research contributes to this literature by showing some surprising effects of semantic diversity. Future work will help to sort out the source of the interaction of word frequency and semantic diversity
and the possible role of any general executive abilities or more specific semantic control abilities in this pattern of interaction.


Brysbaert, M., Warriner, A. B., & Kuperman, V. (2014). Concreteness ratings for 40 thousand generally known English word lemmas. *Behav. Res. Methods, 46*(3), 904-911.


Appendix

ELP Word Reading

Figure A.1 – Median split lexical effects in ELP word reading.
Figure A.2 – Median split lexical effects in SPP word reading.
Figure A.3 – Median split lexical effects in ELP lexical decision.
Figure A.4 – Median split lexical effects in BLP lexical decision.
Figure A.5 – Median split lexical effects in SPP lexical decision.
Figure A.6 – Median split lexical effects in CSDP concreteness decision.
Figure A.7 – Median split lexical effects in IPNP object naming.

Figure A.8 – Median split lexical effects in the errors of MAPPD tasks.