Frequency Drives Lexical Access in Reading but not in Speaking: The Frequency-Lag Hypothesis

Tamar H. Gollan[a]

Timothy J. Slattery[a]

Diane Goldenberg[a]

Eva van Assche[b]

Wouter Duyck[b]

Keith Rayner[a]

[a]University of California, San Diego, USA

[b]Ghent University, Ghent, Belgium

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Corresponding author:

Tamar H. Gollan
Department of Psychiatry
9500 Gilman Drive, 0949
La Jolla, CA 92093-0949
e-mail: *tgollan@ucsd.edu*

Abstract

To contrast mechanisms of lexical access in production versus comprehension we compared the effects of word-frequency (high, low), context (none, low-constraining, high-constraining), and level of English proficiency (monolinguals, Spanish-English bilinguals, Dutch-English bilinguals), on picture naming, lexical decision, and eye fixation times. Semantic constraint effects were larger in production than in reading. Frequency effects were larger in production than in reading without constraining context, but larger in reading than in production with constraining context. Bilingual disadvantages were modulated by frequency in production but not in eye fixation times, were not smaller in low-constraining context, and were reduced by high-constraining context only in production and only at the lowest level of English proficiency. These results challenge existing accounts of bilingual disadvantages, and reveal fundamentally different processes during lexical access across modalities, entailing a primarily semantically driven search in production, but a frequency driven search in comprehension. The apparently more interactive process in production than comprehension could simply reflect a greater number of frequency-sensitive processing stages in production.

Language users have a strong intuition that words refer to the same thing whether they are being perceived or produced. This is particularly true for a given individual – each time you say *apple*, hear someone say *apple,* or read the word *apple*, it's likely that many of the same basic concepts come to mind (e.g., a sweet, crunchy, fruit). Of course an important piece of what makes communication through language possible is that words generally refer to more or less the same thing, regardless of who is producing or perceiving them. So imagine a conversation in which you say "*Do we have any apples?*" and your friend says "*Therez lots of apples in the fridge*," the *apple* that you spoke of and the *apple* your friend mentioned brought the same basic ideas to your mind and that of your friend's. Although conceptual overlap between people (and uses) is not always 100%, which leads to occasional miscommunications and sometimes disappointment (e.g., if you find a green apple when you were hoping for a red one), most of the time there is sufficient overlap for communication to succeed. These observations highlight the common goal in perceived and produced word use: to communicate meaning, regardless of modality (speaking, listening, writing, or reading).

There are some striking parallels between language production and comprehension. However, historically, researchers of language processing have divided themselves into those who study production and those who study comprehension. This division is not necessarily problematic in that similar (or different) conclusions may be reached independently. However, a complete understanding of language use will eventually require at least some direct comparisons of comprehension and production. For example, on one view there are intimate connections between comprehension and production as they occur in dialogue, perhaps the most basic and natural form of language use (Pickering & Garrod, 2004), which necessarily involves rapid transition between production and comprehension. To the extent that common mechanisms are revealed in comprehension and production, this would facilitate such exchanges. On the other hand, differences that arise would need to be accommodated within any theoretical view of alignment between comprehension and production. Similarly, one intriguing and oft-cited theory proposes intimate connections between comprehension and production; in the motor-theory of speech perception (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman & Mattingly, 1985) speech is perceived via top-down synthesis through the production system. Going in the other direction, some critics of the motor-theory have instead argued the reverse; in the sensory-theory of speech production, sensory representations of speech guide production (Lotto, Hickok, & Holt, 2009; Venezia & Hickock, 2009). Extreme versions of these proposals would posit that production and comprehension share the same representations and processes, and would need to be modified to accommodate any differences observed between modalities.

Similarities between comprehension and production: One obvious similarity between comprehension and production is that both processes exhibit robust frequency effects, such that words that are used frequently are processed more quickly than words that are not used as often (e.g., Forster & Chambers, 1973; Oldfield & Wingfield, 1965; Rayner & Duffy, 1986). In both comprehension and production the relationship between counts of frequency and access time is logarithmic, such that small increases in frequency of use at the low end of the use scale have large effects on lexical access time but negligible effects beyond a certain high frequency count. That is, frequency effects seem to be subject to a ceiling (see also below) after which increased uses have little further effect on lexical accessibility (e.g., Griffin & Bock, 1998; Howes & Solomon, 1951). A possibly related finding is that in both comprehension and production, repetition sometimes affects low-frequency words relatively more than high-frequency words (e.g., Griffin & Bock, 1998; Scarborough, Cortese, & Scarborough, 1977; Oldfield & Wingfield, 1965; Rayner & Raney, 1986; though note that frequency effects are usually not eliminated by repetition: Forster & Davis, 1984; Jescheniak & Levelt, 1994; Navarette, Basagni, Alario, & Costa, 2006; but see Griffin & Bock, 1998; Rayner & Raney, 1986). Frequency effects are often viewed as the signature of lexical access in both comprehension and production (e.g., Almeida, Knobel, Finkbeiner, & Caramazza, 2007; Caramazza, 1997; Dell, 1990; Forster & Chambers, 1973; Graves, Grabowski, Mehta, & Gordon, 2007; Levelt, Roelofs, & Meyer, 1999; Rayner, 1998, 2009; Rubenstein, Garfield, & Millikan, 1970), although the locus of the frequency effect has been rigorously debated in both comprehension (e.g., Murray & Forster, 2004) and production (e.g., Jescheniak & Levelt, 1994; see Knobel, Finkbeiner, & Caramazza, 2008, who suggest that frequency likely affects multiple processing stages in production, and Kittredge, Dell, Verkuilen, & Schwartz, 2008 for evidence to this effect).

Another factor that affects comprehension and production similarly is context. Words that occur in highly constraining or predictable contexts (e.g., *Snow White took a bite of a poisonous APPLE*) are recognized/read and produced more quickly (Fischler & Bloom, 1979; Stanovitch & West, 1979; Tulving & Gold, 1963; Griffin & Bock, 1998; Ehrlich & Rayner, 1981; Rayner & Well, 1996) than when they occur in a more neutral context (e.g., *The photographer took a picture of a large APPLE).* Early research on the effects of context on the processing of ambiguous words (with more than one meaning) in comprehension revealed that both meanings are accessed initially, with effects of context arising only at a later processing stage (Swinney, 1979). In these studies, participants listened to constraining sentences like *The man was not surprised when he found several spiders, roaches, and other bugs in the corner of his room.* As they listened they were probed early (e.g., at *bug*), and later in the sentence, for recognition of words related to both meanings of *bug* (insects, and spy-related). Initially, participants were faster to respond to words related to both meanings of ambiguous words (relative to unrelated words), whereas later on, facilitation was only observed for context relevant meanings of the ambiguous word. This implies initial access to all word meanings, but also that context led participants to suppress the irrelevant meaning by the end of the sentence (though the appropriate meaning can be selected very quickly and, for ambiguous words with one highly dominant meaning, access may not be exhaustive; Duffy, Morris, & Rayner, 1987; Rayner & Duffy, 1986; see also Gernsbacher & Faust, 1991). Language production studies also revealed some evidence for exhaustive access to both meanings of ambiguous words. For example, speakers produce low-frequency words more quickly if there is a higher frequency homophone neighbor (e.g., a picture of a *bee* is named more quickly than a picture of an object with a frequency-matched name that does not have a high-frequency counter-part *be*; e.g., Jescheniak & Levelt, 1994; but see Caramazza, Costa, Miozzo, & Bi, 2001). Similarly, speakers benefit from the distractor *dance* when trying to name a picture of a toy *ball* because *dance* activates the Cinderella type of *ball*, which facilitates access to the sounds needed to produce the name *ball* (Cutting & Ferreira, 1999).

Differences between comprehension and production. Despite the similarities between comprehension and production, there are both theoretical and empirical reasons to expect differences between them, starting with the distinct nature of the access problem in the two modalities. In comprehension, individual words must be distinguished from form similar neighbors to identify the correct meaning and this must often be done with an incomplete/noisy signal. Contrastingly, in production highly specific representations of meaning activate lexical candidates that must be selected among meaning-related candidates. Thus, in production, lexical access is guided by meaning (and syntactic class) and ends with the identification of a lexical form, whereas in comprehension the process is reversed, going from lexical forms to semantics. Consequently, an ideal organizational scheme for the mental lexicon in comprehension would not work very efficiently in production, and vice versa (Fay & Cutler, 1977).

One subfield in the literature on language processing that has adhered somewhat less to the traditional division of investigators into those who study comprehension versus those who study production is cognitive neuropsychology. Within this domain, there is some powerful evidence that separate systems serve comprehension and production (Rapp, 2001). The approach taken here is one of detailed investigation of the pattern of preserved versus impaired abilities in single-case studies of individuals with cognitive impairment. With this approach, the functional architecture of the normal cognitive system is revealed through in-depth analysis of cognitive deficits and attempts to identify the locus (or loci) of impairment in well-articulated language processing models. To identify the nature of a deficit, it is necessary to examine performance in every modality of input and output and at multiple levels of processing and representation (e.g., sublexical, lexical, and semantic). The theoretical assumptions inherent to this approach are that the cognitive architecture is the same across individuals, that both the functional and anatomical (brain) architecture are modular to at least some degree, and that brain damage does not introduce new compensatory mechanisms that did not exist prior to brain damage (Coltheart, 2001). In this literature, double dissociations between modalities have been identified. These were apparent in the classical distinction between Broca's and Wernicke's aphasia, but also in more recently identified and specific deficits, for instance with patients who experience problems when writing but not reading and vice versa, or difficulties understanding spoken but not written words despite intact auditory acuity (for a review, see Hillis, 2001). The dissociations observed in this literature imply separate systems for comprehension and production, as well as separate lexicons (and access) for each modality (speaking, writing, reading, and listening; Caramazza, 1997). This type of architecture may not be very economical, but it is not the most conceivable extreme; the line is drawn at the level of meaning where it is assumed that the different modalities ultimately contact a shared semantic system (i.e., the notion of modality-specific semantics is not supported; Shelton & Caramazza, 2001).

Other evidence for distinct processes of lexical access in comprehension versus production concerns the fact that form-related neighbors (i.e., neighborhood density) consistently facilitate access in production but sometimes delay access in comprehension (Dell & Gordon, 2003; Slattery, 2009; for review see Andrews, 1997). Conversely, semantically related words facilitate comprehension (for review see Neely, 1991), but function like competitors, and delay lexical access, in production (e.g., Lupker, 1979; Schriefers, Meyer, & Levelt, 1990; but see Mahon, Costa, Peterson, Vargas, & Caramazza, 2007). Such differences have led some to conclude that distinct representations of lexical form serve comprehension and production (e.g., Zwitserlood, 2003; Roelofs, 2003), with one set serving as the end-point for production processes and the other as the point-of-entry for comprehension. In this view, comprehension and production overlap only at the level of meaning. Although some models do posit a second amodal layer of lexical representations, this level of representation would subserve lexical access itself only in production, not in comprehension (Levelt et al., 1999).

Interactions between frequency and constraint. Interestingly, both in comprehension (Forster & Chambers, 1973; Murray & Forster, 2004; Rayner, 1998; Reichle, Pollatsek, Fisher, & Rayner, 1998) and production (Jescheniak & Levelt, 1994; Levelt et al., 1999) it has been assumed that frequency effects arise primarily at the point where lexical forms are accessed.

Thus, even if separate form-lexicons might serve comprehension and production, both are considered to be sensitive to frequency. Moreover, it has been debated in both comprehension and production research whether processing stages during lexical access are interactive or discrete. And, in both fields, a number of investigators have considered the joint effects of frequency and constraint as a means to decide between models (with interactions supporting interactivity and a lack of interactions supporting seriality). The logic behind this was that frequency and semantic constraint effects should not interact if (a) lexical access proceeds in discrete stages and (b) frequency and semantic constraint effects arise in different processing stages.

The placement of frequency effects at the locus of retrieving lexical forms necessarily separates frequency from constraint effects in both comprehension and production. This is because forms will be accessed relatively late in production, after resolution of competition between semantically related candidates, but early in comprehension, which necessarily begins with the analysis of lexical form and meaning as the endpoint of the process. On the other hand, frequency effects might not be limited to the point of accessing lexical forms (e.g., if retrieval of lexical-semantics were also frequency-sensitive), in which case interactions could arise without interactivity. Thus, the locus or loci of the frequency effect itself in the two modalities could be another source of apparent differences between them.

Some of the studies that investigated constraint and frequency effects reported interactions between them such that low-frequency targets benefited more from constraining context than high-frequency targets (e.g., Griffin & Bock, 1998; Stanovitch & West, 1979; Van Petten & Kutas, 1990). However, others studies found no interaction, particularly in the literatures on written word recognition and reading, where constraining context affected low- and high-frequency words equally (e.g., Forster, 1981; Rayner, Ashby, Pollatsek, & Reichle, 2004). The identification of an interaction between frequency and constraint in production, but not in comprehension, raises the possibility that mechanisms of lexical access interact more with top-down factors in production than in comprehension, or that access to lexical-semantics (where constraint effects could operate) is frequency sensitive for production but not comprehension (this could entail separate lexical-semantic representations for comprehension and production, or just differently weighted connections to lexical-semantic representations; frequency-sensitive going from concepts in but not frequency-sensitive going from lexical-form representations in). However, to date only one study has investigated this interaction in production (e.g., Griffin & Bock, 1998), and no study has compared production and comprehension directly. Thus, the apparent difference between production and comprehension could instead reflect cross-study differences between materials, tasks, and participants, or some combination of these.

Constraint, frequency, and bilingual effects. Constraint and frequency have also figured prominently in the literature on bilingual language processing (another subfield of psycholinguistics which exhibits a less obvious division of researchers into those who study comprehension versus production). A widely accepted assumption in models of bilingual language processing is that bilinguals cannot shut off one language completely to effectively function like monolinguals (e.g., Dijkstra & van Heuven, 2002; Hermans, Bongaerts, de Bot, & Schreuder, 1998; Duyck, Van Assche, Drieghe, & Hartsuiker, 2007; Van Assche, Duyck, Hartsuiker, & Diependaele, 2009; for reviews see Costa, 2005; Kroll, Bobb, Misra, & Guo, 2008; La Heij, 2005; Sebastián-Gallés & Kroll, 2003). The presence of dual-language activation could place bilinguals at a disadvantage when compared to monolinguals, particularly in the domain of language production, where a single language must be chosen for response, so that translation equivalents could function as competitors. Some evidence to support this notion is that bilinguals exhibit small but significant disadvantages relative to monolinguals on a number of production tasks including reduced category fluency (e.g., Gollan, Montoya, & Werner, 2002; Rosselli et al., 2000), higher rates of tip-of-the-tongue state retrieval failures (e.g., Gollan & Silverberg, 2001), slower picture naming times (e.g., Gollan, Montoya, Fennema-Notestine, & Morris, 2005; Ivanova & Costa, 2008), and slower sentence production times (Mackay & Flege, 2004). Similar bilingual disadvantages have been reported in language comprehension tasks such as lexical decision (e.g., Ransdell & Fischler, 1987). Some have suggested that semantically constraining context can reduce the extent to which both languages are active (Schwartz & Kroll, 2006), at least during later stages of word comprehension (Libben & Titone, 2009; but see Van Assche, Drieghe, Duyck, Welvaert & Hartsuiker, in press, for cross-lingual interactions with a high-constraint context during all stages of word comprehension). The proposal that bilinguals effectively function like monolinguals in semantically constraining context leads to the prediction that bilingual disadvantages should be reduced under such conditions. Taking this same logic a step further, the bilingual disadvantage might even be reduced in neutral context relative to no context (e.g., picture naming of objects in isolation) if monolingual context of any kind (e.g., a unilingual sentence) can serve to reduce dual-language activation. These predictions are based on the assumption that dual-language activation leads bilinguals to respond more slowly than monolinguals.

An additional cause of bilingual disadvantages might reflect a simpler and emergent property of frequency effects and patterns of bilingual language use. By virtue of using each language only part of the time, bilinguals have used word forms particular to each language relatively less frequently than monolinguals – i.e., bilingualism entails a frequency-lag (Gollan & Silverberg, 2001; Gollan et al., 2002; Gollan et al., 2005; Gollan, Montoya, Cera, & Sandoval, 2008; Sandoval, Gollan, Ferreira, & Salmon, 2010; for similar ideas see Ivanova & Costa, 2008; Lehtonen, & Laine, 2003; Mägiste, 1979; Nicoladis, Palmer, & Marentette, 2007; Pearson et al., 1997; Ransdell & Fischler, 1987). Supporting this account, the bilingual disadvantage is especially large for retrieval of low-frequency words, whereas little or no bilingual disadvantage is found for production of high-frequency words. Similarly, slowing related to language dominance is particularly large for retrieval of low-frequency words in both comprehension (Duyck, Vanderelst, Desmet, & Hartsuiker, 2008) and production (Gollan et al., 2008; but see Ivanova & Costa, 2008). In this view, lexical representations evolve towards ceiling-level, stable end states, and the monolingual lexicon is closer to these ceiling levels of lexical accessibility than the bilingual lexicon (for further explanation, see Gollan et al., 2008; Murray & Forster, 2004). As language use and proficiency increases, low-frequency words begin to catch-up with high-frequency words in levels of activation, and frequency effects should become smaller.

Thus, (a) monolinguals exhibit smaller frequency effects than bilinguals tested in their dominant language, and (b) bilinguals exhibit smaller frequency effects when tested in their dominant language than in their nondominant language. On this frequency-lag (a.k.a. the "weaker links"; Gollan et al., 2008) hypothesis, bilingual disadvantages should become smaller only where frequency effects also become smaller. For example, the bilingual disadvantage might be reduced with semantic constraint only for production (in which frequency effects are reduced with semantic constraint), but not in comprehension (if frequency effects remain unchanged in semantically constraining context). On the other hand, if bilingual disadvantages are reduced by manipulations that have no influence on the frequency effect, then this would imply that something other than a frequency lag causes the bilingual disadvantage.

To summarize, there are reasons to expect both similarities and differences between the processes of lexical access in comprehension and production. Further considering these similarities and differences seems likely to advance both specific fields, and there are some informative discussions along these lines in the literature (Fay & Cutler, 1977; Garrett, 2001; Hillis, 2001; Jurafsky, 2003; Schiller & Meyer, 2003; Treiman, Clifton, Meyer, & Wurm, 2003). However, the almost complete separation between production and recognition research has precluded a direct empirical comparison of comprehension and production in psycholinguistic research (for a noteworthy exception, see a recent fMRI study revealing shared brain regions for processing meaning across modalities; Awad, Warren, Scott, Turkheimer, & Wise, 2007). In the present study, we therefore considered the joint effects of frequency, contextual constraint, and bilingualism on production (picture naming) and comprehension (reading and lexical decision), with the goal of distinguishing processes that are modality specific from those that are general to language processing. Because there have been far fewer attempts to investigate interactions between frequency and constraint in language production than in comprehension, we begin with production using a picture naming task (Experiment 1). Subsequently, we use the same materials (only substituting words for pictures) to investigate the effects of frequency, constraint, and language proficiency in visual word recognition, operationalized though lexical decision and eyetracking during reading (Experiment 2). We then end with direct comparisons of the observed effects across modalities (comparison of Experiments 1 and 2).

In both Experiments 1 and 2, our primary goal was to test for an interaction between frequency and constraint, and to determine whether the pattern of results observed generalizes to processing at all levels of proficiency. From the perspective of the frequency-lag hypothesis, the manipulation of English proficiency level effectively functions like a tool that allows a between participants manipulation of frequency. That is, if bilinguals use lexical forms less frequently than monolinguals, then this provides an additional opportunity to test for interactions with constraint in both comprehension and production. Based on the frequency-lag hypothesis, we predicted that bilingual effects might resemble frequency effects (e.g., interacting with constraint only in production and not in comprehension), especially at the lowest level of English-proficiency where the frequency of use difference between bilinguals and monolinguals is greatest. A secondary goal was to explore the nature of the bilingual disadvantage, investigating whether it occurs in both comprehension and production, and whether it is reduced by semantically constraining or neutral context.

Experiment 1 – Picture Naming

Methods

Participants

Fifty monolingual English speakers, 50 Spanish-English bilinguals, and 45 Dutch-English bilinguals participated. Monolinguals and Spanish-English bilinguals were undergraduates at the University of California, San Diego and received course credit for their participation, Dutch-English bilinguals were undergraduates at Ghent University in Belgium and either received course credit or were paid for their participation[1]. These three groups of participants were chosen

[1] Note that Belgium consists of a Dutch-speaking community and a smaller French-speaking community. The present participants belong to the first group and are late Dutch-English bilinguals, as they are exposed to English through popular media (music, television, movies, internet, etc.), and receive formal instruction in school on the English language starting from age fourteen.

for their expected three-tiered levels of relative English proficiency with the highest English-proficiency in monolinguals, followed by English-dominant Spanish-English bilinguals, and the relatively lowest level of English proficiency in the Dutch-dominant Dutch-English bilingual group. Spanish-English bilinguals were expected to have a higher level of English proficiency than Dutch-English bilinguals because of their relatively earlier age-of-acquisition (AoA) of English and their years of immersion in an English speaking environment. Conversely Spanish-English bilinguals were expected to have a lower level of English proficiency than monolinguals because of their relatively later AoA of English and their relatively reduced use of English relative to monolinguals (Gollan, et al., 2008). Participants completed a language history questionnaire in which they provided subjective ratings of language proficiency, and as objective measures of English proficiency participants were administered a 40 item multiple choice vocabulary test (Shipley, 1946). Table 1 displays a summary of the participant characteristics.

Materials

Table 2 contains a summary of the materials' characteristics. A list of 45 pairs of high- and low-frequency names of objects was constructed using a standard frequency corpus (Davies, 2007). High- and low-frequency name pairs differed maximally in frequency count while being matched for number of letters and initial phoneme (e.g., for every *apple* an *arrow*). The pictures were black- and-white line drawings produced by an artist who was instructed to make the drawings as simple as she could to elicit the target names. Pictures with names that could not be easily depicted with a simple line drawing were replaced. The HF and LF targets were not matched for codability but we tried as much as possible to select targets with just one name. An estimate of codability can be obtained by counting the number of alternative correct names that speakers produced (e.g., *skates* and *ice skates*, *statue* and *Statue of Liberty*, *basket* and *picnic* *basket*). Virtually all items had between 0- 2 alternative names. About 2/3 of the items in both frequency groups had no alternative names. The average number of alternative names was slightly higher for LF than for HF names but this difference was not significant (p=.33 for monolinguals, p=.13 for Spanish-English, and p=.09 for Dutch-English bilinguals). A slight difference between HF and LF targets emerged when considering the proportion of cases that speakers actually used an alternative name (instead of the experimentally intended target name). For HF targets this occurred just over 1% of the time, but for LF targets it was about 4% of the time (small but significant differences for all speaker groups; *ps* =.03 for monolinguals and Spanish-English bilinguals, p=.05 for Dutch-English). Ten of the target names (5 high and 5 low-frequency) were cognates in Spanish and English (e.g., *paper* is *papel* in Spanish), and forty-one (22 high and 19 low-frequency) were cognates in Dutch and English (e.g., *apple* is *appel* in Dutch) [2]. For each target a highly-constraining and low-constraining sentence context was created. Highly constraining sentences were designed to strongly elicit the target word (e.g., *Snow White ate a poisoned* ______), whereas low constraining sentences were designed to be congruent with the target completion, while also allowing many other possible completions (e.g., *The artist painted the bowl and the* _______). To determine the extent to which sentences created contexts that were high- versus low- constraining, 20 undergraduates at UCSD who did not participate in the experiment, were asked to provide one-word completions for each sentence

[2] The greater number of cognates with Dutch reflects the fact that these languages are more similar (both Germanic), and would reduce to some extent the degree to which Dutch-English bilinguals would be disadvantaged given that cognates are easier for bilinguals to produce (e.g., Costa, Caramazza, & Sebastián-Gallés, 2000). Although we did not manipulate Dutch-English cognate status in our materials we considered whether some of the effects of greatest interest might be modulated by cognate status or not (e.g., the frequency by constraint interaction in Experiments 1 and 2) and found no evidence for any influence of cognate status.

(target completions for high-constraint sentences were produced over 85% of the time, and for low-constraint sentences less than or equal to 3% of the time; see Table 2). Sentences that were not high- or low-constraining were replaced and re-normed with 20 additional undergraduates who did also not participate in the experiment. Highly constraining sentences were slightly longer than low-constraining sentences but length did not differ across the frequency contrast (both *p*s $\geq .24$). High- and low-frequency pairs were divided into three lists of 15 pairs (thus each list contained 30 targets, of which 15 were high-frequent, 15 low-frequent).

Procedure

Each participant completed all three lists but in only one of each of the three conditions (no context, low-constraining context, high-constraining context). Participants saw each picture only once. Assignment of material list to experimental condition was counterbalanced such that each of the three lists was presented in each of the three conditions a roughly equal number of times between participants. The no-context condition was presented separately from the context condition, and the two context conditions were presented together with low-constraining and high-constraining sentences. The order of testing with versus without context was counterbalanced across participants, and materials were presented in a different random order for each participant.

The materials were presented using PsyScope 1.2.5 on a 17-in. monitor Macintosh computer for the monolinguals and Spanish-English bilinguals, and using E-Prime 2.0 for the Dutch-English bilinguals. Care was taken to ensure that stimulus characteristics (e.g., color, resolution, and picture sizes) were identical across labs. Participants wore headset microphones, which recorded naming response times and responses were audio-taped for later verification of accuracy. Participants were instructed to name pictures as quickly and accurately as possible. An experimenter was present throughout the experiment to record responses and the accuracy of voice key triggers.

In the no-context condition, trials began with a central fixation point (‘+’) that was presented for 500 ms and followed by a picture in a 6 x 6 cm area in the center of the computer screen. The picture disappeared once the voice key was triggered. A blank screen was presented for 1.5 s between trials. Participants initiated subsequent trials by pressing the spacebar.

In the context conditions, participants were instructed to silently read the sentences that were presented one word at a time using self-paced visual presentation. Words appeared in the center of the screen and participants pressed the spacebar to move from one word to the next so that each word replaced the previous word in the center of the screen. At the end of each sentence, a picture of an object that was meant to complete the sentence appeared and participants were instructed to name the pictures as quickly and accurately as possible. Pictures remained on the screen until the voice key was triggered. The next trial began 1.5 s later. To encourage participants to pay attention to the sentences, the word “REMEMBER” appeared on the screen after the voice key was triggered on 6 of the 60 trials. Three high-constraint and 3 low-constraint sentences were pre-selected for this purpose. At the prompt, participants were asked to recall the sentence aloud and the experimenter noted the accuracy. These responses were coded as exact or close which were counted as correct, or as incorrect; the rate of correct responses was about 80% or higher in both Experiments 1 and 2, for all participant groups.

Results

Reaction times (RT) under 250 ms and over 5,000 ms were excluded from analyses. In addition, mean RTs were calculated for each participant collapsed across condition, and RTs more than 2.5 SDs above each participant’s mean were excluded from analyses. These trimming procedures excluded 2.2% of the monolinguals', 2.6% of the Spanish-English bilinguals', and 2.1% of the Dutch-English bilinguals' correct and valid RTs. In anticipation of comparisons of the data to those reported in Experiment 2 (see below) the no-context mean correct response RTs were analyzed separately in a 2 x 3 ANOVA with frequency (high, low), as repeated measures factor in the participants analyses, and group (monolingual, Spanish-English, Dutch-English) as a repeated factor in the items analyses. The in-context data were submitted to a 2 x 2 x 3 ANOVA with frequency (high, low) and constraint (high, low) as repeated measures factors, and group (monolingual, Spanish-English, Dutch-English) as a between participants factor in the participants analyses (*F1*). In the items analyses (*F*2) constraint and group were repeated measures factors, and frequency was between items. There were five items (*braid*, *faucet*, *skunk*, *stool*, and *truck*) with missing data points (naming errors) in the no-context and low-constraining context conditions for Dutch-English bilinguals, and 1 item with missing data for Spanish-English bilinguals in the low-constraint condition (which is consistent with the expected relative English proficiency of these two groups). Thus, the degrees of freedom vary slightly from the 2 x 2 x 3 to the 2 x 3 ANOVAs reported below depending on the number of items available for each analysis. The results are shown in Figure 1 (see also summary of results from both Experiments 1 and 2 shown in Table 4).

Picture Naming Out-of-Context: Speakers named pictures with high-frequency names faster than pictures with low-frequency names [$F1(1,142) = 74.65$, $MSE = 16{,}917$, $\eta_p^2 = .35$, $p < .01$; $F2(1,83) = 11.41$, $MSE = 135{,}065$, $\eta_p^2 = .12$, $p < .01$], and monolinguals named pictures more quickly than bilinguals [$F1(2,142) = 33.42$, $MSE = 63{,}213$, $\eta_p^2 = .32$, $p < .01$; $F2(1,83) = 105.92$, $MSE = 263{,}879$, $\eta_p^2 = .56$, $p < .01$]. As previously reported for out-of-context picture naming (Gollan et al., 2008; Ivanova & Costa, 2008), bilinguals exhibited significantly larger frequency effects than monolinguals, [$F1(2,142) = 6.99$, $MSE = 16{,}917$, $\eta_p^2 = .09$, $p < .01$; $F2(1,83) = 5.71$, $MSE = 46{,}183$ $\eta_p^2 = .06$, $p = .02$]. Additionally, the finding of greater frequency effects in bilinguals than monolinguals was robust for both bilingual groups. Spanish-English bilinguals exhibited a greater frequency effect than monolinguals [$F1(1,98) = 6.06$, $MSE = 7{,}301$, $\eta_p^2 = .06$, $p = .02$; $F2(1,88) = 4.47$, $MSE = 10{,}282$ $\eta_p^2 = .05$, $p = .04$], and the frequency effect was even larger in Dutch-English bilinguals who exhibited a marginally greater frequency effect than that seen in Spanish-English bilinguals [$F1(1,93) = 3.41$, $MSE = 23{,}071$, $\eta_p^2 = .04$, $p = .07$; $F2(1,85) = 2.65$, $MSE = 41{,}459$ $\eta_p^2 = .03$, $p = .11$].

Error analyses for picture naming out of context exhibited a similar pattern of results as the RT data with robust main effects of frequency and group (all *p*s < .01), and robust interactions between frequency and group (both *ps* < .01; excluding Dutch-English bilinguals, this interaction was just marginally significant; $p = .11$).

Picture Naming In Context: Speakers named pictures with high-frequency names faster than pictures with low-frequency names [$F1(1,142) = 138.17$, $MSE = 12{,}902$, $\eta_p^2 = .49$, $p < .01$; $F2(1,85) = 12.62$, $MSE = 145{,}862$, $\eta_p^2 = .13$, $p < .01$], and more quickly in high-constraining than in low-constraining context [$F1(1,142) = 478.14$, $MSE = 18{,}997$, $\eta_p^2 = .77$, $p < .01$; $F2(1,85) = 143.05$, $MSE = 69{,}847$, $\eta_p^2 = .63$, $p < .01$]. In addition, monolinguals named pictures faster than bilinguals [$F1(2,142) = 20.80$, $MSE = 120{,}294$, $\eta_p^2 = .23$, $p < .01$; $F2(1,85) = 105.47$, $MSE = 55{,}368$, $\eta_p^2 = .55$, $p < .01$].

As previously reported for monolingual picture naming (Griffin & Bock, 1998), frequency effects were smaller in highly constraining context than in low-constraining context, [$F1(1,142) = 41.87$, $MSE = 7{,}050$, $\eta_p^2 = .23$, $p < .01$; $F2(1,85) = 3.91$, $MSE = 69{,}847$ $\eta_p^2 = .04$, $p = .05$]. In addition, this interaction was not driven by one participant group; monolinguals ($p = .02$), and both bilingual groups (both *ps* $< .01$) exhibited a significant interaction between frequency and constraint (some of these planned comparisons were just marginally significant by F2; see Table 4). As found in out-of-context naming, slowing related to bilingualism was significantly greater in production of low-frequency than high-frequency picture names; that is, bilinguals exhibited significantly larger frequency effects than monolinguals [$F1(2,142) = 16.92$, $MSE = 12{,}902$, $\eta_p^2 = .19$, $p < .01$; $F2(1,85) = 7.03$, $MSE = 55{,}368$ $\eta_p^2 = .08$, $p = .01$], mainly due to slower responses for pictures with low-frequency names. This interaction was primarily driven by the low-constraining context in which Spanish-English bilinguals exhibited a greater frequency effect than monolinguals [though in context this was only significant by participants; $F1(1,98) = 4.67$, $MSE = 5{,}998$, $\eta_p^2 = .04$, $p = .04$; $F2 < 1$], and Dutch-English bilinguals exhibited an even greater frequency effect – significantly greater than that seen in Spanish-English bilinguals [$F1(1,93) = 17.44$, $MSE = 13{,}981$, $\eta_p^2 = .16$, $p < .01$; $F2(1,85) = 4.43$, $MSE = 74{,}408$ $\eta_p^2 = .05$, $p = .05$]. In high-constraining context Spanish-English bilinguals did not exhibit greater frequency effects than monolinguals (both *p*s $\geq .25$), and Dutch-English bilinguals did not exhibit a greater frequency effect than Spanish-English bilinguals (both *p*s $\geq .12$). Thus, both frequency effects and the bilingual disadvantage were modulated by context as would be expected on a frequency-lag account.

Considering bilingualism as a kind of frequency manipulation, there was some indication that bilinguals benefited more from constraint than monolinguals [$F1(2,142) = 3.16$, $MSE = 18{,}997$, $\eta_p^2 = .04$, $p = .045$; $F2(1,85) = 4.86$, $MSE = 45{,}670$, $\eta_p^2 = .05$, $p = .03$], and this interaction was driven by Dutch-English bilinguals' responses to low-frequency words; the interaction between constraint and participant group was no longer significant when the Dutch-English bilinguals were excluded from the analysis; both *p*s $\geq .20$]. There was also some evidence for a three-way interaction between frequency, constraint, and participant type, [significant only by participants [$F1(2,142) = 6.23$, $MSE = 7{,}050$, $\eta_p^2 = .08$, $p < .01$; $F2(1,85) = 1.31$, $MSE = 45{,}670$ $\eta_p^2 = .02$, $p = .26$] such that bilinguals at the very lowest level of English proficiency benefited more from semantic constraint than monolinguals. These results are generally consistent with the frequency-lag account (in that both frequency effects and the bilingual disadvantage were attenuated by constraining context).

The error data exhibited a similar pattern of results as the RT data. There were robust main effects of frequency, constraint, and group (all *p*s < .01), and robust interactions between frequency and group (both *ps* < .01) that remained significant after excluding the Dutch-English bilinguals (both *ps* ≤ .03). None of the other 2-way interactions were, nor was the 3-way interaction, significant in the error data.

To constrain the interference account of bilingual disadvantages, we asked whether context alone (low semantic constraint) was sufficient to reduce the bilingual disadvantage. To this end, we compared out-of-context (bare picture naming) to low-constraining context naming responses in two analyses (Spanish-English bilinguals versus monolinguals, and Dutch-English bilinguals versus monolinguals). As reported above, there were main effects of frequency, and group (all *p*s < .01). In addition, there was a main effect of context such that response times were slower following sentence context relative to out-of-context naming (all *p*s ≤ .01), possibly reflecting ongoing contextual sentence analysis during the process of picture naming. However, there was no indication that low-constraining context affected Spanish-English bilinguals to a greater extent than monolinguals, and also no differential effect of context on Dutch-English bilinguals compared to monolinguals (all *F*s < 1). Thus, it appears that semantic constraint (not just sentence context in the target language) is needed to reduce the disadvantage associated with processing a second and non-dominant language.

Discussion

To summarize the results of Experiment 1, picture naming times exhibited robust main effects of frequency, constraint, and bilingual status. Also, these effects interacted, such that speakers accessed low-frequency names more slowly than high-frequency names particularly in out-of-context or low-constraining context (replicating Griffin & Bock, 1998). An additional finding in Experiment 1, which could be taken as further support for the notion of an interaction between frequency and constraint (assuming second-language use entails a frequency-lag), was that Dutch-English bilinguals benefited more than monolinguals from highly constraining semantic context. Consistent with the notion of a frequency lag for bilinguals in production, slowing related to bilingualism (Spanish-English bilinguals versus monolinguals) and second-language production (Dutch-English bilinguals versus monolinguals) was greater for producing low-frequency than high-frequency names, again particularly in low-constraining and out of context picture naming (replicating and extending Gollan et al., 2008). Moreover, the presence of low-constraining semantic context alone was not sufficient to reduce the bilingual disadvantage (i.e., low relative to no-context). Thus, context influenced the bilingual disadvantage only where it also reduced frequency effects a result that is consistent with the frequency-lag account.

The finding that semantically constraining context reduced both frequency effects and slowing related to second language production supports the proposal of an overlapping locus for the effects of (a) frequency, (b) bilingual disadvantages, and (c) language dominance. Two previous picture naming studies compared frequency effects between monolinguals and bilinguals in their dominant language, and within bilinguals between their dominant and nondominant languages. In both cases bilinguals exhibited a larger frequency effect than monolinguals when tested in their dominant language (Gollan et al., 2008; Ivanova & Costa, 2008). However, in one study (Gollan et al., 2008), as in Experiment 1, frequency effects were also larger in the nondominant than in the dominant language, whereas in the other study (Ivanova & Costa, 2008) frequency effects were equally large in the bilinguals' two languages. Thus, the two studies produced similar findings with respect to the bilingual/monolingual contrast, but discrepant results with respect to interactions between language dominance and frequency. A number of differences could explain the slightly different pattern of results across studies, but the current data rule out some of these possible explanations.

Gollan et al. (2008) had a within participants language dominance contrast (comparing dominant English responses to nondominant Spanish responses within the same group of participants), whereas Ivanova and Costa (2008) had a between participants language dominance contrast (they held language constant and tested two different groups of speakers who were either dominant in Spanish or dominant in Catalan and nondominant in Spanish). The current design was the same as in Ivanova and Costa and used a between participants manipulation of language dominance holding the language of testing constant (i.e., English). However, we still obtained the same pattern of results as Gollan et al. (a larger frequency effect in the nondominant than in the dominant language). Thus, it would seem that the more consistently obtained pattern is a larger frequency effect for the nondominant language. This result is also predicted on theoretical grounds: if reduced frequency of use leads to larger frequency effects across the monolingual/bilingual contrast, then reduced use of a non-dominant language should also lead to larger frequency effects across the language-dominance contrast.

The difference between studies may reflect the fact that Spanish and Catalan are very similar languages and equally dominant in the environment where Ivanova and Costa conducted their study; indeed; the difference in naming RTs between dominant-Spanish and nondominant-Spanish was much smaller in Ivanova and Costa (about 50 ms for both high- and low-frequency targets; see repetition 1 in Table 3, pp 794) when compared with the differences between dominant-English and nondominant-Spanish in Gollan et al. (about 250 ms for high-frequency targets and 500 ms for low-frequency targets; see Figure 1 of Gollan et al., 2008, pp. 795), and dominant-English and nondominant-English in Experiment 1 of the current study (about 120 ms for high-frequency targets and 201 ms for low-frequency targets in out of context naming; see Figure 1). Thus, the increase in the magnitude of the frequency effect (a difference score) may become detectable only at a certain point where language-dominance differences are sufficiently robust.

Returning to the larger implications of the data reported here, Experiment 1 replicated the previously reported interaction between frequency and contextual constraint for spoken language production, and also demonstrated that this interaction arises at three different levels of English proficiency. In addition, we replicated the interaction between frequency and bilingualism for production, showed that the bilingual disadvantage becomes smaller only in conditions where the frequency effect also becomes smaller, and that low-constraining target-language sentence context alone is not sufficient to reduce the disadvantage (only semantically constraining context). In Experiment 2, we tested whether frequency, constraint, and bilingualism exhibit similar effects in written word recognition and reading using the same materials as in Experiment 1 and participants from the same language groups.

Experiment 2 – Reading and Lexical Decision

As reviewed above, several studies of reading comprehension have identified significant effects of frequency and constraint but without any interaction between them (see Rayner et al., 2004 for a summary). Thus, given the findings of Griffin and Bock (1998), and the replication thereof in Experiment 1, there is an apparent difference between effects identified across modalities. In Experiment 2, we aimed to establish whether this apparent contrast could be replicated in a single study, or if between-study variation in methodology might have spuriously introduced the contrast. Because the bulk of studies investigating the joint effects of frequency and contextual constraint in language comprehension involved reading, we contrasted spoken production with reading. Note that in comparing comprehension and production it will ultimately be important to also compare auditory word recognition with production. However, because of possible involvement of production processes in auditory recognition, reading likely provides a stronger starting point for detecting any possible differences between comprehension and production. For example, some have proposed that every spoken utterance is first launched through the auditory comprehension system prior to overt production to check for errors (the "monitor" in language production; Levelt, 1989). If so, it would be more difficult to detect differences between comprehension and production, even if they did exist. Thus, reading may provide an estimate of comprehension processes in a manner as divorced as possible from production (though note that even here similarities could arise because of inner speech during reading).

Methods

Participants

Thirty-six monolingual English speakers, 36 Spanish-English bilinguals, and 27 Dutch-English bilinguals who did not participate in Experiment 1 were recruited for participation in the comprehension tasks (reading and lexical decision). As with the production studies, the monolinguals and Spanish-English bilinguals were undergraduates at the University of

California, San Diego and received course credit for their participation, the Dutch-English bilinguals were undergraduates at Ghent University in Belgium and either received course credit or were paid for their participation. Table 1 displays a summary of the participant characteristics.

Materials

The materials for the comprehension studies were the same as those from the production studies with a few important changes. First and most obviously, the pictures were replaced by their respective word names in all conditions. Second, for the conditions in which context was provided (sentence reading), additional text was added to the sentence following the target words. This was done because in eye tracking studies of reading it is common to avoid having target words occur in sentence initial or final positions. Fixations on words in these positions can be influenced by non-language aspects of the experiment such as orienting to the appearance of the stimuli and the decision to terminate reading on a trial. Additionally, including post-target text avoids sentence wrap-up effects from influencing the eye tracking measures on the target words (Rayner, Kambe, & Duffy, 2000). Finally, for each target word we created an appropriate and pronounceable nonword for use in the lexical decision task. Nonwords were legal and pronounceable stings created by altering two letters of each of the target words (e.g., *apple* became *airle*, and *arrow* became *anrew*).

Procedure

As in Experiment 1, each participant completed all three lists in one of each of the three conditions (no context- lexical decision, low-constraining context, high-constraining context). Assignment of material list to experimental condition was counterbalanced between participants such that each of the three materials lists was presented in each of the three conditions an equal number of times. Therefore, each participant read 60 targets embedded in sentences (15 sentences in each of the frequency by constraint conditions) and performed lexical decisions for 30 words and 30 nonwords in isolation. Across all the participants, each word appeared equally often in each of the context conditions (high constraining, low constraining, and without context), and no participant saw a target in more than one condition. As with the production study, the no-context condition was presented separately from the context condition, and the two context conditions were presented together with low-constraining and high-constraining sentences intermixed in a different random order for each participant. The order of testing with versus without context was counterbalanced across participants.

Eye-movements were recorded via an SR Research Ltd. Eyelink 1000 eye-tracker which recorded the position of the reader's eye every millisecond, and has spatial resolution of less than 0.04°. Participants were seated 55 cm away from a 19 inch ViewSonic VX922 LCD monitor. Head movements were minimized with chin and head rests. Although viewing was binocular, eye movements were recorded from the right eye. The same equipment was used for data collection in both locations (San Diego and Ghent).

At the start of the sentence reading experiment, participants completed a calibration procedure by looking at a sequence of three fixation points randomly presented horizontally across the middle of the computer screen. A validation procedure then repeated this process to check the error of the calibration. If this error was greater than .4 degrees of visual angle the entire procedure was repeated. At the start of each 'with context' trial, a black square (50 pixels wide and 50 pixels tall) appeared on the left side of the computer screen. This square coincided with the left side of the first letter in the upcoming sentence. The sentence replaced this square on the screen once a stable fixation was detected within its area. Sentences were presented as black letters on a white background in 14-point Courier New font with 3.2 letters equaling 1° of visual angle. Participants were instructed to read silently for comprehension and to press a button on a keypad when they finished reading. To encourage participants to pay attention to the sentences, the word “REMEMBER” appeared on the screen following this button press on 6 of the 60 trials. At this prompt, participants were asked to recall the sentence aloud and the experimenter noted the accuracy. Three high-constraint and 3 low-constraint sentences were pre-selected for this purpose. The first eight trials were practice to get the participants accustomed to the procedure.

The lexical decision task was carried out in the same lab space as the sentence reading study and utilized the same chin and head rests on the same computer as when the eye-tracking data were collected during sentence reading. Prior to each trial participants fixated a marker in the center of the computer monitor. Following a 1 second delay a letter string was presented in the center of the monitor and participants were told to press the left button on the keypad if the string was a word and to press the right button if it was a nonword. Participants were instructed to respond as quickly as possible while minimizing errors. The order of the items was randomized separately for each participant, with the first eight items being practice trials.

Results

As in Experiment 1, we first present the results from reading out of context (lexical decision) followed by the reading in context (eye-tracking) results. As shown in Table 3, we examined four standard eye movement measures (Rayner, 1998, 2009): (a) *first fixation duration* (the duration of the first fixation on the target word),[3] (b) g*aze duration* (the sum of all fixations on the target word before moving to another word), (c) *total reading time* (the sum of all

[3] We also analyzed single fixation durations (those cases in which the target was fixated a single time during first pass reading). The basic pattern of results was the same for this measure as for first fixation and gaze duration.

fixations on the target word including regressions), and (d) *skipping probability* (the probability that the target word was skipped on first pass reading). In addition, we also computed an alternative measure in which gaze duration was adjusted to account for skipping; in these analyses, gaze duration for a skipped target word was assigned a value of zero (Just & Carpenter, 1980; Murray, 2000; Rayner, Slattery, Drieghe, & Liversedge, 2010). Briefly summarized, we obtained the same results in first fixation, gaze duration, and total reading times; these differed slightly from skip-adjusted gaze-durations, and considerably from skipping rates. Specifically, only skipping probabilities exhibited a robust interaction between frequency and constraint (albeit of a different nature from that seen in Experiment 1), and the interaction was either completely (*F*s < 1) or largely absent from the other measures. For ease of exposition, the detailed results for first fixation durations and total reading times are presented in Appendix A.

Lexical Decision Out-of-Context: The results of the lexical decision task are shown in Figure 2 including responses to nonwords (the means are shown for completeness though nonwords were not included in any statistical comparisons; see also summary of results in Table 4). Participants produced correct responses to high-frequency words faster than to low-frequency words, [$F1(1,98) = 90.09$, $MSE = 2140.56$, $\eta_p^2 = .48$, $p < .001$; $F2(1,88) = 49.16$, $MSE = 6314.58$, $\eta_p^2 = .36$, $p < .001$], and monolinguals responded more quickly than bilinguals $F1(2,98) = 3.12$, $MSE = 19925.92$, $\eta_p^2 = .06$, $p < .05$; $F2(2,176) = 20.34$, $MSE = 5068.74$, $\eta_p^2 = .19$, $p < .001$]. In contrast to the production data, in which slowing related to bilingualism was robust for both bilingual groups, pairwise comparisons indicated that the monolinguals were only marginally faster than Spanish-English bilinguals (both *p*s < .06), and significantly faster than the Dutch-English bilinguals (both *p*s < .05). In addition, the difference between Spanish-English and Dutch-English bilinguals was significant in the items analysis (p < .05) but did not approach significance in the participant analysis ($F < 1$). Of interest, there was an interaction between frequency and group, [$F1(2,98) = 11.97$, $MSE = 2140.56$, $\eta_p^2 = .20$, $p < .001$; $F2(2,176) = 10.96$, $MSE = 5068.74$, $\eta_p^2 = .11$, $p = .001$]. However, only Dutch-English bilinguals exhibited a larger frequency effect than the other two groups (both ps < .005), whereas Spanish-English bilinguals and monolinguals exhibited the same size frequency effect (both Fs < 1). This contrasts with the production data, in which both Spanish-English and Dutch-English bilinguals exhibited larger frequency effects than monolinguals.

Error analyses exhibited a similar pattern of results as the RT data with robust main effects of frequency and group (all ps < .001), and robust interactions between frequency and group (both $ps < .001$; the main effect of participant type and the interaction with frequency was not significant without the Dutch-English bilinguals; $Fs < 1$).

Thus, the out-of-context (lexical decision) data exhibit striking differences with respect to the production data reported in Experiment 1. In particular, slowing associated with bilingualism was not as robust (only the Dutch-English bilinguals responding to written words in their second language were markedly slower than the monolinguals). Similarly, whereas the interaction between frequency and group was present in production at all levels of English-proficiency (comparing monolinguals to Spanish-English bilinguals, monolinguals to Dutch-English bilinguals), in lexical decision, the frequency effect was larger only in the participant group that was least proficient in English.

A similarity that did emerge was that the frequency effect was significantly larger both in picture naming and in lexical decisions when the targets were in a non-dominant language (English for the Dutch-English bilinguals) than in a dominant language (English for the Spanish-English bilinguals), confirming previous results for both production and comprehension (respectively Gollan et al., 2008 and Duyck et al., 2008).

Reading in Context (Eye-tracking): Gaze durations are our primary measure of target word processing as they are the sum of all fixations on the target words prior to leaving it in either direction (contingent on it not being initially skipped). Gaze durations are often interpreted as a measure of lexical access (Rayner, 1998, 2009). This measure is also the most appropriate for comparison to other tasks such as production and lexical decision (which have only a single dependent measure of processing time) and has been shown to correlate best (of the various fixation time measures) with lexical decision and naming times (Schilling, Rayner, & Chumbley, 1998). To facilitate comparison with Experiment 1, the means for the gaze durations are shown in Figure 3 (these same means appear in Table 3). Because of the large difference in baseline between eye-tracking measures and explicit responses, lexical decision times are shown separately (see Figure 3). Gaze durations where shorter on high than low frequency words, [$F1(1,96) = 77.39$, $MSE = 498.64$, $\eta_p^2 = .45$, $p < .001$; $F2(1,88) = 25.03$, $MSE = 2082.80$, $\eta_p^2 = .22$, $p < .001$], and shorter on high than on low constraint target words, [$F1(1,96) = 24.32$, $MSE = 587.83$, $\eta_p^2 = .20$, $p < .001$; $F2(1,88) = 20.20$, $MSE = 1329.62$, $\eta_p^2 = .19$, $p < .001$]. There was also a main effect of group indicating that gaze durations were shorter for monolinguals than for bilinguals, [$F1(2,96) = 10.80$, $MSE = 4679.98$, $\eta_p^2 = .18$, $p < .001$; $F2(2,176) = 88.42$, $MSE = 943.96$, $\eta_p^2 = .50$, $p < .001$]. Planned comparisons indicate that gaze durations for monolinguals were significantly shorter than for Spanish-English bilinguals (both *p*s < .05), and both of these groups of readers had shorter gaze durations than the Dutch-English bilinguals, (all *p*s < .01); thus, slowing associated with bilingualism was more robust (applying to both bilingual groups) in context with the gaze-duration measure than it was out of context with the lexical-decision task (in the Dutch-English group was significantly slower, but the Spanish-English group was only marginally slower, than monolinguals).

In stark contrast to the production data (in Experiment 1), there was no indication that frequency interacted with constraint in gaze duration times (both *F*s < 1), the bilingual disadvantage was not larger for low frequency words than for high frequency words (both *F*s < 1), and there was no three-way interaction between frequency, constraint, and group, (*F*s < 1). There was an interaction between constraint and group, [$F1(2,96) = 3.51$, $MSE = 587.83$, $\eta_p^2 = .07$, $p < .05$; $F2(2,176) = 4.53$, $MSE = 1046.40$, $\eta_p^2 = .05$, $p < .05$], however it was entirely different in nature from that observed in the production data, and not the interaction that would be predicted based on the three-tiered manipulation of English proficiency. Specifically, Spanish-English bilinguals benefited more than monolinguals, (ps < .005) and marginally more than Dutch-English bilinguals (ps < .08), from semantically constraining context (but see the analysis of skipping rates below), but constraint effects between the two groups that differed most in English proficiency (monolinguals and Dutch-English bilinguals), did not differ, (both *F*s < 1). As we will see below, this difference seemed to be attributable to a tradeoff between gaze durations and skipping rates and between group differences in these two measures.

Thus, contrary to the results of the production study RTs, there was no indication of an interaction between frequency and constraint in any of the standard fixation duration measures (see also Appendix), and interactions between frequency and bilingualism were also rather different across the two experiments. The contrast between results observed in production (Experiment 1) versus comprehension (Experiment 2) is not unexpected given previously published results (e.g., Griffin & Bock, 1998 versus Rayner et al., 2004). However, the observation of this contrast in the same study, using the same materials, and the same participant populations, provides confidence that the differences observed across studies reflect an actual difference between modalities. Also of note with respect to the predictions of the interference account of bilingual disadvantages, in production there was some evidence for an attenuation of the bilingual disadvantage in context, whereas in reading if anything the bilingual disadvantage was more robust in context (though in Experiment 2 this difference could reflect task differences between lexical decision and gaze-duration rather than a context effect). In addition, an unexpected finding from the perspective of the frequency-lag hypothesis was the presence of a disadvantage without an interaction with frequency in gaze-durations.

Another important dependent measure in eye movement studies of reading is skipping rate. Skipping rates of target words are often interpreted as a measure of processing difficulty, with increased skipping rates for targets that are easier to process (i.e. shorter words, higher frequency words, more predictable words). In the current study, (see Figure 3 panel B and Table 3) the skipping rate of high frequency target words was 14.22% but only 12.16% for low frequency target words, a difference that was significant in the participants' analysis but only marginal over items, [$F1(1,96) = 4.81$, $MSE = 85.96$, $\eta_p^2 = .05$, $p < .05$; $F2(1,88) = 2.80$, $MSE = 226.10$, $\eta_p^2 = .03$, $p = .098$]. More importantly, contextual constraint (or predictability) has a strong influence on skipping rates (Rayner, 1998, 2009). Not surprisingly then, high constraint targets were skipped 14.91% of the time while low constraint targets were only skipped 11.46% of the time, [$F1(1,96) = 10.01$, $MSE = 115.67$, $\eta_p^2 = .09$, $p < .001$; $F2(1,88) = 7.56$, $MSE = 190.57$, $\eta_p^2 = .08$, $p < .01$]. There was also a main effect of group on skipping rate, [$F1(2,96) = 10.75$, $MSE = 316.47$, $\eta_p^2 = .18$, $p < .001$; $F2(2,176) = 47.14$, $MSE = 101.16$, $\eta_p^2 = .35$, $p < .001$], as monolinguals were more likely to skip targets (18.70%), than Spanish-English bilinguals (12.39%), who were more likely to skip targets than Dutch-English bilinguals (8.47%), (all *p*s < .05).

Of interest, skipping rates paralleled the production data in that frequency effects were larger when semantic constraint was low than when it was high, [$F1(1,96) = 7.75$, $MSE = 69.45$, $\eta_p^2 = .08$, $p < .01$; $F2(1,88) = 4.07$, $MSE = 190.57$, $\eta_p^2 = .04$, $p < .05$]. In addition, there was some indication of a group by constraint interaction, [$F1(2,96) = 2.76$, $MSE = 115.67$, $\eta_p^2 = .05$, $p = .068$; $F2(2,176) = 3.30$, $MSE = 123.85$, $\eta_p^2 = .04$, $p < .05$], but this was in the opposite direction of the effect seen in fixation duration measures with Spanish-English bilinguals exhibiting a smaller constraint effect than monolinguals (both *p*s < .05), and trending in the same direction when compared to Dutch-English bilinguals (both *p*s < .12). However, there was no indication of an interaction between group and frequency, both *F*s < 1. The three-way interaction did not approach significance (*F*s < 1).

The different pattern of results for fixation duration and skipping rate measures complicates the interpretation of the eye movement data. However, two other eye movement studies that also manipulated contextual constraint and frequency found an interaction between these variables in skipping rates despite not finding such an interaction in the overall fixation durations (Hand, Millet, O'Donnell, & Sereno, 2010, Rayner et al. 2004). Both of these earlier studies ignored the interaction in skipping when interpreting fixation duration effects as there is evidence to suggest that the decision of when to move the eyes and where to move is independent (Rayner, 1998, 2009). However, due to the goals of the current studies, resolving such complications in the data patterns of these measures is critical. One technique that has been used to reconcile such differences (see Just & Carpenter, 1980; Murray, 2000; Rayner et al., 2010) is to average in a zero to gaze durations for every skip. The logic inherent to this procedure is that skipped words are processed in the parafovea to a large enough extent that they don't require a direct fixation for lexical access, and that this will be more likely to happen when overall lexical processing is easier. After averaging zeros in, gaze duration times remained shorter on high than low frequency target words, [$F1(1,96) = 49.28$, $MSE = 1060.60$, $\eta_p^2 = .34$, $p < .001$; $F2(1,88) = 16.45$, $MSE = 4329.66$, $\eta_p^2 = .16$, $p < .001$], and shorter on high than on low constraint targets, [$F1(1,96) = 27.14$, $MSE = 1338.28$, $\eta_p^2 = .22$, $p < .001$; $F2(1,88) = 23.45$, $MSE = 2178.12$, $\eta_p^2 = .21$, $p < .001$], and were affected by group, [$F1(2,96) = 15.93$, $MSE = 7266.21$, $\eta_p^2 = .25$, $p < .001$; $F2(2,176) = 125.84$, $MSE = 1365.18$, $\eta_p^2 = .59$, $p < .001$]; gaze durations with zeros averaged in were shorter for monolinguals than for the bilinguals (all *p*s < .005), and shorter for Spanish-English bilinguals than Dutch-English bilinguals (both *p*s < .01).

The procedure of averaging zeros in to gaze durations also introduced a hint of an interaction between constraint and frequency, but this was only marginally significant in the participants analysis and did not approach significance by items, [$F1(1,96) = 3.43$, $MSE = 587.14$, $\eta_p^2 = .03$, $p = .067$; $F2(1,88) = 1.33$, $MSE = 2178.12$, $\eta_p^2 = .02$, $p = .253$]. Additionally, the interaction between constraint and group that had been significant in both the duration and skipping measures (though in opposite directions) did not approach significance in this alternative measure (both *F*s < 1). None of the other interactions approached significance (all *F*s < 1).

Thus, after taking measures to consolidate the differences between skipping rates and fixation times, a clearer picture emerges. Whereas we observed significant interactions between frequency and constraint in language production, these effects are largely absent in reading. Similarly, whereas we found significant interactions between frequency and group in language production, these effects were completely absent for reading in context.

Comparing Comprehension and Production

The contrast between the results reported in Experiment 1 and those of Experiment 2 imply a distinct effect of frequency on lexical access in production versus comprehension. In comprehension, frequency seems to operate independently of context, primarily serving to initiate lexical access via form-driven frequency-sensitive search process. In production, frequency effects seem to be modulated by context, influencing access but only as a part of a meaning-initiated search that can be affected by frequency, but is not frequency driven. Direct comparisons of comprehension and production are difficult to achieve because of the different baselines inherent to the different tasks (fixation times in reading are relatively short whereas picture naming and lexical decision times are much longer). To facilitate more direct comparisons across modalities we conducted two sets of analyses including (a) a baseline adjustment, and (b) vincentile plots.

To adjust for baseline differences in our measures we calculated proportionally adjusted frequency effects for each participant in each of the three conditions in Experiments 1 and 2 as follows:

(low frequency – high frequency)/((low frequency + high frequency)/2)

For this purpose, we used picture naming times from Experiment 1, and gaze-duration (without zeroes averaged in) and lexical decision times in Experiment 2. These proportional frequency values were then submitted to a 2 x 3 x 3 ANOVA with modality (production, comprehension), and participant group (monolinguals, Spanish-English bilingual, Dutch-English bilingual) as non-repeated factors, and contextual constraint (out of context, low-constraint, and high-constraint) as repeated factors, to determine the relative size of the frequency effect in comprehension and production, and whether this is modulated by context. The results of this analysis are shown in Figure 4 with separate panels for each participant group.

Briefly summarized, the relative magnitude of the frequency effect in production (Experiment 1) versus comprehension (Experiment 2) varied with contextual constraint. Monolinguals and Spanish-English bilinguals exhibited a similar pattern of results, which was slightly different from that seen in Dutch-English bilinguals. However, in all three participant groups, semantic constraint reduced the size of the frequency effect in picture naming. Overall, proportionally adjusted frequency effects across experiments revealed significant main effects of language such that monolinguals exhibited smaller frequency effects than bilinguals [F (2,238) = 15.76, MSE = .02, η_p^2 = .12, p < .01], a main effect of modality such that production resulted in larger frequency effects than comprehension [$F1$(1,238) = 6.22, MSE = .02, η_p^2 = .03, p = .01], and a main effect of contextual constraint such that frequency effects were smallest in highly-constraining semantic context [*F1*(1,238) = 4.41, *MSE* = .02, η_p^2 = .02, *p* = .04].

These main effects were qualified by a significant interaction between contextual constraint and modality (experiment) such that frequency effects were larger in production than in comprehension in no- or low-constraining context, but smaller or similarly sized in production than in comprehension when in highly constraining context. None of the other interactions approached significance (all *p*s > .16), except for the interaction between language and modality (*p* = .07), which was driven exclusively by Dutch-English bilinguals. Comparing monolinguals to Dutch-English bilinguals (excluding the Spanish-English group), there were main effects of language (*p* < .01), modality (*p* = .03), contextual constraint (*p* = .05), and a significant interaction between language and modality (*p* = .03). However, comparing monolinguals to Spanish-English bilinguals (excluding Dutch-English bilinguals), the main effect of language remained significant (*p* = .03), and the interaction between constraint and modality was quite robust (*p* < .01), but none of the other main effects or interactions approached significance.

Planned comparisons focusing on the context conditions (low- versus high-constraining) in each participant group revealed a significant cross-over interaction between modality and contextual constraint in monolinguals (*p* = .04), and a marginally significant cross-over interaction in the same direction in Spanish-English bilinguals (*p* = .08), such that frequency effects were larger in production than in comprehension in low-constraining context, but smaller in production than in comprehension in high-constraining context. Dutch-English bilinguals exhibited a similar interaction (*p* = .01), but the size of the frequency effects in production did not dip below comprehension in highly constraining context (no-cross-over). Comparing the different modalities for the out-of-context conditions, Spanish-English bilinguals exhibited significantly greater frequency effects in production than in comprehension (p = .01), but for monolinguals the frequency effect did not vary in magnitude across modalities (see panel A of Figure 4), whereas Dutch-English bilinguals exhibited a very large frequency effect in comprehension, as large as that in production (see panel C of Figure 4).

To further facilitate the comparison between comprehension and production, illustrating the effects of frequency and constraint across the full range of processing times in each task, we constructed vincentile plots (Vincent, 1912). Vincentile plots (Ratcliff, 1979; Staub, White, Drieghe, Hollway, & Rayner, 2010) have been recently recommended (e.g., Balota et al., 2008; Yap & Balota, 2007) for deriving better informed theoretical implications based on between condition latency differences which can arise from differences in mode RT, in the tails of the RT distributions, or in both. Vincentile plots are constructed by first sorting the responses for each participant by condition in order (fastest to slowest), and then assigning times for each participant into bins ranging from fastest to slowest. For current purposes we assigned each participants' data points into 5 bins with a maximum of 3 data points per participant per bin per condition (some bins had fewer than 3 data points for each participant because of missing data/outlier removal). In Experiment 1 the data from all 145 participants, and in Experiment 2 the data from all 99 participants, were averaged into each bin. Subsequently, an average time for each bin in each condition is calculated, and when graphed these means illustrate how the effects of interest vary across the distribution. The means for each bin as a function of frequency and constraint are shown in Figure 5 with the production data in the top panel and the reading data (unadjusted gaze duration times) in the bottom panel (for simplicity of presentation, out of context data are not shown).

The most immediately obvious difference between production and comprehension is in the effect of context. Though constraining context speeds processing in both comprehension and production, the effect appears to be much larger in production: here, the low-constraint and high-constraint naming times do not overlap at all, whereas in reading the separation is less clear. More specifically, for picture naming times, semantic constraint seems to be more powerful than frequency effects (e.g., high-constraint low-frequency points are faster than the low-constraint high-frequency points), whereas in reading frequency was a stronger determinant of gaze duration times (low-frequency means tend to be slower than high-frequency means regardless of constraint). The vincentile bins also illustrate the consistency of the reported effects across the distribution of times. In the top panel, the separation between high-and low-frequency targets is larger in low-constraint than it is in high-constraint at all 5 time bins (i.e., the frequency effect is smaller in semantically constraining context for production). In the bottom panel, the separation between high- and low-frequency means for gaze duration is about equal in low-constraint (triangles and Xs) and high-constraint conditions (diamonds and squares; i.e., the frequency effect is not modulated by context for reading). The figures also show that frequency effects in gaze duration times are very small in the first time bin, as well as in production with low-constraint context in the first two bins.

A 2 x 2 x 5 ANOVA with frequency, constraint, and vincentile bins as factors confirmed these conclusions. In production there were significant two-way interactions (all ps $< .01$) between frequency and vincentile points, constraint and vincentile points (such that effects were larger in slower RT bins), as well as the already reported frequency by constraint interaction, but there was no indication that the latter interaction varied with vincentile bin [$F1(1,139) = 1.33$, $MSE = 39,394$, $\eta_p^2 = .01$, $p = .25$]. In comprehension, the two-way interactions between frequency and vincentile points and constraint and vincentile points were significant (both ps $<$

.01), but the frequency by constraint interaction, and the three-way interaction were not (both *F*s < 1). Altogether, the proportional analyses and the vincentile plots confirm our conclusions with respect to the effects of frequency and constraint in comprehension versus production, while illustrating their consistency across the distribution of RTs.

General Discussion

The goal of this study was to identify the mechanisms of lexical access that are modality specific and to distinguish them from those that are language general, aiming at a better understanding of the differences and commonalities that underlie the cognitive processes associated with language production versus comprehension. A review of these different literatures indicated a contrast between studies of picture naming and studies of word recognition with respect to the joint effects of word frequency and semantically constraining context on lexical access. The data reported here provide strong evidence confirming this striking contrast between modalities.

Using the same materials in picture naming, lexical decision, and eye-tracking, with three groups of participants at different levels of English proficiency, we observed robust main effects of frequency, semantic constraint, and participant group on both picture naming and eye-tracking measures. However, whereas picture naming produced robust interactions between frequency and constraint, these were largely absent in reading measures. Similarly, only picture naming (but not reading) revealed an interaction in the expected direction between English proficiency level (a proxy of frequency) and constraint (such that slowing associated with a low proficiency level was attenuated in production but not in comprehension), Slowing associated with bilingualism appeared to be more robust in production than in comprehension (at least for lexical access out of context). Direct comparisons of picture naming and reading measures (after adjusting for the baseline level in the respective response measures; see Figure 4) revealed that frequency effects were larger in production than in comprehension without semantic constraint, but smaller in production than in comprehension in highly constraining semantic contexts (for all participants with English as their dominant language, including monolinguals). In addition, constraint effects were larger in production than in comprehension (see Figure 5).

Table 4 summarizes the pattern of statistical significance for all major contrasts in Experiments 1 and 2. A summary of effect sizes is also provided for effects of crucial importance for this study (e.g., note that the constraint effects are highly robust statistically in both experiments, although the size of the effect appears to be much larger in picture naming than in reading).

The Role of Frequency in Lexical Access.

The results reported here imply differences in the cognitive mechanisms underlying language comprehension versus production. As outlined above, frequency would logically be assigned a very different role when the process of lexical access begins with meaning and ends with access to lexical forms (in production), when compared with a process that begins by accessing lexical forms and ends with processing of meaning (in comprehension). The data we reported suggest an unequivocal role for frequency in lexical access during reading that is (if not completely, then) relatively independent from later processing effects such as the interpretation of meaning. In contrast, in production, the role of frequency is attenuated (or even eliminated in some cases; Griffin & Bock, 1998) by semantic context. Thus, in comprehension, lexical access itself is a frequency driven process, whereas lexical access during production is primarily a semantically driven process with the expression of frequency effects coming and going based on the relative absence or presence of semantic constraint.

Two aspects of the data we reported would seem to challenge this claim. The first is the interaction between frequency and constraint in word skipping rates for reading in context. In particular, readers were less likely to skip a target word if it was a low-frequency word that occurred in low-constraining context, although frequency did not influence skipping rates otherwise (see bottom panel of Figure 2). Note that the analogous interaction in picture naming was of a different form; specifically, in naming times, frequency effects were present in all conditions (including highly constraining context), but they were larger in low-constraining semantic context. Although the skipping data are interesting in their own right, the vast majority of words are not skipped, and it isn't as clear what to make of skipping data as is the case with fixation time measures (because assumptions must be made with respect to how skipped words are processed). To incorporate the skipping data into our analyses we relied on a measure that combines skipping rates and gaze-duration times (see Table 3). This approach makes the (likely overly conservative) assumption that skipped words are processed in no time. Despite this conservative approach, the analyses of skipping adjusted gaze duration times failed to produce robust interactions between frequency and constraint (only a marginal effect in the participants analysis, and no effect by items). Thus, we might temper our claims here: rather than saying that there was absolutely no evidence for an interaction between frequency and constraint in reading measures, it is rather that the evidence for an interaction was both qualitatively different in reading than in production, and considerably less robust in reading than it was in production.

A second question concerns the magnitude of the frequency effect in the two modalities. For all participant groups, frequency effects were as large (or in some cases even larger) in production as in comprehension, both without context and in low-constraining semantic context. For the least English-proficient group (Dutch-English bilinguals) this was true even in highly constraining semantic context. If frequency plays a less central role in lexical access for production, then why were frequency effects sometimes so large in production? In particular, how do we reconcile the claim that frequency plays a central role in lexical access for comprehension but not production, with the fact that frequency effects weren't consistently smaller in production than comprehension? Importantly, our comparisons of comprehension and production relied on baseline adjusted measures of the frequency effect (see Figure 4), thus it is not the case that frequency effects were large in production simply because picture naming times are substantially longer than fixation times in reading (see Figures 1 and 2). In addition, monolinguals also exhibited the modulation of frequency effects by modality and constraint (such that frequency effects tended to be larger in production than in reading without constraining context, but smaller than in reading with constraining context); hence, the modulation applied even at the highest proficiency levels.

Frequency-lag for Production versus Comprehension. One interesting, though admittedly speculative, possibility is that production could lag behind comprehension in frequency of use. If reading has a higher cumulative frequency over a lifetime than speaking (at least for some people, including the participants in the current study), this could explain why frequency effects can still be quite large in production even though access is not primarily frequency driven in production. Although we learn to speak as children long before we learn to read, reading rapidly becomes a high-frequency activity early in life (in school at age 6, and after school in homework, email, and reading for pleasure, etc.). Moreover, when people read it is often one-sided (they don't write at the same time), whereas speaking is more often divided time taking turns with auditory comprehension (except for folks who talk to themselves). In addition, many people often listen to a single speaker. Current estimates of how many words are spoken in a day by college students is about 16,000 (Mehl, Vazire, Ramirez-Esparza, Slatcher, & Pennebaker 2007). Assuming college-students read anywhere from 2-8 hours/day, at a rate of about 300 words/minute (Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007; Taylor, 1965), this would translate into many more words read than spoken/day[4] (300*60*2= 36,000 and 300*60*8=144,000).

If frequency effects become smaller and smaller with increased use, this should lead to smaller frequency effects in the more often used modality. Similarly, a life-time of using two languages leads older bilinguals to have smaller frequency effects than young bilinguals (albeit only in the non-dominant language; Gollan et al., 2008). However, an implicit assumption in this line of reasoning is that frequency effects reflect a simple and cumulative count of the absolute number of exposures; this view has been questioned at least for visual word recognition (Murray & Forster, 2004; see also Gollan et al., 2008). Moreover, it would be very difficult to actually verify whether people indeed speak less than they read. And, even if this lag could be verified, it might only apply at high levels of education, although there are reasons to believe that the production lag should apply more broadly. Specifically, picture naming is one of the most sensitive tasks to even very mild brain damage, whereas reading is highly resistant to many forms of brain damage and is therefore often used as an estimate of pre-damage IQ levels (Lezak, Howieson, & Loring, 2004). The sensitivity of production but not reading to brain damage implies fundamental differences between them. A different but related reason why production might lag behind comprehension is that production may require a greater number of exposures to reach ceiling levels of proficiency than does reading. In this case, production would lag behind comprehension even if people were to speak as often as, or even more often than, they

[4] This way of estimating reading frequency was suggested to us by Mark Liberman.

read.

The notions of a frequency lag for production relative to comprehension, or that a greater number of exposures is needed to approach ceiling levels of lexical accessibility for production than for comprehension, fits well with the observation that comprehension precedes production when monolingual children learn their first language. Similarly, adults learning a new language can comprehend (and often also read) much better than they can speak the new language. That said, it is not transparent how one might test whether ceiling had been reached when comparing speaking and reading, or how this might be implemented within processing models (perhaps with different selection thresholds for comprehension versus production). What is needed here is to specify the stages of lexical access for comprehension versus production, and where frequency effects are represented in each.

The Locus of the Frequency Effect. To determine more specifically why frequency, constraint, and their interaction (or lack thereof) might vary with modality, it is useful to consider which representations and processes might be shared or different between them. As already noted, it is generally assumed that comprehension and production access shared conceptual representations, and that lexical representations are not shared at the level of form. It is also generally agreed that (even though they are not shared between modalities) lexical form representations are frequency sensitive in both comprehension and production. But beyond these extreme endpoints (on which all models would agree) several different options can be considered. For production, some have argued that frequency effects are restricted exclusively to the retrieval of lexical forms (implemented as higher resting activation levels for high- than for low-frequency words within the lexical representation itself; Jescheniak & Levelt, 1994). With this rather severe restriction of the locus of frequency effects in production it is difficult to see why frequency effects would be greater in production than in comprehension without making additional assumptions (such as those just outlined in the section entitled Frequency-Lag for Production versus Comprehension).

Number of Frequency-sensitive Processing Stages. Instead, it may be that frequency effects arise in relatively more processing stages in production than in comprehension. Consistent with this claim, Kittredge et al. (2008) recently challenged the proposal that only lexical-form access is frequency sensitive by demonstrating that semantic errors (which are often considered to arise prior to word-form selection) are frequency sensitive. That is, the probability of making a semantic related error (e.g., saying *orange* instead of *apple*) was lower for high- (e.g., *apple*) than for low-frequency (e.g., *cherry*) target words, even after controlling for other variables that are correlated with frequency (e.g., imageability, density, length). Although phonological errors (e.g., *pillow* instead of *pineapple*) were more sensitive to frequency than semantic errors, in both cases the frequency effect was highly robust, both ps $< .01$, and thus they proposed that both lexical-semantic and lexical-form access are frequency-sensitive. Similarly, Knobel et al. (2008) suggested that frequency effects could arise at three loci in the production architecture: in the connections from meaning to lexical form, in the lexical representations themselves, and in the connections from the lexical representations to the sounds needed to assemble spoken words.

On this view, production would involve at least one more frequency-sensitive processing stage than comprehension. If lexical-semantic (lemma) selection is the critical extra frequency-sensitive stage for production, then the greater effect of frequency on production than comprehension could only be explained if lemmas are not shared between modalities. Levelt et al., (1999, pg. 7) proposed two distinct layers of whole-word lexical representations in which lemmas represent semantic and syntactic information, are accessed prior to word-form representations (called lexemes), and are shared between modalities: *"… recognizing a word, whether spoken or written, involves accessing its syntactic potential, that is, the perceptual equivalent of the lemma, we assume activation of the corresponding lemma-level node. In fact…all production lemmas are perceptual lemmas; the perceptual and production networks coincide from the lemma level upwards…*". Given the hypothesis of shared lemmas, it might instead be stipulated that the outgoing (production) connections from meaning to lemmas also are frequency sensitive, whereas the ingoing (comprehension connections) from written and spoken forms to lemmas are not frequency sensitive. Note also that the notion of a modality neutral layer of lexical representations (i.e., lemmas) is not universally accepted (e.g., Caramazza, 1997). Still, the same general problem arises in models without lemmas – some accommodation must be made to explain why frequency effects are sometimes larger in production than in comprehension despite greater sensitivity in production processes to other variables (e.g., semantic constraint).

The extent to which lemmas are or are not shared between comprehension and production also has implications for the extent to which production and comprehension can or cannot be based on each other (in whichever direction; motor theory of perception, Liberman & Mattingly, 1985 or sensory theory of speech, Venezia & Hickock, 2009), and how alignment occurs between modalities in dialogue (Pickering & Garrod, 2004). At one extreme, alignment might be pushed entirely outside the language system and up to the conceptual level; at the other extreme, any differences between modalities might be explained in terms of processing rather than representation (Ferreira, 2004). In developing such theories it would be useful to spell out precisely how much sharing is necessary for alignment to succeed both in terms of representation and processing involved.

It might be suggested that a different pattern of results will be found when comparing spoken production with listening comprehension (instead of reading), and if so this would open up the possibility that lemmas are shared only for listening and speaking, and therefore also that frequency and constraint might interact in auditory comprehension. This would have to be tested in a separate study. However, if reading involves phonological activation (for review see Frost, 1998), the distinction between auditory and reading comprehension is weak. In addition, it could be argued that task and measure-specific factors in the current paradigms played a role in the differences we observed, and that there are fundamental differences in what is being measured in comprehension and production. Naming involves elaborate planning and motor execution of a series of phonemes in a very specific order, with precise pronunciation and, for non-native speakers, also a change in accent. Although ultimately comprehension may certainly also involve very specific and elaborate processing, this may not be measured experimentally (instead what is measured is processing to the point that a saccade or a decision can be made). Thus, because word frequency influences access to lexical forms for both comprehension and production, the absolute size of the effect may have more to do with the specific processes associated with form retrieval in each case, and the number of exposures needed to reach ceiling levels of proficiency in each case. Although word frequency is not usually assumed to influence all of these processes the possibility for a frequency effect at each of these stages exists.

Specifically, at least in principle, frequency could play a role at all processing steps needed to access and produce a picture name including concept selection, lexical-semantic (lemma) access, lexical-form (lexeme) access, and even phonetic-articulatory planning (see more on this below). Frequency effects are usually assumed not to affect conceptual access (e.g., Oldfield & Wingfield, 1965; Knobel et al., 2008) but some studies have shown effects along these lines (e.g., one study identified similarly sized frequency effects in lexical decision and an object decision task; Kroll & Potter, 1984). In contrast, gaze durations could primarily reflect processing steps up to the point of lexical access, but not subsequent steps in the comprehension process because conceptual access could easily continue after gaze shifts to the subsequent word. However, the presence of semantic constraint effects on gaze durations (Rayner & Well, 1996; and other effects of semantic manipulations on gaze duration; e.g., Duffy et al., 1988) suggests that this view may be too simplistic.

Implications for Interactivity. Returning to one of the starting points for the present study, recall the apparent contrast between studies suggesting production appears inherently more interactive than comprehension. If frequency and semantic constraint affect the same processing stage (lexical-semantic retrieval), then interactions between them could be explained without positing interactivity between processing levels (i.e., without postulating that word-form retrieval can feed activation back up to influence lexical-semantic retrieval). Thus, production will appear to be more interactive than comprehension, not because there is more interactivity in the system when going from meaning to words than the reverse, but rather because relatively more processing stages are frequency sensitive in production than in comprehension, and in production (but not in comprehension) frequency and meaning influence the same processing stage.

Within the proposal of more frequency sensitive processing stages in production than in comprehension, it is quite impressive that frequency effects can sometimes be eliminated in production in high semantic constraint (Griffin & Bock, 1998). The relative weakness of frequency effects in language production research has also been described in this way in the context of naturally occurring speech errors: "*Put briefly, the places in language generation for which lexical frequency effects should have a natural expression in speech error patterns show* *pallid or inconsistent effects*" (Garrett, 2001). All this is to say that although frequency effects may be very large in production without semantic constraint, when semantic constraint is present, frequency effects in production are rather weak.

Implications of bilingual effects.

Our three-tiered manipulation of English proficiency level (with monolinguals being more proficient than English-dominant Spanish-English bilinguals, who in turn were more proficient in English than Dutch-dominant Dutch-English bilinguals), provides a further means for evaluating differences between comprehension and production, while also having implications for models of bilingual language processing. Most broadly relevant, we suggested that where participant group by constraint interactions are found, this may constitute additional evidence for frequency by constraint interactions assuming a that bilingualism entails a frequency-lag and that there is limit on the extent to which activation can accumulate in lexical representations with frequency of use (Gollan et al., 2008). Here, we assume that the monolingual lexicon is closer to ceiling levels of activation, and that monolinguals are thus accessing higher-frequency lexical representations than bilinguals. In this respect, we obtained further evidence for interactive effects of frequency and constraint in production but not in comprehension. Specifically, Dutch-English bilinguals (at the lowest level of English-proficiency) benefited from semantic constraint more than monolinguals, but only in Experiment 1 (picture naming) and not in Experiment 2 (eye-tracking). Although there was some tendency in the fixation times for Spanish-English bilinguals to benefit more from context than monolinguals, this did not seem to be related to the level of English proficiency as Dutch-English bilinguals (less English proficient than Spanish-English bilinguals) did not exhibit this effect. Instead, the interaction in Experiment 2 seemed to reflect a trade-off with skipping rates such that Spanish-English bilinguals' skipping rates did not vary with context (whereas for the other two participant groups, skipping rates did vary with context). Altogether these results then again provide stronger evidence for an interaction between frequency of English use and semantic constraint in production than in comprehension.

The pattern of slowing related to bilingualism and second language use in Experiments 1 and 2 provides some additional evidence for separation between modalities (with distinct frequency counters in comprehension and production). In picture naming out of context, bilinguals were significantly slower than monolinguals, even when producing picture names in their dominant language (i.e., comparing Spanish-English bilinguals to monolinguals). In contrast, out of context reading in the lexical decision task seemed to be less sensitive to slowing related to bilingualism (slowing was statistically robust only at the lowest level of English proficiency, Dutch-English bilinguals). A possible explanation for the sometimes greater bilingual disadvantage in production than in comprehension is that bilinguals (but not monolinguals) may exhibit frequency effects in articulation. Articulation processes are usually assumed to be at ceiling for monolinguals, but may not be for bilinguals who have had less practice with producing non-native sound combinations. The proposal that production lags behind comprehension in frequency of use (whether because speaking is a less frequent activity than reading or because speaking requires more frequent use to achieve proficiency) also provides a ready explanation for this difference.

In this view, the frequency lag associated with bilingualism may be greater for production than for comprehension because all language users are closer to ceiling levels of lexical accessibility in reading. Thus, Spanish-English bilinguals are closer to "catching up" with monolinguals in terms of frequency of use in reading than in speaking, and only Dutch-English bilinguals lag clearly behind monolinguals in both modalities, exhibiting significant slowing and greater frequency effects (albeit the increased frequency effect was obtained only in lexical decisions in Experiment 2). This interpretation predicts that in comprehension measures of more difficult targets than those employed here, bilinguals should exhibit a disadvantage even in the dominant language. Supporting this view, vocabulary tests (which include very difficult items typically towards the end of the test) often reveal lower scores in bilinguals than in monolinguals (Bialystok, Luk, Peets, & Yang, 2010; Portocarrero, Burright, & Donovick, 2007). Indeed, in both Experiments 1 and 2, Spanish-English bilinguals obtained slightly but significantly lower Shipley English-vocabulary scores than monolinguals (both *p*s $< .01$).

Another reason why slowing related to bilingualism might sometimes be more robust in production than in comprehension, and for the interaction between participant group and constraint in Experiment 1 is dual-language activation. In production, a single response, and therefore also an output language must by definition be selected, so that dual-language activation might therefore be quite disruptive (Hermans et al., 1998; but see Costa & Caramazza, 1999). In contrast, in recognition, readers may rely solely on bottom-up activation, without even having to make a language selection, as long as the input matches a stored lexical representation. To the extent that translation equivalents might become active in language comprehension, this should be relatively less disruptive given that both activate the intended meaning. Previous studies have led to the hypothesis that semantically constraining context may act to reduce, or even eliminate entirely (Schwartz & Kroll, 2006; van Hell & de Groot, 2008; Libben & Titone, 2009) the effects of dual-language activation (but see Duyck et al., 2007; van Assche et al., in press, and Experiment 2 of this study).

Above, we speculated that context of any kind might have similar effects relative to no context. Anecdotally, all bilinguals have had the experience that it feels easier to retrieve words in a nondominant language when surrounded by context that supports activation of that language. However, we obtained no evidence that slowing related to bilingualism or second language use was attenuated by non-constraining context (in production where we could make this comparison; see the last paragraph in results section of Experiment 1). Even with highly constraining semantic context, only Dutch-English bilinguals benefited more from context than monolinguals, but both bilingual groups responded more slowly than monolinguals (in Experiment 1). In comprehension there were even some effects in the opposite direction. That is, Spanish-English bilinguals were only marginally slower than monolinguals in lexical decisions, but had significantly longer gaze duration times (see Table 4 for a summary). This could be an uninteresting consequence of the different types of measures (lexical decision versus gaze durations), or the contrast could suggest a kind of trade-off such that context reduces some aspects of the bilingual disadvantage, but also introduces some disadvantage associated with the added burden of having to process syntax in a non-dominant language.

Thus, our inclusion of participants at three different levels of English proficiency strengthens the conclusions drawn here by demonstrating generalizability to a broad range of types of language users, and by manipulating frequency in more than one way (comparing high- and low-frequency words, and also comparing speakers who have used English exclusively/monolinguals versus those who used English relatively less frequently as a second language). At the same time, the results reported here provided additional evidence to constrain the frequency-lag account of bilingual disadvantages, demonstrating that it is more robust in production than in comprehension, and challenging this account by showing that slowing associated with bilingualism can arise without any interaction with frequency (e.g., in gaze duration times Experiment 2). Similarly, our results will constrain the interference model of bilingual disadvantages by demonstrating that context does not reduce bilingual disadvantages very much (only at the lowest proficiency level and only if it is highly semantically constraining context). Importantly, the two accounts of the bilingual disadvantage (frequency-lag and dual-language activation) are not mutually exclusive (see also Gollan et al., 2008), and it is likely that more than one mechanism will be needed to explain processing differences between bilinguals and monolinguals including disadvantages and advantages (Bialystok, Craik, Green, & Gollan, in press).

Conclusions. In the present study, we considered the joint effects of frequency, semantic constraint, and language proficiency, on lexical access in language comprehension and production and provided empirical evidence pointing to fundamental differences in lexical search between comprehension and production, thus confirming theoretically motivated reasons for expecting these differences. More specifically, multiple aspects of our data suggested that (a) production is a process driven by semantic constraint, whereas (b) comprehension is frequency driven. In addition, relative to comprehension, production is either less practiced, more difficult, involves a greater number of frequency-sensitive processing stages or some combination of these options. For this reason, (c) frequency effects can sometimes be larger in production than in comprehension (even in monolingual speakers, and even though access in production is semantically driven), (d) frequency and constraint interact in production but not (or much less so) in comprehension, and (e) bilingual disadvantages and language dominance effects are sometimes larger for production than for comprehension. It remains to be seen whether production will always necessarily lag behind comprehension for lexical access out of semantic context, or whether practice could attenuate this basic difference between modalities. However, the fundamental differences in cognitive processes underlying lexical selection in comprehension versus production likely cannot be attenuated by any amount of language use. In this respect, the data and interpretation presented here demonstrate flexibility in the language system to adjust its' representational and search mechanisms in order to optimize the differing needs when deriving meaning from lexical form compared to finding forms to express intended meanings, and places constraints on the extent to which the mechanisms of language comprehension and production can be shared or aligned in naturally occurring language use.

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Appendix A: First Fixation Duration and Total Fixation Times.

Fixations shorter than 80 ms that were within 1 character of a previous or subsequent fixation were combined with that fixation; all other fixations less than 80 ms were eliminated (2.5% of all fixations). Trials with track loss on or near the target word were also eliminated (4.6% of all trials). In addition, mean fist fixation duration, gaze duration, and total time on the target were calculated for each participant, and trials in which these measures was more than 2.5 SDs above the participant's mean were excluded from analyses. This trimming procedure excluded 4.2% of the monolinguals', 4.2% of the Spanish-English bilinguals', and 4.4% of the Dutch-English bilinguals' remaining sentence reading trials.

First fixations on high frequency target words were shorter than those on low frequency targets, [$F1(1,96) = 46.67$, $MSE = 347.25$, $\eta_p^2 = .33$, $p < .001$; $F2(1,88) = 29.35$, $MSE = 822.53$ $\eta_p^2 = .25$, $p = .001$]. However, the main effect of constraint was only marginally significant on first fixation duration, [$F1(1,96) = 2.87$, $MSE = 334.08$, $\eta_p^2 = .03$, $p = .094$; $F2(1,88) = 2.58$, $MSE = 811.63$, $\eta_p^2 = .03$, $p = .112$]. There was also a main effect of group, [$F1(2,96) = 3.63$, $MSE = 2510.09$, $\eta_p^2 = .07$, $p < .05$; $F2(2,176) = 28.51$, $MSE = 582.29$, $\eta_p^2 = .25$, $p < .001$]. Planned comparisons indicate that first fixation durations for monolinguals and Spanish-English bilinguals were not significantly different in the participants analysis ($F < 1$), but monolinguals first fixation durations were shorter than Spanish-English bilinguals in the items analysis, [$F2(1,89) = 4.24$, $p < .05$]. Additionally, Dutch-English bilinguals had longer first fixations than monolinguals ($p = 0.016$), and marginally longer first fixations than Spanish-English bilinguals ($p = 0.057$).

There was no indication of an interaction between frequency and constraint in the first fixation data; the benefit of a semantically constraining context was not larger for low frequency targets than for high frequency ones (both Fs < 1), and no interaction between group and frequency, slowing related to bilingualism was not greater for low-frequency than high-frequency targets, [no frequency by group interaction both *F*s < 1], nor was there a three way interaction between these variables, [$F1(2,96) = 1.12$, $MSE = 273.33$, $\eta_p^2 = .02$, $p = .33$; $F2(2,176) = 1.35$, $MSE = 571.79$, $\eta_p^2 = .02$, $p = .263$]. There was a significant constraint by group interaction, [$F1(2,96) = 3.82$, $MSE = 333.36$, $\eta_p^2 = .07$, $p < .05$; $F2(2,176) = 3.80$, $MSE = 571.79$, $\eta_p^2 = .04$, $p < .05$], not the interaction predicted based on the three-tiered manipulation of English proficiency; Spanish-English bilinguals benefited more from semantically constraining contexts than Dutch-English bilinguals, (ps < .05), and marginally more than the monolinguals, (ps < .06), but constraint effects between the two groups that differed most in English proficiency (monolinguals and Dutch-English bilinguals), did not differ, (both *F*s < 1). Summarizing the first fixation data, the most striking difference with respect to Experiment 1, was the lack of interactions in the reading data, but the presence of interactions in the production data, between frequency and constraint, and between frequency and participant group.

The pattern of results for total fixation times was similar to that found for first fixations and gaze duration. That is, total fixation time was shorter on high than low frequency targets, [$F1(1,96) = 78.47$, $MSE = 1397.63$, $\eta_p^2 = .45$, $p < .001$; $F2(1,88) = 23.58$, $MSE = 6206.42$, $\eta_p^2 = .21$, $p < .001$], and shorter on high than on low constraint targets, [$F1(1,96) = 11.83$, $MSE = 2002.53$, $\eta_p^2 = .11$, $p < .001$; $F2(1,88) = 11.21$, $MSE = 3943.63$, $\eta_p^2 = .11$, $p < .001$], and there was again a main effect of group indicating that total fixation times were shortest for monolinguals, [$F1(2,96) = 16.58$, $MSE = 14584.22$, $\eta_p^2 = .26$, $p < .001$; $F2(2,176) = 102.37$, $MSE = 3788.89$, $\eta_p^2 = .54$, $p = .001$]. Planned comparisons indicate that total fixation times for monolinguals and Spanish-English bilinguals were shorter than for Dutch-English bilinguals, (*p*s < .001), however, the difference between monolinguals and Spanish-English bilinguals was only marginal, (*p*s < .08). An examination of the interaction effects in the total time measure showed that there was still no indication that frequency interacted with constraint (both *F*s < 1).

Additionally, for the first time in the reading data, there was some hint of a greater frequency effect in bilinguals. However, this interaction between participant group and frequency was only marginally significant in the participants analysis, [$F1(2,96) = 3.08$, $MSE = 1397.63$, $\eta_p^2 = .06$, $p = .051$], and did not approach significance in the items analysis $F2(2,176) = 1.29$, $MSE = 3788.89$, $\eta_p^2 = .01$, $p = .278$]. Finally, the interaction between group and constraint that had been significant for first fixation and gaze duration was not significant for total fixation time, [$F1(2,96) = 1.15$, $MSE = 2002.53$, $\eta_p^2 = .02$, $p = .322$; $F2(2,176) = 1.89$, $MSE = 3121.03$, $\eta_p^2 = .02$, $p = .154$], and the three-way interaction did not approach significance (*F*s < 1).

Acknowledgements

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Table 1.
Average, standard deviation, and range of participant characteristics in Experiments 1 and 2.

	Experiment 1 – Picture Naming						Experiment 2 - Reading					
	Monolinguals (n = 50)		Spanish-English bilinguals (n = 50)		Dutch-English bilinguals (n = 45)		Monolinguals (n = 36)		Spanish-English bilinguals (n = 36)		Dutch-English bilinguals (n = 27)	
Participant Characteristic	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Age	20.3	1.6	20.0	3.5	19.3	1.5	20.4	1.5	20.3	1.6	19.4	1.5
AoA English	0.1	0.3	3.7	2.9	10.8	2.5	0.2	0.6	3.4	3.2	10.9	2.8
English self-rated speaking[a]	7.0	n/a[b]	6.5	0.8	5.1	0.8	7.0	n/a[b]	6.6	0.6	4.9	0.9
English self-rated reading[a]	7.0	0.1	6.5	0.8	5.5	0.7	6.9	0.2	6.7	0.5	5.6	0.7
Percent daily use of English	98.4	4.2	83.1	14.0	6.3	7.1	99.9	0.3	81.7	16.6	6.0	6.5
Percent daily reading in English	97.0	4.4	82.0	12.9	15.1	13.0	98.3	2.7	78.5	13.4	13.9	8.4
Percent correct on Shipley English vocabulary test	77.4	6.5	72.7	7.4	61.7	7.7	78.0	10.6	72.4	6.5	57.4	8.0

[a] Proficiency level based on self-ratings using a scale of 1-7 with 1 being “little to no knowledge” and 7 being “like a native speaker.”
[b] All monolinguals rated themselves at ceiling on this question.

Table 2. Name characteristics for items in high-frequency and low-frequency pairs in Experiments 1 and 2, and t-tests for the difference between high- and low-frequency targets.

		BYU corpus[a]	CELEX Total[a]	Celex Written[a]	Celex Spoken[a]	Kucera & Francis[a]	length in syllables	length in phonemes	length in letters	ortho-graphic N	phono-logical N	High Constraint Norming[b]	Low Constraint Norming[b]
high-frequency	M	79.8	85.4	88.2	48.9	82.0	1.4	4.2	5.4	3.7	10.8	87.5	3.0
	SD	78.3	75.6	76.0	90.0	76.8	0.5	1.1	0.8	3.8	7.2	14.0	6.0
	max	420.6	403.7	391.4	560.8	350.0	3.0	9.0	9.0	19.0	29.0	--	--
	min	14.9	12.7	13.7	0.8	6.0	1.0	3.0	4.0	0.0	0.0	--	--
low-frequency	M	9.3	9.8	10.4	3.3	9.4	1.4	4.4	5.4	3.3	9.7	85.5	2.0
	SD	5.1	7.6	8.0	4.0	8.7	0.5	1.0	0.8	3.2	7.4	13.0	4.5
	max	21.2	40.1	42.2	17.7	34.0	3.0	8.0	9.0	13.0	37.0	--	--
	min	1.3	0.0	0.0	0.0	0.0	1.0	3.0	5.0	0.0	0.0	--	--
	t-value	6.03	6.67	6.83	3.40	6.31	0.20	0.92	0.14	0.45	0.72	0.67	0.90
	p-value	0.00	0.00	0.00	0.00	0.00	0.84	0.36	0.89	0.65	0.47	0.51	0.37

[a]Values represent frequency per million.
[b]Percent of people (n=20) who entered the target word as the sentence completion in the constraint norming study.

Table 3. Participant means and standard errors in parentheses for eye-tracking measures in Experiment 2.

		Monolingual		Spanish-English Bilinguals		Dutch-English Bilinguals	
		Low Constraint	High Constraint	Low Constraint	High Constraint	Low Constraint	High Constraint
First Fixation	LF[a]	216 (5.1)	216 (5.3)	228 (5.1)	217 (5.2)	233 (5.9)	239 (6.1)
	HF[a]	210 (4.5)	205 (4.7)	212 (4.5)	205 (4.7)	221 (5.2)	220 (5.4)
Gaze Duration	LF	235 (6.9)	231 (6.8)	261 (6.9)	240 (6.8)	280 (8.0)	273 (7.8)
	HF	222 (6.7)	213 (5.8)	239 (6.7)	219 (5.8)	260 (7.8)	249 (6.7)
Total Time	LF	288 (12.4)	284 (12.8)	328 (12.4)	299 (12.8)	391 (14.3)	372 (14.8)
	HF	268 (11.1)	256 (10.2)	292 (11.1)	274 (10.2)	346 (12.8)	326 (11.8)
Skipping Rate	LF	13.1 (1.9)	22.3 (2.2)	9.9 (1.9)	13.2 (2.2)	4.7 (2.1)	9.7 (2.5)
	HF	18.3 (1.9)	21.1 (2.1)	14.7 (1.9)	11.7 (2.1)	8.0 (2.2)	11.5 (2.4)
Alt. Gaze Duration	LF	204 (9.0)	181 (8.8)	238 (9.0)	209 (8.8)	269 (10.4)	249 (10.2)
	HF	182 (8.3)	168 (7.5)	206 (8.3)	193 (7.5)	240 (9.6)	222 (8.7)

Note: All measures are in milliseconds except for skipping rate which is a percentage.
[a] LF = low-frequency, HF = high-frequency

Table 4. Summary of statistical significance (and effect size for contrasts of interest) in Experiments 1 and 2.

		Experiment 1				Experiment 2			
		significance		η_p^2		significance		η_p^2	
Out of Context 2 x 3 ANOVA									
Main Effects		F1	F2	F1	F2	F1	F2	F1	F2
Frequency	high-frequency < low-frequency	**	**	0.35	0.12	**	**	0.48	0.36
Participant Group	monolinguals < Spanish-English < Dutch-English	**	**	0.32	0.56	*	**	0.06	0.19
	Dutch-English vs. monolingual	**	**	0.40	0.56	*	*	0.08	0.26
	Spanish-English vs. monolingual	**	**	0.20	0.53	†	†	0.04	0.33
	Spanish-English vs. Dutch-English	**	**	0.14	0.32	*F* < 1	*	0.01	0.05
Interaction									
Frequency x Participant Group	bilingual disadvantage larger for low-frequency than for high-frequency targets	**	*	0.09	0.06	**	**	0.20	0.11
	Dutch-English vs. monolingual	**	*			**	**		
	Spanish-English vs. monolingual	*	*			*F* < 1	*F* < 1		
	Spanish-English vs. Dutch-English	†	†			**	**		
In Context 2 x 2 x 3 ANOVA									
Main Effects									
Frequency	high-frequency < low-frequency	**	**	0.49	0.13	**	**	0.45	0.22
Constraint	high-constraint < low-constraint	**	**	0.77	0.63	**	**	0.20	0.19
Participant Group	monolinguals < Spanish-English < Dutch-English	**	**	0.23	0.55	**	**	0.18	0.50
	Dutch-English vs. monolingual	**	**	0.29	0.56	**	**	0.25	0.67
	Spanish-English vs. monolingual	**	**	0.14	0.65	*	*	0.06	0.25
	Spanish-English vs. Dutch-English	**	**	0.08	0.26	**	**	0.10	0.39
2-way Interactions									
Frequency x Constraint	frequency effect is bigger in low-constraint than in high-constraint	**	*	0.23	0.04	*F* < 1	*F* < 1	--	--
	monolinguals	*	†			F < 1	F < 1		
	Spanish-English	**	n.s.			F < 1	F < 1		
	Dutch-English	**	†			F < 1	F < 1		

		Experiment 1				Experiment 2			
		significance		η_p^2		significance		η_p^2	
Frequency x Participant Group	bilingual disadvantage larger for low-frequency than for high-frequency targets	**	**	0.19	0.08	$F < 1$	$F < 1$	--	--
	Dutch-English vs. monolingual	**	**			F < 1	F < 1		
low constraint	Spanish-English vs. monolingual	*	$F < 1$			n.s.	F < 1		
	Spanish-English vs. Dutch-English	**	*			F < 1	F < 1		
	Dutch-English vs. monolingual	*	n.s.			F < 1	F < 1		
high constraint	Spanish-English vs. monolingual	n.s.	n.s.			F < 1	F < 1		
	Spanish-English vs. Dutch-English	n.s.	n.s.			F < 1	F < 1		
Constraint x Participant Group	bilingual disadvantage larger in low-constraint than in high-constraint	*	*	0.04	0.05	*	*	0.07	0.05
	Dutch-English vs. monolingual	**	*			F < 1	F < 1		
low frequency	Spanish-English vs. monolingual	n.s.	$F < 1$			*	*		
	Spanish-English vs. Dutch-English	*	†			†	†		
	Dutch-English vs. monolingual	$F < 1$	$F < 1$			F < 1	F < 1		
high frequency	Spanish-English vs. monolingual	$F < 1$	$F < 1$			n.s.	†		
	Spanish-English vs. Dutch-English	$F < 1$	$F < 1$			n.s.	n.s.		
3-way	bilinguals benefit more from constraint than monolinguals only for low-frequency targets	**	n.s.	0.08	0.02	$F < 1$	$F < 1$	--	--
	Dutch-English vs. monolingual	**	n.s.						
	Spanish-English vs. monolingual	n.s.	$F < 1$						
	Spanish-English vs. Dutch-English	*	n.s.						

**$p \leq .01$, *$p \leq .05$, † $p \leq .10$, n.s. = not significant but F > 1

Figure Captions.

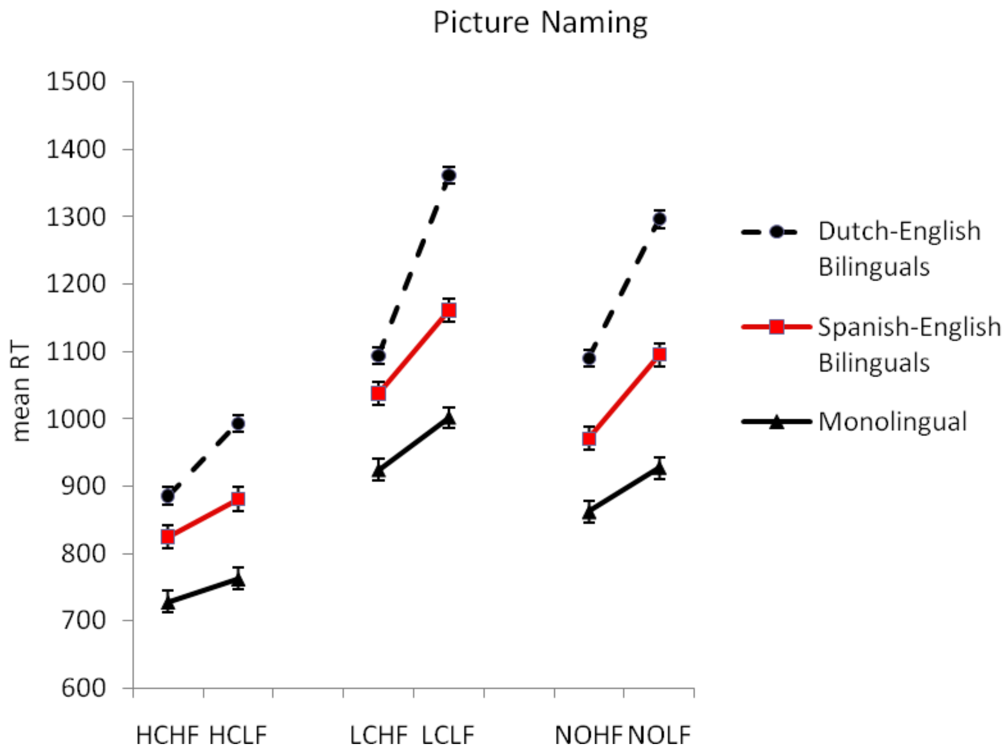
Figure 1. Picture naming times in milliseconds (top panel) and error rates (bottom panel) in each of the 6 conditions for each participant type in Experiment 1. Means are taken from participants analyses, error bars are standard errors for each condition. HC = high semantic constraint, LC = low semantic constraint, HF = high frequency, LF = low frequency, NO = no context.

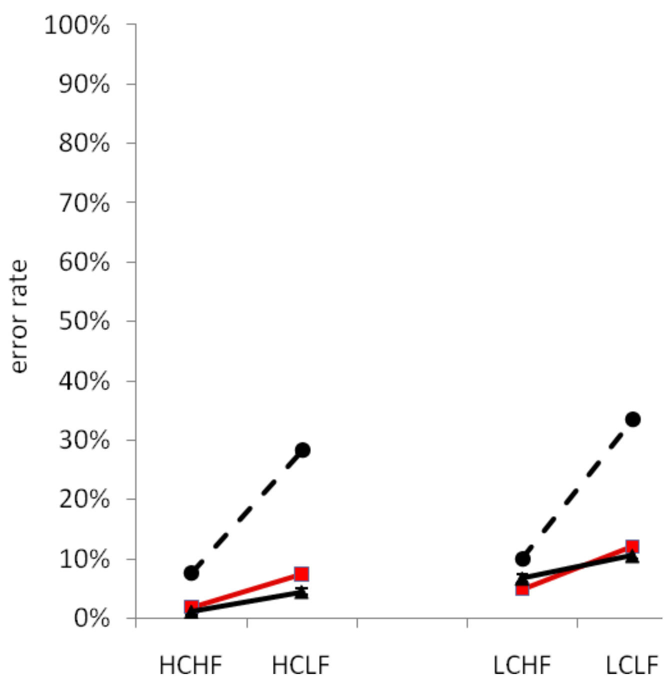
Figure 2. Lexical decision times in milliseconds (top panel) for high- and low-frequency targets in the out-of-context condition for each participant type in Experiment 2. Means are taken from participants analyses, error bars are standard errors for each condition. HF = high frequency, LF = low frequency, NW = nonword.

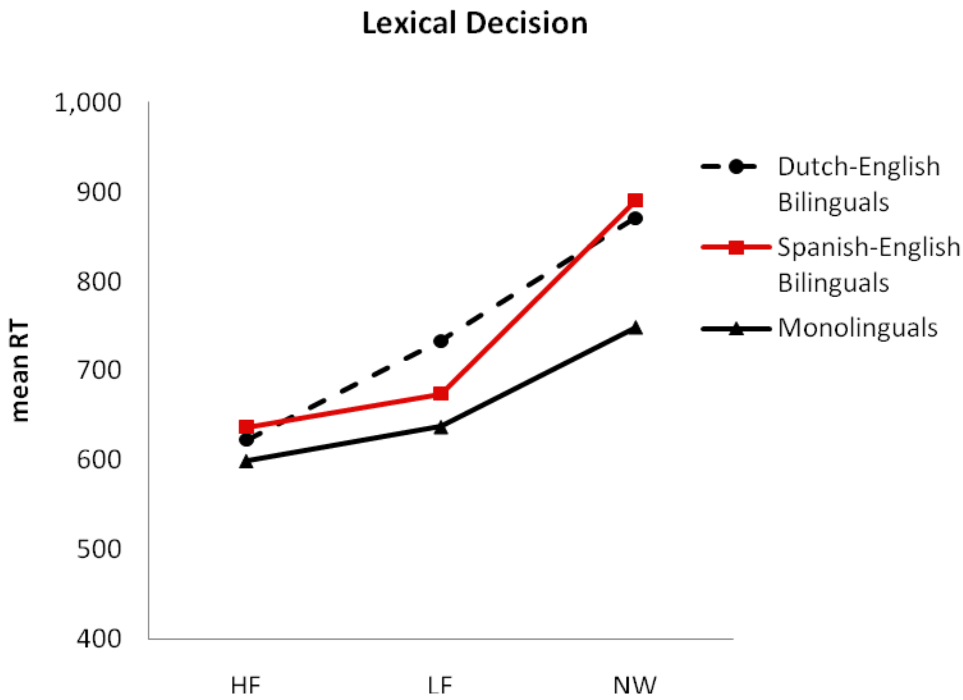
Figure 3. Gaze duration times in milliseconds (top panel) and word skipping rates (bottom panel) in each of the 4 in-context conditions for each participant type in Experiment 2. Means are taken from participants analyses, error bars are standard errors for each condition. HC = high semantic constraint, LC = low semantic constraint, HF = high frequency, LF = low frequency.

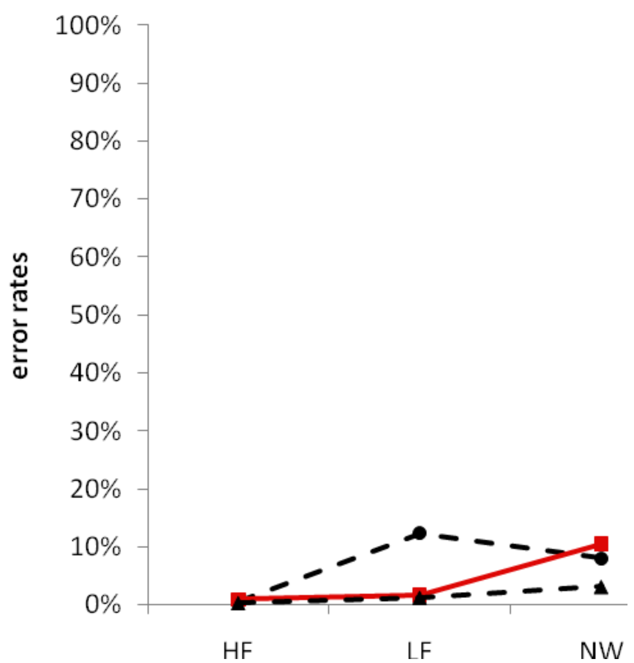
Figure 4. The size of the frequency effect in each condition in picture naming (Experiment 1) and reading (Experiment 2) as a proportion of baseline (LF – HF)/((LF + HF)/2)) for monolinguals (panel A), Spanish-English bilinguals (panel B), and Dutch-English bilinguals (panel C). The size of the frequency effect was calculated using picture naming times for all conditions Experiment 1, gaze duration times for in-context reading, and lexical decision times for out-of-context reading in Experiment 2.

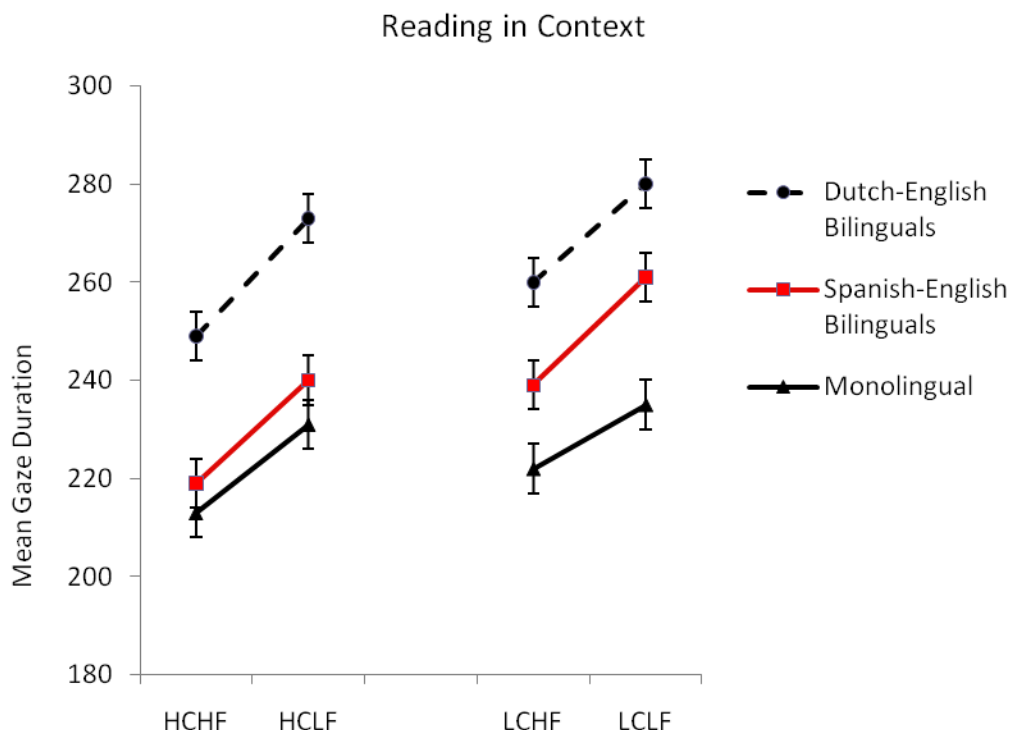
Figure 5. The effects of frequency and constraint on picture naming times (panel A) and gaze duration times (not adjusted for skipping; panel B) in 5 vincentile bins reflecting participants' fastest and slowest (and three levels in between) response times in each condition (see text for additional explanation). Note that the scales on the y-axes were set to maximize differences between the four points in each bin.

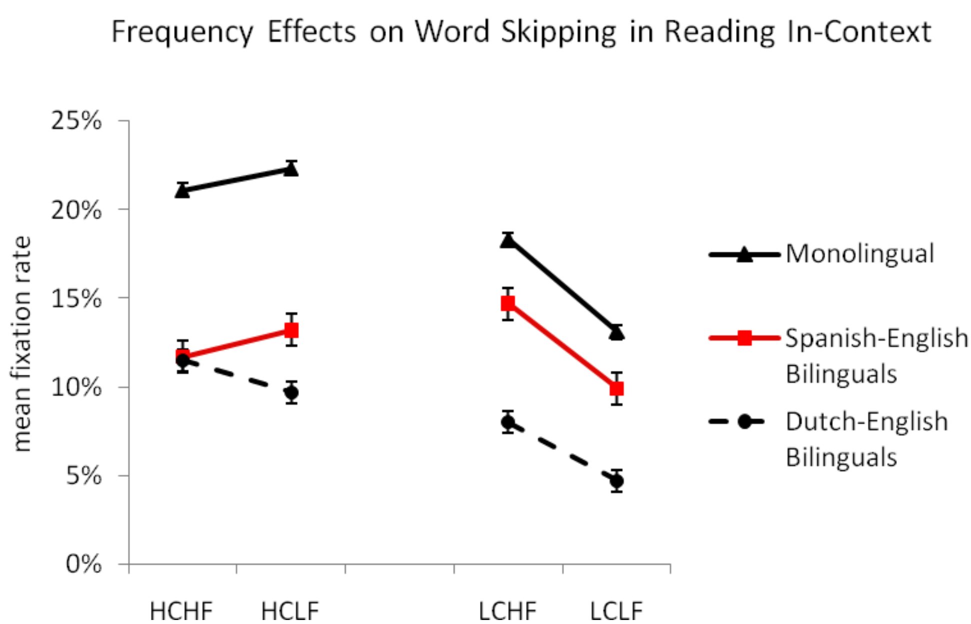

Picture Naming
mean RT
1500
1400
1300
1200
1100
1000
900
800
700
600
HCHF HCLF
LCHF LCLF
NOHF NOLF
Dutch-English Bilinguals
Spanish-English Bilinguals
Monolingual

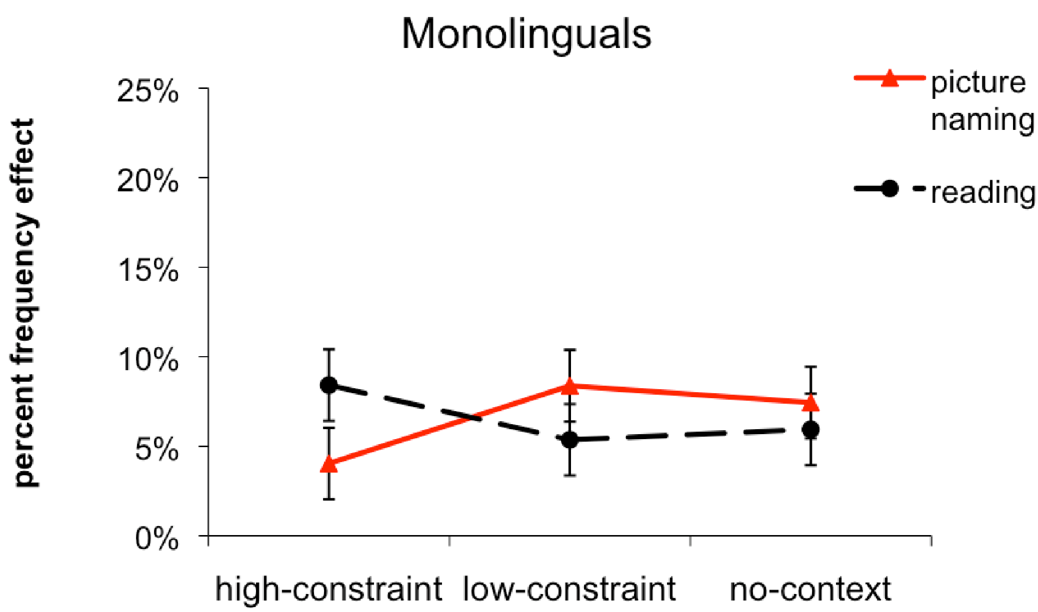

error rate
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
HCHF
HCLF
LCHF
LCLF


Lexical Decision
1,000
900
800
700
600
500
400
mean RT
HF
LF
NW
Dutch-English Bilinguals
Spanish-English Bilinguals
Monolinguals

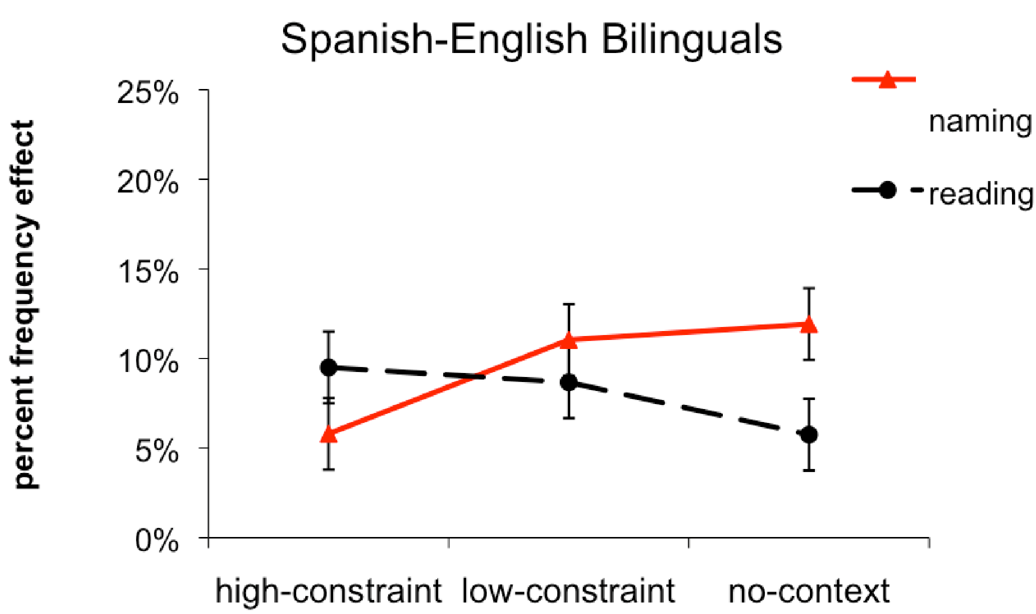

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
error rates
HF
LF
NW


Reading in Context
Mean Gaze Duration
300
280
260
240
220
200
180
HCHF
HCLF
LCHF
LCLF
Dutch-English Bilinguals
Spanish-English Bilinguals
Monolingual

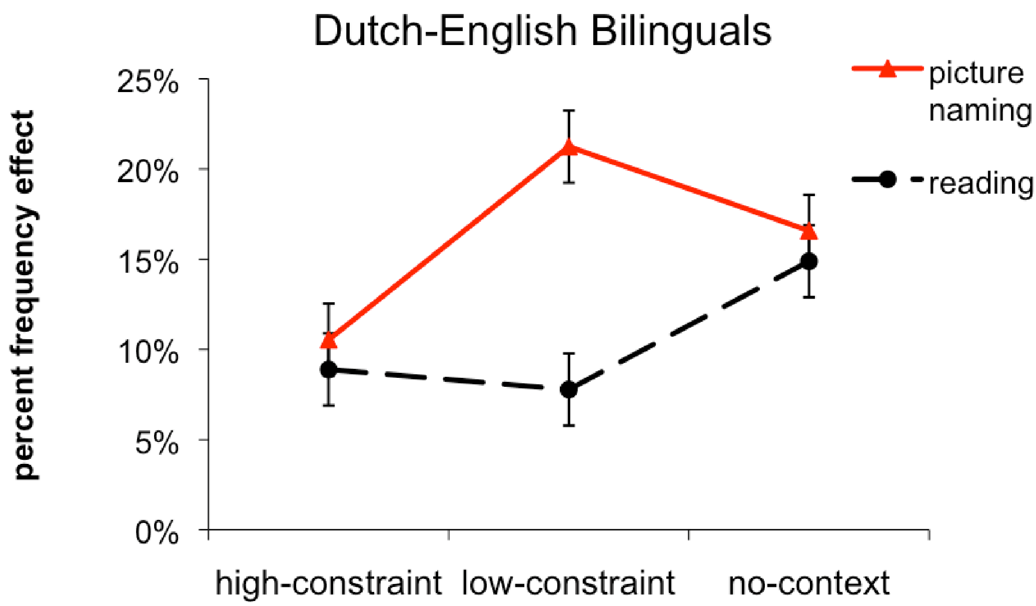

Frequency Effects on Word Skipping in Reading In-Context
mean fixation rate
25%
20%
15%
10%
5%
0%
HCHF
HCLF
LCHF
LCLF
Monolingual
Spanish-English Bilinguals
Dutch-English Bilinguals



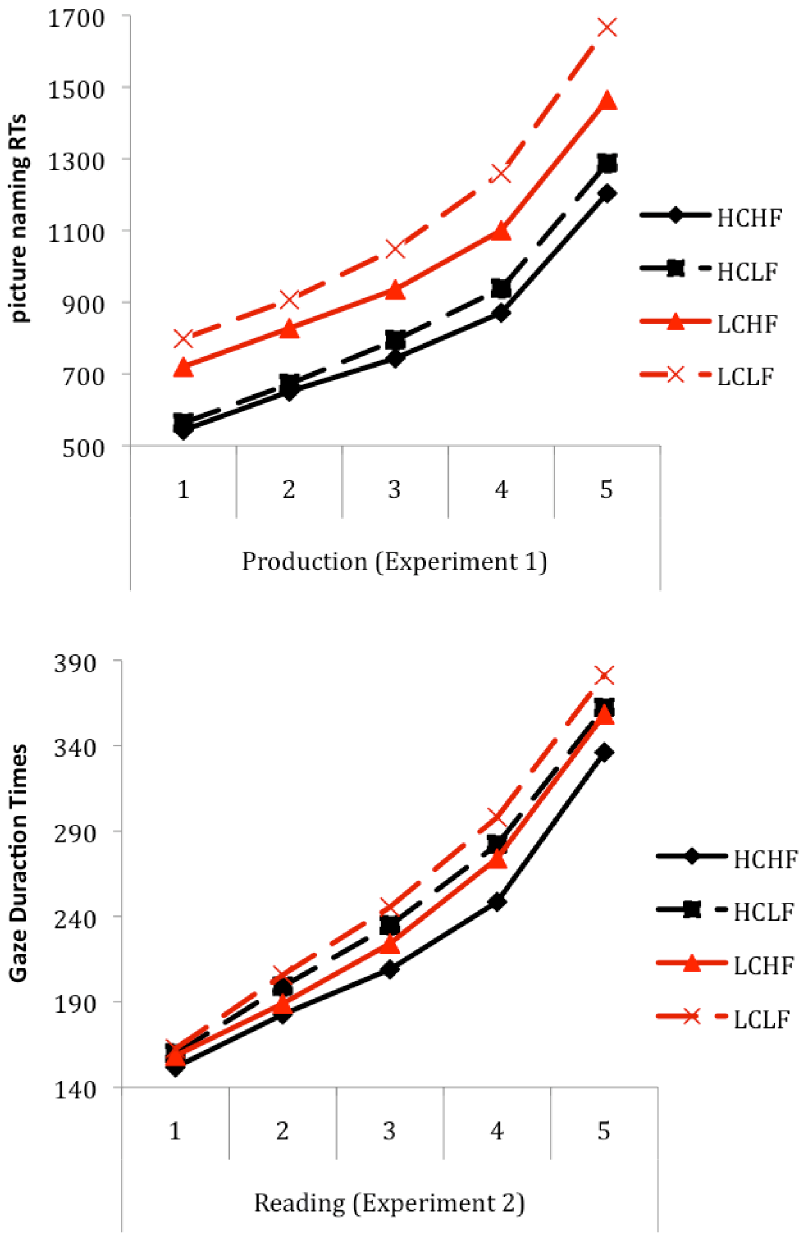
panel A



panel B


Dutch-English Bilinguals
picture naming
reading
percent frequency effect
25%
20%
15%
10%
5%
0%
high-constraint
low-constraint
no-context

panel C


picture naming RTs
1700
1500
1300
1100
900
700
500
1
2
3
4
5
Production (Experiment 1)
HCHF
HCLF
LCHF
LCLF
Gaze Duraction Times
390
340
290
240
190
140
1
2
3
4
5
Reading (Experiment 2)
HCHF
HCLF
LCHF
LCLF