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Constraint, Word Frequency, and the Relationship between Lexical Processing Levels in Spoken Word Production

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Producing a word to express a meaning requires the processes of lexical selection and phonological encoding. We argue that lexical selection is influenced by contextual constraint and phonological encoding by word frequency, and we use these variables to assess the processing relations between selection and encoding. In two experiments we examined latencies to name pictures presented within sentences. The sentences varied in degree of constraint, whereas the target picture-names varied in frequency. In both experiments, targets that followed constraining sentences showed substantially reduced frequency effects. When the targets followed incongruent sentence frames, the frequency effect returned. The results offer new support for the predictions of cascade theories of word production.

Word frequency and contextual constraint have traditionally been studied as factors important to the recognition of words. Words that are high in frequency are processed with greater speed and accuracy than are low-frequency words in many tasks, such as visual word naming and lexical decision (e.g., Forster & Chambers, 1973), auditory lexical decision (e.g., Taft & Hambly, 1986), and normal reading, as reflected in eye movement records (e.g., Rayner, 1977). In these same tasks, words that are somewhat predictable are identified more rapidly and successfully than less predictable words (e.g., Fischler & Bloom, 1979; Inhoff, 1984; Moss, Ostrin, Tyler, & Marslen-Wilson, 1995; Stanovich & West, 1979).

The effects of frequency and contextual constraint have received less attention in the production of language. Although a speaker's choice of words is surely driven more by the thought to be conveyed than by the use of words in past conversations, various consequences of word frequency and contextual constraint are evident in the fluency of speech. In addition, the nature of the relationship between lexical frequency and word-selection constraints is a key point of debate in theories of word production, inasmuch as the theories postulate fundamentally different relationships between the representations they directly influence. To investigate this relationship, we begin with a sketch of current views about word production, and then consider evidence about how the processes are affected by frequency and constraint.

Word Production Processes

A basic point of agreement in word production research is that retrieving a word during normal speech requires at least two lexically specific steps (e.g., Bock, 1987; Dell & O'Seaghdha, 1992; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997; Kempen & Huijbers, 1983; Levelt, 1989). One of these steps

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recruits lexical-semantic and syntactic information, while the second recruits phonological information (i.e., the sounds and perhaps the prosody).

The motivation for two different lexical stages came originally from speech error data, which suggested that the characteristics of word exchanges (e.g., saying *the map on the cat* instead of *the cat on the map*) and semantically related word substitutions (e.g., saying *dog* instead of *cat*) are different from those of sound exchanges (e.g., saying *keggy lat* for *leggy cat*) and phonologically related word substitutions (e.g., saying *cab* for *cat;* Butterworth, 1982; Fromkin, 1971; Garrett, 1975). Further evidence came from picture-word interference studies, which demonstrated different time courses for semantic and phonological effects (e.g., Levelt, Schriefers, Vorberg, Meyer, Pechmann, & Havinga, 1991; Peterson & Savoy, in press; Schriefers, Meyer, & Levelt, 1990). Recent studies probing the information available in anomic and normal tip-of-the-tongue states provide converging evidence for two separate retrieval operations (Badecker, Miozzo, & Zanuttini, 1995; Miozzo & Caramazza, 1997; Vigliocco, Antonini, & Garrett, 1997). These studies show that Italian speakers who are unable to name a word nonetheless know word-specific grammatical information about the word they want to say. This is true even when they have little knowledge of the word's sounds. For instance, grammatical gender in Italian is not derivable from conceptual information or, in the conditions of these experiments, from partial phonological information. Rather, determining gender requires accessing information specific to the intended word. Thus, it appears possible to access a word's meaning and syntactic information without simultaneously retrieving phonological information. Accordingly, most theories of production postulate a step in which lexical entries for words (*lemmas*) are selected based on message specifications, making grammatical information available, and another step in which phonological information is retrieved and assembled (e.g., Dell et al., 1997; Garrett, 1975; Kempen & Huijbers, 1983; Levelt, 1989; Roelofs, 1992).

Despite broad agreement about the existence of two functional stages, the relationship between them is a focus of controversy. One class of theories holds that phonological encoding can begin before word selection is completed, so the two stages are not wholly independent (e.g., Dell et al., 1997; MacKay, 1982; Riddoch, 1987; Stemberger, 1985). These will be referred to as cascade theories. Note that this class includes interactive activation models in which representations used early in processing may affect and be affected by the state of later representations (e.g., Dell et al., 1997) as well as cascade models that simply permit early representations to activate later ones before early processing is completed (e.g., Riddoch, 1987). The most compelling evidence for cascaded processing is Peterson and Savoy's (in press) demonstration that, when naming an object that can be denoted with near synonyms (e.g., an upholstered piece of living room furniture can be called a *couch* or a *sofa*), phonological encoding is initiated for both alternatives. Peterson and Savoy found that preparing to name a picture of a couch facilitates pronunciation of the words *count* (phonologically related to *couch*) and *soda* (phonologically related to *sofa*) at short picture-word stimulus-onset asynchronies (SOAs). At longer SOAs, facilitation was found only for words phonologically related to the modal picture names, not for words phonologically related to synonyms of the names. This suggests that phonological encoding of both candidates, *couch* and *sofa*, is begun before lemma selection is completed. After selection, phonological encoding continues only for the selected word. Thus, phonological word-forms receive continuous information about the processing of lemmas.

A different view is that selection and phonological encoding take place in discrete stages (e.g., Butterworth, 1989; Garrett, 1975, 1988; Levelt, 1989; Levelt, Roelofs, & Meyer, in press; Roelofs, 1992): Word selection precedes phonological encoding, with selection completed before encoding begins. Critically, there is no influence from activity during lemma selection on phonological encoding. Evidence for the temporal discreteness of the two stages comes from a study by Schriefers, Meyer, and Levelt (1990). In a picture-word interference study, auditorily presented distractor words that were semantically related to a target-picture name (e.g., the word *goat* presented with a picture of a sheep) interfered with its production only when presented 150 ms before the target. In contrast, phonologically related distractors (e.g., the word *sheet* presented with a picture of a sheep) affected picture naming only when presented simultaneously with the picture onset or 150 ms after the picture appeared. Thus, at none of the three tested points was there simultaneous sensitivity to both semantically and phonologically related distractors. This is consistent with the idea of independent processing stages.

A further implication of the strong separation between lemma selection and phonological encoding is that factors acting only at the word-selection stage should have no consequences for phonological encoding. In Roelofs' (1992) model, a pointer from a lemma to its phonological form only becomes available with the lemma's selection, and in Butterworth's (1989) theory, the output of the word selection stage is an address in a phonological lexicon. Thus, following word selection, phonological processes are set in motion unaffected by any events during selection itself. Regardless of whether the forces that favor selection of a particular word are strong or weak, and whether selection is slow or fast, all selected lemmas begin phonological encoding as equals. In contrast, cascade theories predict that facilitation during word selection can accrue to subsequent phonological encoding. To set the stage for testing these predictions, in the next two sections we lay out the arguments for associating constraints from message specifications with the process of selection, and word frequency with the process of phonological encoding.

Effects of Constraint in Word Production

In word production, the pragmatic and semantic specifications of a concept to be expressed drive the selection of a lemma. Selection is hypothesized to occur when a lemma is identified that satisfies a particular set of specifications. To the degree that this process is simplified by richer message specifications, lexical selection should be affected by redundancy. Here we are using *redundancy* to refer to the degree of constraint on word selection due to specifications of meaning, grammatical class, connotations, and so on (see Shannon, 1951). A lexical entry is redundant to the extent that message specifications and constraints activate it and no other entries. Thus, either increasing the number of candidates or decreasing the constraints for selection results in less redundancy.

There are at least two lines of evidence showing that redundancy in message specifications strongly facilitates word selection. The first involves the choice of object names. Many studies have demonstrated substantial name-agreement effects in object naming but not in object recognition tasks (e.g., Johnson, 1992; Lachman & Lachman, 1980; Wingfield, 1967, 1968). The more alternative names there are for an object, the longer it takes to select and produce one. Presumably fewer message features are active for an object with low name-agreement and the features that are present do not converge on a single word. In contrast, basic-level names (e.g., *cat* vs. *animal* or *Siamese*) and names for objects that are typical of the categories to which they belong (e.g., a cat vs. a whale as mammals) are produced more readily and reliably than nonbasic-level terms and atypical object names (e.g., Brown & Lenneberg, 1954; Lachman, 1973; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). Basic-level categorizations differ from others in being overdetermined, with "attributes common to all or most members of the category" (Rosch, 1978, p. 31). Likewise, typical objects are "those members of a category that most reflect the redundancy structure of the category as a whole" (Rosch, 1978, p. 37). Assuming that the redundant attributes are incorporated into message specifications for such objects, the consistency with which the names are produced (i.e., selected) can be attributed to redundancy facilitating their selection.

Conversely, members of the same taxonomic category (e.g., squirrel and chipmunk) interfere with one another when presented as target and distractor name in tasks such as picture naming (e.g., Lupker, 1979; Wheeldon & Monsell, 1994), word generation from definitions (La Heij, Starreveld, & Steehower, 1993), cued recall (Humphreys, Lloyd-Jones, & Fias, 1995), and translation (e.g., La Heij et al., 1990). This inhibitory effect of taxonomically related distractors in word production can be seen as a consequence of reducing the redundancy of message features.

A second line of evidence for the effect of redundancy on selection comes from hesitations in speech. Since hesitations often signal problems in lexical access, it is noteworthy that hesitations rarely precede words that are highly constrained by the subject matter (Schachter, Christenfeld, Ravina, & Bilous, 1991; Schachter, Rauscher, Christenfeld, & Crone, 1994) or by grammatical function (Goldman-Eisler, 1958; Maclay & Osgood, 1959). Complementary findings from experimental manipulations of contextual constraint show that words are produced faster in sentence contexts when they are predictable in that context (Cohen & Faulkner, 1983; Goldman-Eisler, 1958b; Griffin, 1995; Zacks, Hasher, & Griffin, 1994), whereas words are produced more slowly with increases in the number of context-appropriate synonyms for them (Daneman & Green, 1986; see also Lachman, 1973).

These results indicate that the redundancy of a word for a speaker strongly affects its production. Because redundancy in this sense is a product of how much converging evidence the communicative intention provides for a particular word's semantic specifications, the observed effects are most plausibly associated with selection processes.

Effects of Word Frequency in Word Production

Like redundancy, word frequency is associated with variations in lexical processing. Oldfield and Wingfield (1965) were the first of many to report word-frequency effects on picture naming latencies (e.g., Bartram, 1974; Humphreys, Riddoch, & Quinlan, 1988; Huttenlocher & Kubicek, 1983; Jescheniak & Levelt, 1994; Lachman, 1973; Lachman, Shaffer, & Hennrikus, 1974). The time needed to translate words from one language to another is also sensitive to the frequency of the response word (e.g., Cattell, 1887/1949; de Groot, 1992; Jescheniak & Levelt, 1994). In both cases, higher frequency words are initiated more rapidly.

There is mounting evidence that the word-frequency effect found in word production is due mainly to accessing the phonological forms of words. When tasks are specifically chosen to delineate the processes thought to underlie word production, frequency effects have been found primarily in those tasks requiring phonological encoding (Jescheniak & Levelt, 1994). For instance, tasks associated with conceptual identification such as category naming and same-different decisions for words and pictures are not sensitive to word frequency (Wingfield, 1967, 1968). Likewise, execution of articulatory movements to pronounce a word does not consistently give rise to a frequency effect (Forster & Chambers, 1973).

Further support for attributing frequency effects to phonological forms comes from studies of homophone production. Homophonous words like *bank* (the side of a river) and *bank* (a financial institution) must have separate lexical entries to reflect their different meanings and, in some cases, syntactic features. However, they have the same phonological shape, and may consequently share a phonological representation. If they do, the frequency of accessing the phonological representation would be greater than the frequency of either word alone. Consistent with this, response latencies for producing low-frequency meanings of homophones such as *weak* or (river) *bank* resemble those for high-frequency words matched to high-frequency meanings (Jescheniak & Levelt, 1994). Similarly, Dell (1990) found that high- and low-frequency meanings of homophones were equally involved in experimentally elicited slips of the tongue, even though low-frequency words are generally more vulnerable to phonological speech errors than are high-frequency words (Stemberger & MacWhinney, 1986). Furthermore, the frequency of a homophone's phonological form (as opposed to the frequency of a homophone's meaning) was a more reliable predictor of speech errors in Dell's study. Based on these results, homophones are hypothesized to share a single phonological representation which encodes their joint frequencies, but to have different lemmas representing their separate semantic and syntactic specifications (Griffin, 1995; Jescheniak & Levelt, 1994). The frequency of use for the shared phonological representation determines the behavior of homophones in production measures sensitive to word frequency.

More evidence comes from word substitution errors. There are two kinds of word substitutions, semantic (e.g., saying *dog* for *cat*) and phonological (e.g., saying *cab* for *cat*). Semantically related substitutions are thought to be selection errors, because the substitute's semantic specifications resemble those of the intended word. In contrast, phonologically related substitutions appear to result from errors in phonological encoding, because the substituted word sounds like the intended word but means something different. In keeping with the view that frequency affects phonological-form retrieval more than selection, speech error corpora show that the frequency of substituted words tends to be higher than that of intended words in phonological word-substitutions, but not in semantically related word-substitutions (del Viso, Igoa, & Garcia-Albea, 1991; Hotopf, 1980; Kelly, 1986; but see Levelt, 1989).

In sum, there is converging evidence from studies of ambiguous and unambiguous words, from latency and error measures, and from errors in spontaneous speech that frequency effects in production are often traceable to the phonological form. But we should note that the picture is not entirely consistent. There is some evidence that when word selection is unusually difficult due to time pressure or brain damage, frequency may influence selection by making high-frequency words more likely to be selected (e.g., Kirshner, Webb, & Kelly, 1984; Nickels & Howard, 1994; Santo Pietro & Rigordsky, 1982; Vitkovitch & Humphreys, 1991). Also, a weak frequency effect has been found in gender decision latencies (deciding whether a Dutch word takes the determiner *het* or *de;* Jescheniak & Levelt, 1994). So, although the frequency effects found in phonological encoding are larger and more reliable than those found in selection, there may be circumstances in which selection reacts to the frequency of forms. This takes us back to the question of how selection and form retrieval are coordinated in the course of production.

Constraint and Word Frequency in Production Theories

In both discrete-stage and cascade theories, constraint should influence the time course of selection. Constraint decreases competition among lemmas by reducing the number of competitors or magnifying the strength of one candidate. In contexts with few constraints, many lemmas may be activated as potential candidates for expressing the specifications of the message. These lemmas compete for selection. The greater the competition is, the longer the selection process takes. Redundant contexts, in contrast, produce a set of specifications with which fewer lemmas are consistent. Thus, competition is lower and a lemma can be selected more rapidly. This has been incorporated in both types of theories using Luce's choice rule (e.g., Roelofs, 1992) and mutual inhibitory connections (e.g., Stemberger, 1985). Regardless of the mechanism, relative strength and number of competitors have the same effect.

The two classes of theories diverge in their treatment of word frequency. The cascade models that allow bi-directional flow of activation accommodate frequency effects in both selection and phonological processing by appealing to feedback of activation from phonological forms to lemmas (Dell, 1990; Griffin, 1995). Two-stage theorists, on the other hand, attribute frequency effects primarily to phonological encoding (Jescheniak & Levelt, 1994; Levelt & Wheeldon, 1994).

In line with their differing assumptions about the coordination of selection and retrieval, discrete-stage and cascade theories also make different predictions about how constraint and word frequency combine to affect word production. In discrete-stage theories (e.g., Butterworth, 1989; Levelt et al., in press; Roelofs, 1992), constraint affects the outcome and speed of lemma selection, but not the subsequent phonological encoding. Thus, any effects that occur during phonological encoding are impervious to redundancy. Accordingly, any effects of frequency in phonological encoding should simply sum with the effects of constraint in lemma selection.

In cascade theories the picture is different. Constraint affects the activation levels of lemmas, but because lemmas continually send activation on to their phonological forms, constraint indirectly affects phonological processing as well (e.g., Dell, 1986; Dell et al., 1997; MacKay, 1982; Stemberger, 1985). In itself this continuous flow of activation does not predict a change in the effect of frequency on phonological encoding. However, limits on activation levels prevent processing from undergoing unlimited facilitation, modulating frequency effects at different levels of constraint. Figure 1 shows how these two properties impact the activation of forms when a logistic function determines activations. Given equivalent degrees of constraint, selected lemmas for high- and low-frequency words send equal amounts of input activation, I, to their phonological forms. Frequency differences in resting levels of activation, R, determine how far from asymptote each form's activation is initially and thereby affect how much a form may benefit from input activation. Changes in the height on the curve in Figure 1 represent the degree to which a form increases in activation, Δa. High-frequency forms start off higher on the activation curve than low-frequency forms do, but this means that they begin at points where the activation function has a shallower slope. Consequently, low-frequency words benefit more than high-frequency words from the same amount of constraint. When constraint is low or moderate, a difference in activation between high- and low-frequency forms remains after selection because phonological forms remain relatively close to their resting activation levels. Increased constraint facilitates the production of low-frequency forms more than high-frequency forms, diminishing the difference between the two.

In summary, discrete-stage theories predict that phonological encoding will be unaffected by the amount of evidence (i.e., redundancy or constraint) guiding lemma selection. Cascade theories predict that greater support for a selected word facilitates its phonological encoding. So, a critical difference between classes of theories stems from the limits the theories place on the communication and use of information during selection and retrieval.

In the following experiments, we tested these predictions using a picture naming task. The first experiment established benchmark frequency effects for our picture materials when the pictured objects were named in isolation. In Experiments 2 and 3, the same high- and low-frequency pictures were presented, rebus-style, as completions for sentence frames of low, medium, or high contextual constraint. Experiments 2 and 3 differed in the proportion of constrained picture-name completions that participants encountered, in order to assess any differences due to strategic prediction of pictures from sentence frames. In these last two experiments, we examined how latencies to name the pictures changed under different conditions of frequency and constraint.

EXPERIMENT 1

Experiment 1 was a simple picture naming study. Its purpose was to establish that the materials to be used in subsequent studies produced reliably faster naming latencies for high-frequency than for low-frequency words when the pictures were presented in isolation. In addition, the pictures were named three

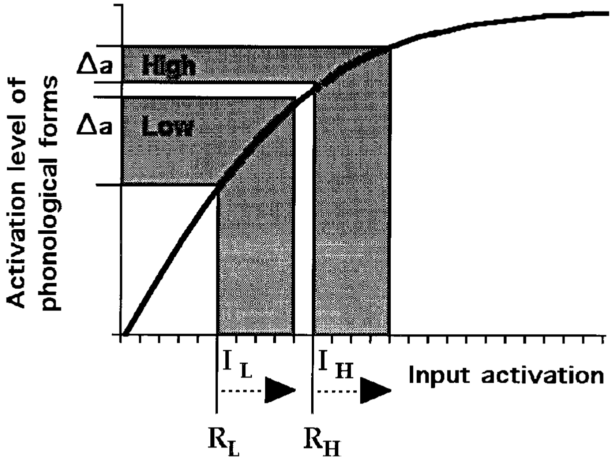

FIG. 1. The diagram illustrates that the same amounts of input activation from contextual constraint in a cascade model may benefit low-frequency phonological forms (Low) more than high-frequency forms (High). The curve shows the upper region of a logistic function in which the activation level of a phonological form, *a,* is equal to $1/(1 + e^{-(R + I)})$, where *R* is the resting level of activation and *I* is the activation from input. The input activation from a selected lemma causes the activation level of a form to increase by Δa in accordance with the activation function. Higher resting levels of activation place high-frequency forms closer to the asymptote of the activation function initially. Their activation levels are less affected by input activation due to the nonlinearity of an activation function.

times in the course of the experiment to determine whether the magnitude of the high-frequency advantage diminished with repetition, as is typically found in word recognition (e.g., Scarborough, Cortese, & Scarborough, 1977) and picture naming studies (e.g., Oldfield & Wingfield, 1965).

The design of the experiment incorporated one unique feature. In order to separate the effects of repeating specific pictures from the general effects of practice on the picture naming task, new experimental items were introduced at different points in the stimulus list. Although it is highly unlikely that a general practice effect could account for much (if any) of the large facilitatory effect typically found in studies of repetition, previous production studies do not permit one to disentangle the effects of the repetition of individual items from experience in performing the task.

Method

Participants. Thirty-three undergraduates at the University of Illinois participated to fulfill a requirement of an introductory psychology course or in return for $5. All were native speakers of American English.

Materials. The stimuli consisted of 60 pairs of pictures with high- and low-frequency names. Half of the pairs were fillers and half were the critical stimuli. The majority of the pictures came from Snodgrass and Vanderwart (1980), and the remainder from the Huitema collection (1996). The high-frequency critical stimuli had names with a mean frequency of 110 occurrences per million in the CELEX spoken frequency count (Baayen, Piepenbrock, & Van Rijn, 1993) and 183 in the Francis and Kucera (1982) count of written words; low-frequency names had mean counts of 15 and 28 in each database respectively. Each high-frequency picture was matched with a low-frequency picture on name agreement (.95 agreement for high and .97 for low; Huitema, 1996). High- and low-frequency picture-names had an equal number of syllables and were also matched on number of phonemes (3.43 and 3.50 for high and low), and initial phoneme (24 exact matches, 3 pairs beginning in vowels, and 3 pairs with slightly different features). Object-decision latencies (time to identify a pictured object as real) were available from Huitema (1994) for 29 of the 30 pictures with high-frequency names and for 26 of the 30 with low-frequency names. Unpaired *t* tests indicated that the high- and low-frequency pictures did not differ significantly in object-decision latencies (566 vs. 586) or accuracy (.975 vs. .975), *t*s <1. This suggests that the high- and low-frequency pictures were equally recognizable.

Apparatus. The experiment was run on a Macintosh Quadra 650. Participants wore Shure SM10A microphone headsets which were connected to PsyScope button boxes acting as voice keys and providing millisecond timing accuracy (Cohen, MacWhinney, Flatt, & Provost, 1993). Pictures were displayed on 17 in. Macintosh monitors. The same apparatus was used in all experiments reported here.

Design and procedure. Participants were tested individually. They were instructed to quickly and accurately name each picture shown. Pictures were displayed in a 6×6 cm square area in the center of the computer screen and remained visible until the voice key was triggered. A 1.5 s intertrial interval followed. Participants were allowed to rest between blocks. An experimenter was present throughout the experiment noting each response and whether the voice key triggered with the onset of the response.

Critical stimuli were divided into three groups (A, B, and C) of 10 matched pairs of high- and low-frequency pictures. Filler pictures were placed in three groups (X, Y, and Z) of 20 pictures each. The stimulus list included all critical stimuli and fillers assembled into five blocks of 60 pictures each. The sequence of picture groups is shown in Table 1. In order to reduce the confounding of presentation with position in the experiment, the following scheme was used. In the first block, the first presentation of Group A critical items occurred with two filler pictures intervening between each critical picture. Both groups X and Y of the filler pictures were presented once in the first block. In the second block, participants saw Group A pictures for the second time and Group B for the first time, interleaved with second presentations of Group X fillers. In the third block, Group A pictures were presented for the third and final time, while Group B pictures appeared for the second time and Group C pictures for the first time. No fillers appeared in the third block. The fourth block consisted of pictures from Groups B, C, and Y, and the fifth and final block contained pictures from Groups C, Z, and Y. No consecutive pictures were ever presented in the same order twice. This was accomplished by changing the orders of filler pictures and critical pictures from one block to the next such that presentations of the same critical picture were separated by 58-62 intervening pictures. Three stimulus lists were created by rotating the groups of critical pictures through each Group A, B, and C, in a Latin square design. Each participant saw only one stimulus list.

TABLE 1

Counterbalancing Design Employed in Experiment 1

	Order within block		
Block	1st	2nd	3rd
1	X	Y	A
2	B	X	A
3	C	B	A
4	C	Y	B
5	C	Z	Y

Word frequency and presentation number were within-subjects factors. Each participant received 30 high-frequency and 30 low-frequency pictures, and saw every picture three times in the course of the experiment. Presentation (first, second, or third display of a picture) was manipulated within items and frequency (high- vs. low-frequency picture-name) was manipulated between items.

Results

Critical trials were excluded from further analysis if the voice key was not validly triggered (3.4% of the trials), the target picture

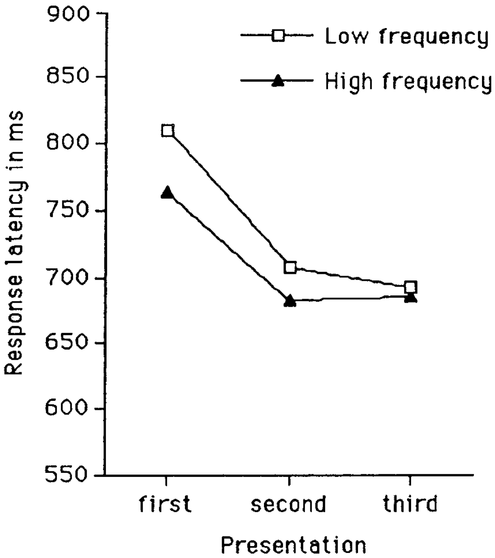

FIG. 2. The picture naming latencies displayed were calculated using subject means from Experiment 1. The corresponding item means for first, second, and third presentations, respectively, were 819, 704, and 691 ms for low-frequency names, and 764, 682, and 681 ms for high-frequency names.

name was not produced (2.8%), or if on an earlier trial the naming of the item was flawed, altering the number of times the item was named correctly (3.6%). Responses were also excluded if their latencies were greater than 3 s or less than 200 ms, or beyond 2.5 standard deviations of a participant's mean latency for the remaining correct responses (2.8%[1]). All means reported below were calculated over subjects, but two sets of analyses of variance were performed on the data, one based on subject variability (F_1) and the other based on item variability (F_2). The alpha level was set at .05.

Figure 2 displays the mean response latencies for each condition. Overall, high-frequency picture names were produced faster than low-frequency names. With repeated picture presentations, responses became faster (averaging 787 ms on the first presentation, 696 ms on the second), although the third presentation showed little improvement over the second (690 ms). The magnitude of the frequency effect decreased from 46 ms on the first presentation to 25 on the second and 7 on the third presentation. These observations were supported by 2 (Frequency) by 3 (Presentation) analyses of variance. There were significant main effects of frequency, $F_1(1,32) = 22.9$; $F_2(1,58) = 5.9$, and presentation, $F_1(2,64) = 205.8$; $F_2(2,116) = 155.3$. The interaction between frequency and presentation was also significant, $F_1(2,64) = 12.2$; $F_2(2,116) = 6.3$. The frequency differences at the first and second presentations were significant both by subjects and items (95% confidence interval for comparing two means was 11.2 ms by subjects and 18.8 ms by items), but the difference at the third presentation did not approach significance.

The mean latencies for the first presentations of experimental pictures in each block are shown in Figure 3. To check for effects of practice on picture-naming latencies, an additional analysis was performed with block as an added factor with three levels: early, middle, and late. There was no main effect of block, $F_1(2,64) = 1.6$; $F_2(2,116) = 1.4$, $ps > .2$, and no significant interactions between block and the other factors, $F_1 < 1.4$; $F_2 < 1$. Thus, naming latencies did not decrease with non-specific practice nor was the frequency effect attenuated by non-specific practice.

The percentage of trials excluded from analyses of response latencies was greater on the first presentation for low-frequency pictures than for high-frequency pictures. On additional presentations, the difference between the two types of pictures decreased and reversed, with slightly more excluded trials occurring for high-frequency pictures. These percentages are reported in Table 2. Analyses of variance were carried out on the percentages of excluded trials. There was a significant main effect of presentation, $F_1(2,64) = 4.8$; $F_2(2,116) = 4.2$, but not of frequency, Fs <

[1] No correct response latencies from Experiment 1 were excluded from analyses for being too fast. High- and low-frequency conditions in Experiment 2 each had 2 fast correct response latencies excluded and in Experiment 3, 5 fast responses each.

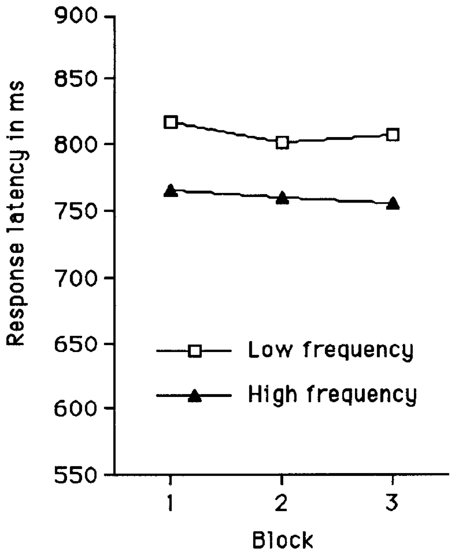

FIG. 3. Mean picture naming latencies (by subjects) for first presentations by blocks in Experiment 1. The corresponding item means for low-frequency names were 827, 812, and 819 ms for the first, second, and third blocks, respectively. For high-frequency names, they were 771, 763, and 760.

1. As in the analyses of response latencies, the interaction between frequency and presentation was significant, $F_1(2,64) = 14.4$; $F_2(2,116) = 9.7$. On first picture presentations, significantly more low-frequency trials were excluded from analyses than high-frequency trials were (the 95% confidence interval was 2.23% by subjects and 3.94% by items). Also significant were the differences between the exclusion rate for low-frequency pictures on the first presentation and those in the other conditions. Overall, it appears that accuracy was not compromised for speed. Looking at a subset of the excluded trials, high- and low-frequency pictures were named with nearly equal consistency, as shown on the right side of Table 2. This supports the argument that the high- and low-frequency pictures were equally identifiable, both conceptually and linguistically, as the object decision and picture-naming norms suggested.

Discussion

The results of Experiment 1 showed a substantial frequency effect, with high-frequency picture names produced reliably faster than low-frequency names. Given that speaking is a highly trained task, it is unsurprising that participants showed no benefit of non-specific practice in naming pictures over the course of the experiment. In contrast, word-specific practice reduced naming latencies and the influence of word frequency, replicating several earlier studies (e.g., Bartram, 1973, 1974; Monsell, Matthews, & Miller, 1992; Oldfield & Wingfield, 1965; Thomas, Fozard, & Waugh, 1977; Wheeldon & Monsell, 1992).

This attenuation of the frequency effect with repetition runs counter to the findings of Jescheniak and Levelt (1994). They found no reliable change in the magnitude of a 62 ms frequency effect over three presentations. However, the first presentation of pictures in their study occurred prior to the experiment when participants viewed the pictures and

TABLE 2

Percentage of Trials Excluded from Analyses of Response Latencies

Experimental condition	Excluded trials: Low frequency	Excluded trials: High frequency	Non-modal name exclusions: Low frequency	Non-modal name exclusions: High frequency
	Experiment 1			
Presentation				
First	16.7	11.3	3.3	3.3
Second	10.3	12.1	2.8	1.8
Third	11.2	13.3	3.1	2.2
	Experiment 2			
Constraint				
Low	15.5	12.1	4.8	2.9
Medium	10.7	12.1	2.1	3.8
High	4.8	8.6	0.5	3.3
	Experiment 3			
Constraint				
Incongruent	16.9	12.4	5.7	3.0
Medium	8.9	6.9	2.0	1.3
High	4.9	11.3	1.3	3.0

Note. The excluded trials were those eliminated from analyses of response latencies. The non-modal name exclusions are trials on which participants named pictures with non-target words and these trials constitute a subset of the excluded trials.

their names. Usually the benefit of repetition in naming latencies is seen in comparing the first and second presentations of pictures (Bartram, 1974; Oldfield & Wingfield, 1965; Thomas et al., 1977). Because the participants were familiarized with the pictures before the picture naming experiments, this major portion of the repetition effect is missing from Jescheniak and Levelt's data, probably resulting in the absence of a repetition by frequency interaction.

Still, pre-exposure of pictures cannot account for the persistence of the frequency effect in Jescheniak and Levelt's word production experiments. Among the picture naming studies that have found persistent, albeit attenuated, frequency effects after the first few presentations, the common factors appear to be disparities between high- and low-frequency words on name uncertainty and phonological factors such as length (Bartram, 1974; Oldfield & Wingfield, 1965). This argues that the difference that persists may not be attributable to frequency. Despite selecting only pictures with high name-agreement in norms, it may be that Jescheniak and Levelt's low-frequency pictures were still less codable, and thus harder to name than their high-frequency pictures. Consistent with this is their finding of significantly higher error rates for low-frequency than for high-frequency names. However, as Jescheniak and Levelt argue, the determination of gender for a picture name should be equally affected by name uncertainty. Yet no persistent frequency difference was found in gender decisions for the same materials, making uncertainty a less likely culprit.

EXPERIMENT 2

In Experiment 2, we examined whether word frequency affects the production of words in sentence contexts. To do this we presented the critical pictures from Experiment 1 in rebus fashion, to form completions for sentences. The sentence frames provided high, medium, or low levels of constraint on the upcoming picture names. Increased constraint in sentence frames should increase the redundancy of the message specifications for picture names. Low-constraint frames were designed to be semantically uninformative, providing no meaningful context. In contrast, high-constraint frames were designed to elicit the picture names with high reliability in the absence of the actual pictures. Medium-constraint sentences fell in between.

The goal of these manipulations was to competitively test the predictions of discrete and cascade theories of word production. Discrete-stage theories predict no reduction of frequency effects from increases in contextual constraint, because the factors operate at different processing stages. In contrast, cascade theories predict a reduction in the impact of frequency as the level of contextual constraint grows.

Method

Participants. Forty-two students participated, were selected, and compensated as in the previous experiment. None of them had taken part in Experiment 1.

Materials. The same critical pictures were used as in Experiment 1. Sentences were created for each critical picture at high, medium, and low levels of contextual constraint. Each high- and medium-constraint sentence was normed by 25 students who did not take part in any of the experiments. They were asked to provide up to three completions for each incomplete sentence (Schwanenflugel, 1986). Two kinds of cloze probabilities (Taylor, 1953) were derived from the completions. The *first response* probability is the proportion of participants who gave the target word as their first completion. The *overall* probability was calculated by taking the number of times a word was given as a completion, regardless of whether it was the first, second, or third completion given, and dividing by the number of participants who completed the sentence. The mean cloze probabilities for high- and medium-constraint sentence completions are shown in Table 3. In all cases, the most likely completions for the sentence frames were the target names of pictures with which the sentences were paired, or were no more than .04

in cloze probability from the most likely completion.

The 20 low-constraint sentences were written to be equally acceptable when completed by any picture. Sentence length within each level of constraint did not differ for high- and low-frequency targets. A complete list of the critical sentences appears in the Appendix.

In addition to the 60 experimental pictures, 60 filler pictures were used with medium- to high-constraint sentences. The first response probabilities for picture names ranged from .35 to 1.00.

Design and procedure. Participants were asked to silently read sentences which appeared one word at a time in the center of the computer screen. Every trial began with a fixation point displayed for 500 ms, followed by words displayed for 285 ms each. Sentences ended with a picture that participants were instructed to name as quickly and accurately as possible. The pictures remained on the screen until the voice key was triggered. The next trial began 1.5 s after the voice key triggered. Three practice trials preceded the 120 experimental and filler trials.

An experimenter was present throughout the experiment to record participants' responses and any failures of the voice key. Every twenty trials participants were asked to repeat the last sentence they read. This task was included to check that sentence frames were being read. The experimenter noted whether or not the participant was able to repeat the gist of the sentence. Participants were tested one at a time.

Three stimulus lists were created with 60 experimental pictures, 20 at each level of constraint. The high- and low-frequency pictures appeared in a different constraint condition on each list, in the same pseudo-random order. Each critical picture was preceded by an unrelated filler picture whose name had a different initial phoneme and for which the sentence frame was unrelated to the critical picture.

Frequency (high vs. low) and constraint (high, medium, or low) were within-subject factors with each participant seeing ten different pictures in each cell of the design. Constraint was manipulated within items. Across lists and participants each picture occurred at each level of constraint an equal number of times.

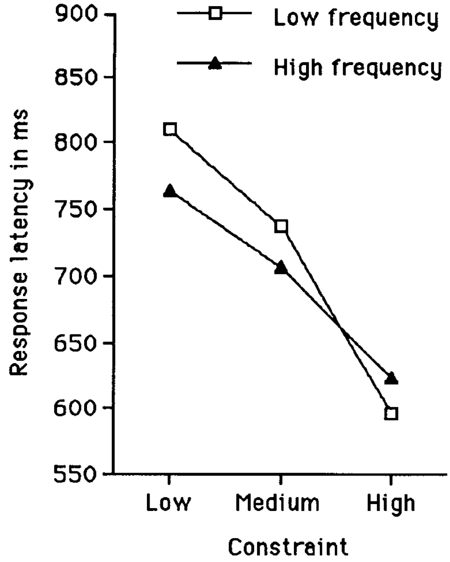

FIG. 4. Mean picture naming latencies (by subjects) at three levels of sentential constraint in Experiment 2. Mean latencies by items for low, medium, and high constraint, respectively, were 825, 739, and 597 ms for low-frequency names, and 768, 712, and 624 ms for high.

Results

Critical trials were excluded from further analysis if the voice key was not properly triggered (3.9% of the trials) or the target picture name was not produced (2.9%) or produced disfluently (1.4%). Also excluded were trials with response latencies greater than 3 s or less than 200 ms, as well as any of the remaining trials for which the latencies fell beyond 2.5 standard deviations of a participant's mean (2.6%). Participants were able to report the gist of the last sentence on most test trials ($M = 91\%$, $SD = 14$).

Mean picture naming latencies are shown in Figure 4. High-frequency pictures were named faster than low-frequency pictures (698 to 715 ms), and constrained pictures were named faster than unconstrained (610 at high, 723 at medium, and 787 at low). However, the magnitude of the frequency difference diminished with increasing constraint. Naming latencies for pictures in low-constraint sentences showed a 46 ms frequency difference identical to the difference found in first-presentation latencies in Experiment 1. Medium-constraint sentences yielded a 30 ms difference, while high-constraint sentences yielded a -27 ms difference. These patterns were tested with 2 (Frequency) by 3 (Constraint) analyses of variance. The most important effect, the interaction between frequency and constraint, was significant both by subjects and items, $F_1(2,82) = 13.0$; $F_2(2,116) = 4.7$. With 95% confidence intervals of 21.5 ms by subjects and 38.6 ms by items, the 46 ms frequency difference for low-constraint names was significant both by subjects and items, whereas the differences for medium- and high-constraint frames were only significant by subjects. The main effect of constraint was significant, $F_1(2,82) = 148.5$; $F_2(2,116) = 93.3$, and the main effect of frequency, compromised by the interaction with constraint, was significant only by subjects, $F_1(1,41) = 5.0$; $F_2 < 1$.

Again, analyses were carried out on the percentage of trials excluded from analyses of response latencies. In general, conditions associated with longer response latencies showed a greater number of excluded trials, suggesting that there was no speed-accuracy trade-off (see Table 2 again). There was a significant main effect of constraint, $F_1(2,82) = 13.9$; $F_2(2,116) = 9.2$, but no significant main effect of frequency, Fs < 1. The interaction between constraint and frequency was significant by subjects but not by items, $F_1(2,82) = 3.3$; $F_2(2,116) = 2.3$, $p > .10$. Calculation of 95% confidence intervals revealed no significant differences between the percentage of excluded high- and low-frequency trials at any level of constraint (95% confidence intervals were 4.01% by subjects and 4.78% by items).

Discussion

The word frequency effect in picture naming latencies diminished with increased contextual constraint and actually disappeared at the highest level of constraint. Indeed, highly constrained sentences produced a reversal in the frequency effect, with lower frequency names produced faster than higher frequency names. However, this reversal in mean latencies may be artifactual. Low-frequency targets tended to be somewhat more constrained than high-frequency targets in the high-constraint condition, as Table 3 shows. The reversal of the frequency effect in mean latencies may be due to this small difference in constraint. Furthermore, the negative correlations between response latencies and log frequency (spoken frequency from CELEX) at each level of constraint indicates that increased frequency did not generally correspond to higher latencies for high-constraint items, $r(60) = -.004$, *ns*, for high; $r(60) = -.190$, *ns*, for medium; $r(60) = -.219$, $p < .10$, for low-constraint.

Although the results suggest that effects of constraint and frequency are not independent, it could be argued that a predictive strategy was responsible for the interaction. In such an account, participants may have performed a word-picture matching task rather than a picture naming task. A sentence frame of moderate- or high-constraint could have led participants to generate a completion that was only produced if it corresponded to the presented picture. If the concept named by the generated word did not match the picture, a new name would be retrieved. This would account for the lack of a frequency effect in the high-constraint condition, because the word-picture matching task does not typically produce a frequency effect (Wingfield, 1968). For medium-constraint frames, the generated word would match the pictured target only about half of the time, resulting in a combination of word-picture matching latencies for correct predictions and picture naming times for incorrect predictions. Averaging the two types of latencies would attenuate the frequency effect in picture naming. The experimental materials encouraged the use of such a strategy because 83% of the sentences provided some semantic constraint on the pictures, and pic-

TABLE 3

Mean Cloze Probabilities for Sentence Targets and Example Sentences for Each Condition

Constraint	Freq.	1st	Overall	Example sentence frames	Target
				Congruent	
High	High	.85	.97	George taught his son to drive a	car
	Low	.92	.98	On windy days the boy went outside to fly his	kite
Medium	High	.40	.68	The commercial was for a new	car
	Low	.42	.60	He bought string for his	kite
Low	High			The participant in the experiment saw a picture of a	car
	Low			The eraser couldn't get rid of the picture of the	kite
				Incongruent[a]	
High	High			The Earth revolves around the	car
	Low			For service it was necessary to ring a little	kite
Medium	High			The noblemen hunted a wild	car
	Low			The dirty laundry was in a old	kite

Note. Freq. is short for word frequency. 1st stands for first response cloze probabilities.
[a] These frames only appeared in Experiment 3.

ture names never violated the constraints of the sentence frames. To determine whether sentential constraints modulate frequency effects in the absence of consistent predictability, Experiment 3 was designed to discourage strategic use of sentential contexts to generate completions.

EXPERIMENT 3

In Experiment 3 we decreased the number of sentence frames that were related to picture targets. Experiments on word recognition have shown that the proportion of trials in which the prime is related to the target (the *relatedness proportion*) influences the degree of facilitation observed (Tweedy, Lapinski, & Schvaneveldt, 1977; see Neely, 1991, for review): The higher the relatedness proportion, the greater the semantic priming effect. Presumably, this is due to expectancies modulating the degree of priming. To our knowledge, relatedness proportions have been manipulated in picture naming only in one semantic priming study (Huttenlocher & Kubicek, 1983).

To discourage the development of expectancies, roughly one out of five pictures was congruent with the preceding sentence frame in Experiment 3 (compared to five out of six in Experiment 2). In addition, incongruent sentence frames replaced low-constraint frames to introduce violations of the sentences' semantic constraints as another type of non-supportive context. So, unlike Experiment 2, there was a low incidence of appropriate contextual constraint as well as violations of constraints in the materials.

Method

Participants. Forty undergraduate students from the same population as previous experiments participated. None of the students took part in the earlier experiments. Data collected from two additional participants were not used due to equipment problems in one case and a lisp in the other.

Materials. The same critical high- and low-frequency pictures and their high- and medium-constraint sentence frames were used as in Experiment 2. New sentence frames were paired with critical pictures to form the incongruent-constraint conditions. Example frames appear in Table 3. Norms indicated that the incongruent, high-constraint frames had a mean first response probability of .94 in eliciting their target words (that were semantically and phonologically unrelated to critical picture names). Each incongruent frame of medium constraint had a .55 probability of eliciting a particular word on average. In norms, these incongruent frames never elicited the names of the critical pictures to which they were matched. The 60 critical pictures were divided among the four sentence context types (from the crossing of congruity and constraint) as follows: Four stimulus lists were created so that each picture appeared with a different type of context on each list and each list contained either 14 or 16 pictures in each context type, evenly split between high and low frequency. To control for any differential effect of particular incongruent sentences, an additional four stimulus lists were created which differed only in that the incongruent sentences assigned to high- and low-frequency pictures were exchanged for 50 of the 60 items. Thus, sentence characteristics such as length, constraint, and so on, were nearly equated for the two levels of frequency across subjects.

There were 80 filler trials. Twenty of the low-constraint sentence frames from Experiment 2 were paired with 20 filler pictures. The sentence frames for the 60 filler pictures from Experiment 2 were re-paired to create incongruent trials. So, each list contained 140 trials of which 30 were congruent and critical, 30 incongruent and critical, 60 incongruent fillers, and 20 neutral fillers.

Design and procedure. The procedure was the same as in Experiment 2 with one exception. Participants were asked to repeat more sentences (10) at pseudo-random intervals to counteract the possibility that the low relatedness-proportion discouraged attending to frames.

Frequency (high vs. low), sentence congruity (congruent vs. incongruent), and constraint (high vs. medium) were within-subjects factors. Congruity and constraint were manipulated within items, while frequency was a between-items factor. Each item was viewed at each combination of congruity and constraint by 10 participants and each participant saw either 7 or 8 items in each condition.

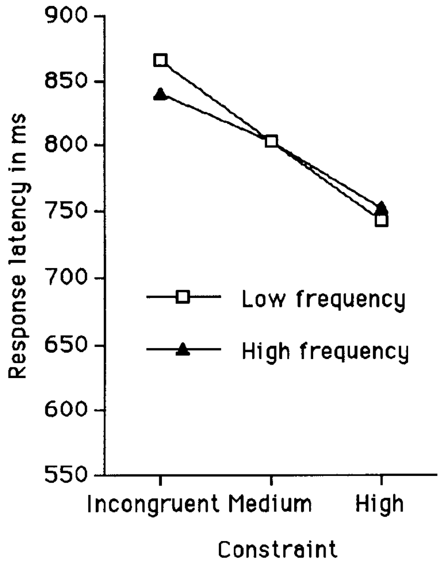

FIG. 5. Picture naming latencies in Experiment 3 showing the interaction between Constraint and Frequency. Mean latencies by items for incongruent, medium, and high constraint, respectively, were 881, 806, and 744 ms for low-frequency names, and 841, 800, and 765 ms for high.

Results

Response latencies on critical trials on which target names were produced not at all or disfluently (3.8%) were excluded, as were trials on which voice key errors occurred (4.3%). In addition to these trials, response latencies greater than 3 s or less than 200 ms were excluded, as were any of the remaining latencies which were beyond 2.5 standard deviations of a participant's mean latency (3.2%). Participants successfully recalled the gist of most sentences on which they were tested (M = 94%, SD = 8).

In the first analyses, all incongruent frames were treated as low-constraint frames with respect to the following picture and the analyses were identical to those carried out for Experiment 2. Mean response latencies are displayed in Figure 5. Overall, high-frequency pictures were named slightly faster than low-frequency pictures (798 vs. 805 ms), and more constrained pictures were named faster than less constrained (748 at high, 803 at medium, and 854 at incongruent). Again, the magnitude of the frequency difference diminished with increasing target-appropriate constraint. Naming latencies for pictures in incongruent-constraint sentences showed a 27 ms frequency difference, medium-constraint sentences yielded no difference, while high-constraint sentences yielded a -9 ms difference. As in Experiment 2, picture naming latencies following high- and medium-constraint sentence frames showed minimal frequency differences whereas the low- and incongruent-constraint frames showed a greater difference.

Analyses of variance performed on the data of Experiment 3 showed a pattern similar to that in Experiment 2. There was no main effect of frequency, *F*s < 1, but there was an interaction of frequency and constraint that was marginal by subjects and significant by items, $F_1(2,78) = 3.0$, $p < .06$; $F_2(2,116) = 3.6$. The 95% confidence interval for the interaction was 21.6 ms by subjects and 31.5 by items, making only the frequency difference for the incongruent-constraint condition significant. The main effect of constraint was also significant, $F_1(2,78) = 71.5$; $F_2(2,116) = 44.8$.

As in Experiment 2, the percentage of trials excluded from calculations of response latencies tended to decrease with increased constraint except in the high-constraint, high-frequency condition (see Table 2 again). As with the response latencies, analyses of variance for exclusions showed a significant interaction between constraint and frequency, $F_1(2,78) = 7.1$; $F_2(2,116) = 5.2$, a significant main effect of constraint, $F_1(2,78) = 12.3$; $F_2(2,116) = 9.1$, but no main effect of frequency, *F*s < 1. The difference between high- and low-frequency targets was significant by subjects and marginal by items in the incongruent constraint condition and the frequency reversal in the high-constraint condition was significant by both (95% confidence intervals were 4.27% by subjects and 4.92% by items). This pattern suggests that accuracy and speed both improved with increased constraints.

The mean response latencies for the high- and medium-constraint incongruent sentence frames were examined separately. A second set of analyses was performed to evaluate the effect of constraint for incongruent frames. In the 2 (Frequency) $\times$ 2 (Constraint) analyses of variance, the effect of frequency was significant by subjects but not by items, $F_1(1,39) = 6.0$, $MSE = 5581$; $F_2(1,58) = 2.68$, $MSE = 17960$, $p < .11$, and the effect of constraint was not significant alone, $F_1(1,39) = 2.2$; $F_2(1,58) = 1.53$, *p*s $> .14$, or in its interaction with frequency, *F*s < 1.

Discussion

Experiment 3 yielded a significant difference in naming latencies for high- and low-frequency pictures only when sentences did not contextually support the target picture completions. As in Experiment 2, this frequency difference was eliminated when the pictures were preceded by appropriately constraining sentence frames. So, Experiment 3 successfully replicated the results of Experiment 2 in circumstances that discouraged the participants from predicting the upcoming picture target.

The results of Experiment 3 differed from those of Experiment 2 in that response latencies in the congruent conditions were about 100 ms slower overall and more variable. The low relatedness-proportion probably motivated participants to process pictures more thoroughly before responding, because the cues to picture identity coming from sentence frames were less likely to be reliable. The manipulation of constraint in incongruent sentence-picture pairs had little effect. Pictures following incongruent sentences of high constraint did not take significantly more time to name than those following incongruent medium-constraint frames.

The presence of a constraint by word-frequency interaction in Experiment 3 renders less likely the idea that Experiment 2's results were due to generating sentence completions and matching them to pictures. Such a strategy would be successful for less than 20% of the trials in Experiment 3. Further evidence against anticipatory sentence completion is the similarity across experiments in the least supportive and medium-constraint contexts. In Experiment 2, the medium- and low-constraint response latencies differed by 64 ms and in Experiment 3 the medium- and incongruent-constraint latencies differed by 51 ms. Had participants been generating completions when they could, there should have been less cost from unconstraining frames than from constraining frames that were incongruent with the pictured targets. The actual difference was in the opposite direction.

GENERAL DISCUSSION

In review, the first experiment demonstrated a robust frequency effect in naming latencies when pictures were presented in isolation. The frequency effect diminished with repeated naming of the same pictures. These results replicate earlier studies (Oldfield & Wingfield, 1965), setting the stage for an examination of how frequency interacts with constraint. Experiment 2 showed that the frequency effect disappeared with increases in contextual constraint. The final experiment yielded the same result even when participants were discouraged from using sentence contexts to predict picture targets. The results complement and extend work addressing the relationship between the stages of picture naming by Humphreys, Riddoch, and Quinlan (1988), Peterson and Savoy (in press), and Starreveld and La Heij (1996). These experiments may also be seen as an experimental replication of Beattie and Butterworth's (1979) observations for spontaneous speech. Beattie and Butterworth found that hesitations were in general more likely prior to low- than high-constraint words, but hesitations were not significantly affected by constraint when only high-frequency words were considered. Also, words of low constraint were more hesitant when they were low as opposed to high in frequency, and the frequency difference in hesitations reversed but not significantly for high-constraint words. This suggests that a frequency by constraint interaction much like the one found in the present experiments occurs in natural speech.[2]

In this final section, we discuss the validity of our manipulation of redundancy in production, alternative accounts of the data, how the results bear on the two classes of word production theories, and how the theories accommodate this pattern of data.

Manipulation of Constraints on Word Selection

Clearly, one cannot directly assess either the redundancy of message specifications for word selection or the onset of word-production processes in spontaneous speech. Hence, the task used in this study consisted of naming pictures which were preceded by sentence frames. It thereby combined an estimate of the onset of processing for a particular picture name with a quantifiable manipulation of contextual constraint. The weakness of the task is that the sentence contexts were read by participants rather than being generated by them. Although reading sentence frames differs from generating messages, the product of comprehension should be similar to the conceptual representations that speakers normally develop. In any case, to evaluate the predictions made by cascade and discrete theories, what is required is that the contexts directly influence only the processes which precede

[2] Although the high-constraint sentences eliminated frequency differences in the present experiments, word frequency often plays a role in normal sentence production. The high-constraint frames used here were far more constrained than sentences in normal speaking contexts. The frames alone could reliably elicit target names over 90% of the time and were combined with pictures which elicited target names over 95% of the time. Our medium constraint frames, which reduced but did not consistently eliminate frequency effects, were probably closer to the higher levels of constraint found in normal speaking for nouns. Although particular low-frequency words occur seldom by definition, over 15% of all the words examined by Beattie and Butterworth were defined as low in both constraint and frequency (less than 101 occurrences per million) while 24% of all the words were high in frequency and low in constraint. This suggests that there are ample opportunities for such interactions to arise in the timing of speech.

phonological encoding. In other words, our interpretation of the results requires that sentence frames do not activate phonological forms without the mediation of concepts or lexical entries.

Several findings in the literature strongly suggest that the effect of constraint in Experiments 2 and 3 arose before the retrieval of phonological forms. First, robust effects of constraint from sentence frames have been found in object-identification tasks which do not require word selection or retrieval of phonological forms (e.g., Kroll, 1990; Potter, Kroll, Yachzel, Carpenter, & Sherman, 1986). This indicates that a significant portion of constraint's influence on picture processing occurs for non-verbal responses. Second, when context effects are compared for picture and word targets, pictures appear to show earlier facilitation from context as measured by evoked response potentials (Ganis, Kutas, & Sereno, 1996). This is consistent with the idea that pictures have a privileged route to meaning and conceptual integration, and that the contextual facilitation for pictures is not due to prediction of their names but to direct integration into a conceptual representation (e.g., Kroll, 1990; Kroll & Potter, 1984; Potter, et al., 1986). Finally, in studies of sentence comprehension, the effect of sentential context is modulated by the degree to which it supports the dominant interpretation of a homonym (e.g., Duffy, Morris, & Rayner, 1988; Rayner, Pacht, & Duffy, 1994). Being predictive of a form is not enough. For example, constraining the final word in a sentence to *ball* is helpful only when the constraints converge on the *game*- rather than *dance*-related meaning. Taken together, the evidence suggests that sentence frames constrain the conceptual representations which drive lexical selection rather than the assembly of the phonological form.

Given that constraint influences the conceptual system, one might argue that the interaction between constraint and frequency occurs there as well. The evidence is otherwise. Object identification and categorization (as reflected in tasks such as object decision, word-picture matching, and manual or verbal categorization) do not show word frequency effects (e.g., Jescheniak & Levelt, 1994; Wingfield, 1967, 1968; but see Kroll & Potter, 1984). Even if conceptual- or lemma-level frequency differences existed and were eliminated by constraint and redundancy, there should still be a frequency effect in phonological encoding unless, as cascade theories posit, the benefits of constraint persisted.

Another account of the data is that sentence frames not only constrained concepts and lemmas but also primed phonological forms via associative links. Levelt (1989) posited facilitatory connections between phonological forms of associated words (e.g., *ice* and *cold*) to account for an effect of word frequency on word substitutions. The intended words would activate associated words via these connections and occasionally be replaced by words that had the advantage of higher frequency. If constrained sentences were more likely to contain words associated with names of target pictures, priming from these associates could have caused a frequency by associative-relatedness interaction to occur. Specifically, associates in the sentence frames could have activated the phonological forms of target names, bringing phonological forms of high-frequency targets close to asymptote, and reducing the frequency effect. To assess the viability of this account, a new group of 32 participants rated the associative relatedness of picture names to the content words in their corresponding sentence frames. Targets at each level of constraint and frequency were split into groups containing higher- and lower-than-median levels of association. Had associative relatedness driven the interaction between constraint and frequency, one would expect that the high- and medium-constraint sentences containing highly associated words to show smaller frequency differences than those with weakly associated words. However, the conditions showed no such systematic difference in the pattern of response latencies based on the degree of association between words in frames and picture names. In fact, the means were slightly in the opposite direction of an associative account's predictions with highly associated high-constraint frames yielding a -25 ms frequency effect in Experiment 2, whereas the less associated frames yielded a -28 ms frequency effect (in Experiment 3 the mean effect sizes were -4 and -37 respectively). This suggests that it was the conceptual representation of the frame, not associative priming, that created the facilitatory constraint effects.

Without creating far-reaching inconsistencies with previous research, the interaction between constraint and frequency cannot be accounted for by placing the influence of both factors at the same stage of processing. Although models of word production that posit only one lexical stage of processing may readily account for the present data (e.g., Starreveld & La Heij, 1996), they fail to account for other facts of language production and learning (e.g., Badecker et al., 1995; Dell et al, 1997; Vigliocco et al., 1996).

Discrete Two-Stage Theories

The results of the present experiments are not consistent with existing discrete two-stage theories of word production (e.g., Butterworth, 1989; Jescheniak & Levelt, 1994; Levelt et al., in press; Roelofs, 1992). Because the output of word selection serves only to identify the word to be phonologically encoded, there is no opportunity for the amount of constraint present in word selection to moderate the impact of word frequency in phonological encoding. Thus, this class of theories predicts simple summation of the effects of constraint and frequency.

To reconcile discrete theories with the data, a basic assumption must be altered. It would be sufficient to weight the output of the word selection process by the amount of evidence favoring the selected word. So, in terms of our task, picture names constrained by sentence frames would provide stronger input to their phonological forms than picture names in weaker contexts. Because nonlinear activation functions do not distinguish between the two classes of theories, a discrete theory with this change in assumptions would make the same predictions about the interaction between contextual redundancy and word frequency as a cascade model. Such a change would maintain the *temporal* separation of processing stages in discrete theories, because the two processing stages need not overlap in time.

Cascade Theories

The class of theories we have called cascade theories (e.g., Dell, 1986; MacKay, 1982; Riddoch, 1987; Stemberger, 1985) successfully predicted the interaction between contextual constraint and word frequency because of two properties. First is a limit on activation levels which makes the activation function nonlinear. This means that two facilitatory factors may simply summate when weak because an asymptotic activation level is not approached. Increased constraint brings an item's activation close to asymptote where additional activation is of no consequence. For low-frequency forms, each increase in top-down activation reduces the difference in activation between high- and low-frequency forms. The importance of nonlinearity in processing has been emphasized in interactive-activation and connectionist models for a number of reasons (e.g., accounting for interactions of word frequency with other factors; McClelland & Rumelhart, 1985; Plaut, McClelland, Seidenberg, & Patterson, 1996; see also McClelland, 1987), but particularly because it is required to perform complex calculations such as the exclusive-or problem (cf. Williams, 1986).

The second property is more critical, and involves the cascade of activation. This allows high-level representations to pass information to lower levels of representation about the evidence in favor of a decision. Specifically, the higher activation levels of redundantly specified lexical entries is reflected in the amount of activation that their phonological forms receive. At the level of phonological forms, this top-down activation combines with differences in activation due to frequency of use. The consequence, we argue, is the interaction of word frequency with contextual redundancy found in Experiments 2 and 3. This critical property is present in interactive-activation models (e.g., Stemberger, 1985) as well as models that restrict the direction of the flow of information (Riddoch, 1987). Of the class of cascade theories considered here, Stemberger's (1985) account is the one that most clearly incorporates both the nonlinearity and information-flow assumptions that allow constraint on word selection to modulate the impact of word frequency.

APPENDIX

List of Critical Stimuli Used in Experiments 2 and 3

	Target	Sentence frame	1st	Overall
		High constraint		
1	car	George taught his son to drive a	0.77	1.00
	kite	On windy days the boy went outside to fly his	0.92	1.00
2	ear	He couldn't hear well because of the infection in his left	1.00	1.00
	ax	He chopped down the tree with an	0.89	1.00
3	hand	Everyone was shocked when Mark was willing to shake his enemy's	0.92	1.00
	hook	The fisherman attached the worm to the	1.00	1.00
4	leg	The skier fell and broke his	0.69	1.00
	lock	The bike was protected from theft by an expensive	0.77	1.00
5	moon	The astronauts landed on the	0.96	1.00
	match	He lit the candle with one	0.92	1.00
6	window	To get some cool air in the apartment, they put the fan in the	0.88	1.00
	whistle	The referee stopped the game by blowing his	0.96	1.00
7	brain	He was afraid that drugs would damage his	0.88	0.96
	broom	He swept the floor with the	0.88	1.00
8	bed	Bob was tired so he went to	0.73	0.96
	bone	While Suzy was eating chicken, she choked on a	1.00	1.00
9	bomb	The plane exploded because of a hidden	0.92	1.00
	badge	To prove he was a police officer, he showed the woman his	0.85	1.00
10	dress	The bridesmaid wore an ugly	0.92	1.00
	drum	The people marched to the beat of a loud	0.92	0.96
11	clock	They didn't know what time it was because they couldn't find a	0.69	1.00
	crown	On top of his head, the king wore an extremely expensive	0.96	1.00
12	door	Always knock before you open my	0.96	0.96
	dog	The little puppy grew up to be a huge	1.00	1.00
13	nose	Vic sneezed and blew his	0.96	1.00
	nail	The wooden board splintered when the carpenter tried to insert the	0.85	0.96
14	arm	The pitcher was unable to throw the ball because of his broken	0.58	0.85
	owl	The campers were frightened by the hoot of an	0.96	1.00
15	glass	She poured the lemonade into a tall	0.73	1.00
	ghost	The castle was haunted by a frightening	0.85	0.92
16	baby	They bought a crib for the	1.00	1.00
	button	His coat was open because it was missing a	0.88	1.00
17	book	The author signed a copy of her new	0.88	1.00
	bee	The boy was stung by the	0.88	1.00
18	pencil	To fill in the bubble sheet the student needed a sharp	1.00	1.00
	pumpkin	For Halloween, they carved up a large	0.96	0.96
19	bottle	There was glass all over the sidewalk from a broken	0.81	0.92
	carrot	Bugs Bunny chewed on a	1.00	1.00

APPENDIX—*Continued*

	Target	Sentence frame	1st	Overall
20	star	The hopeful girl wished upon a	0.96	0.96
	scarf	To protect his neck from the cold he wore a long	0.77	0.85
21	plant	No one remembered to water the	0.62	0.96
	purse	She kept lipstick and a compact in her	0.92	1.00
22	foot	The clumsy man stepped on her	0.62	0.85
	frog	The tadpole grew up to be a big	0.88	1.00
23	eye	She put a contact lens in her	0.85	1.00
	eggs	The hen laid some	0.96	1.00
24	key	He couldn’t unlock the door without the right	1.00	1.00
	cow	The farmer milked the	0.92	0.92
25	ball	The pitcher threw the	0.85	0.92
	bat	The baseball player swung the	0.92	0.96
26	knife	He stabbed the man with a sharp	0.65	1.00
	knot	The sailor tied the rope with a complicated	0.96	1.00
27	ring	He bought his girlfriend an engagement	1.00	1.00
	lion	The king of the jungle is the	0.88	0.92
28	box	When his new computer finally arrived, he ripped open the	0.85	1.00
	bowl	She ladled the soup into her	0.88	1.00
29	house	They moved into a new	0.80	0.88
	heart	The Valentine’s Day card was shaped like a	1.00	1.00
30	gun	The bank robber aimed at the security officer and fired the	0.88	0.92
	comb	He parted his hair with a	0.96	1.00
		Medium constraint		
1	car	The commercial was for a new	0.19	0.54
	kite	He bought string for his	0.42	0.58
2	ear	He decided to pierce his	0.58	0.85
	ax	Abe cut the plank of wood with an	0.33	0.56
3	hand	He couldn’t write because of his sore	0.19	0.77
	hook	The fish swallowed the	0.31	0.54
4	leg	The girl asked her friends to sign the cast on her	0.46	0.96
	lock	The thief picked the	0.58	0.58
5	moon	The satellite orbited the	0.15	0.77
	match	The brush fire was started by just one	0.50	0.69
6	window	He accidentally broke the	0.27	0.42
	whistle	The end of the game was marked by a	0.15	0.23
7	brain	The surgeon botched the lobotomy and destroyed the patient’s	0.42	0.62
	broom	He cleaned the walkway with a	0.50	0.81
8	bed	He lay down on the	0.27	0.73
	bone	The dog gnawed on a small	0.65	0.81
9	bomb	The mailman delivered a mysterious package which contained a	0.42	0.46
	badge	The police officer showed the man his	0.50	0.65
10	dress	The princess wore a	0.50	0.69
	drum	The musician pounded on a	0.31	0.62
11	clock	The class was so boring all he could do was watch the	0.35	0.46
	crown	They stole the queen’s	0.38	0.62
12	door	The girl crept slowly toward the	0.42	0.58
	dog	At the park she saw a man with a	0.19	0.31
13	nose	He decided to pierce his	0.38	0.92
	nail	She stepped on a	0.23	0.35
14	arm	He had a scratch on his	0.19	0.65
	owl	He was as wise as a	0.62	0.62
15	glass	Water spilled all over the floor when he knocked over the	0.56	0.76
	ghost	The murderer was haunted by his victim’s	0.38	0.50

APPENDIX—*Continued*

Target		Sentence frame	1st	Overall
16	baby	The young couple wanted to have a	0.65	0.73
	button	She sewed on a new	0.58	0.62
17	book	The unsuccessful student went out and bought a new	0.31	0.46
	bee	The buzzing sound was made by a	0.44	0.64
18	pencil	The student needed a	0.38	0.54
	pumpkin	They made a pie from the pulp of a	0.35	0.54
19	bottle	The bartender dropped an empty	0.38	0.81
	carrot	They fed the horse a	0.23	0.54
20	star	The best students received a sticker shaped like a	0.46	0.65
	scarf	The sick man kept his neck warm with a fuzzy	0.52	0.64
21	plant	She poured water on the	0.15	0.42
	purse	The woman put her wallet back in her	0.69	0.96
22	foot	The man injured his	0.23	0.46
	frog	The little kid wanted to jump like a	0.46	0.54
23	eye	A bit of dust irritated his	0.65	0.81
	eggs	He fried some	0.31	0.38
24	key	In the mysterious box, they found a	0.15	0.23
	cow	The farmer had an old	0.19	0.35
25	ball	The dog was taught to catch a thrown	0.41	0.86
	bat	He swung the	0.65	0.69
26	knife	The mugger threatened his victim with a	0.50	0.96
	knot	The man couldn't loosen the	0.23	0.46
27	ring	The jeweler put a diamond on the	0.58	0.92
	lion	The wildlife photographer was frightened by the roar of a hungry	0.58	1.00
28	box	The mover carried a heavy	0.50	0.58
	bowl	The left-over soup was put into a small	0.31	0.77
29	house	The real-estate agent celebrated the sale of another	0.69	0.77
	heart	The best students received a sticker shaped like a	0.23	0.58
30	gun	The robber had a	0.58	0.85
	comb	Eliza was pleased with her new brush and	0.77	0.92
		Low constraint		
		At the end of the sentence was a drawing of a		
		On the large computer screen, she saw a small picture of a		
		Daniel examined the drawing of the		
		In the center of the screen she saw a picture of a		
		The display contained a		
		The drawing was of a		
		There was a small drawing of a		
		It took some time to draw the picture of the		
		The last work in this sentence is followed by a drawing of a		
		Someone drew a picture of a		
		There was a smudge on the picture of the		
		The next image you will see is a		
		Peter saw a drawing of a		
		The participant in the experiment saw a picture of a		
		The eraser couldn't get rid of the picture of the		
		The tall man was shown a drawing of a		
		There was a display of a		
		The image on the screen is a		
		Soon you will see a		
		The computer will display a		

Note. The first line of each numbered sentence pair is for the high-frequency target, and the second sentence is for the low-frequency target. The columns labeled 1st and Overall show the first response and overall sentence completion probabilities from the norms described in the Materials section of Experiment 2.

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