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Dominance and context effects on activation of alternative homophone meanings

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Abstract

Two eye-tracking during listening experiments found frequency and context effects on fixation probability of pictures representing multiple meanings of homophones. Participants heard either an imperative sentence instructing them to look at a homophone referent (Experiment 1) or a declarative sentence that was either neutral or biased towards the homophone's subordinate meaning (Experiment 2). At homophone onset in both experiments, participants viewed four pictures: 1) a referent of one homophone meaning, 2) a shape competitor for a non-pictured homophone meaning, and 3) two unrelated filler objects. In Experiment 1, meaning dominance affected looks to both the homophone referent and the shape competitor. In Experiment 2, compared to neutral contexts, subordinate-biased contexts lowered the fixation probability for shape competitors of dominant meanings, but shape competitors still attracted more looks than chance. We discuss the consistencies and discrepancies of these findings with the Selective Access and Reordered Access theories of lexical ambiguity resolution.

Intuition suggests that we normally settle on the appropriate meaning of a lexically ambiguous word immediately if the context is sufficiently informative, e.g., *Chris needed some money, so he went to the* *bank*. In fact, a large number of experimental studies have demonstrated that sentence context influences the timing and/or degree to which the alternative meanings are activated (e.g., Dopkins, Morris, & Rayner, 1992; Lucas, 1999; Sereno, Brewer & O'Donnell, 2003, Tabossi, 1988). However, the relative frequency of the alternative meanings is also clearly important. When presented in a neutral sentence context, the more frequent, dominant meaning of an ambiguous word is activated more quickly and persists longer than less frequent, subordinate meanings (e.g., Simpson & Burgess, 1985; Simpson & Krueger, 1991).

Most of the current debate in the domain of lexical ambiguity resolution rests on the fate of the dominant meaning when the context supports the subordinate meaning. The Reordered Access account of Duffy, Morris, and Rayner (1988) maintains that both the subordinate meaning (activation boosted by context) and the dominant meaning (activated due to its frequency) compete for selection. Thus, in contexts supporting subordinate meanings, reading times for ambiguous words are slow, compared to an unambiguous control word that is matched in corpus frequency to the overall frequency of the ambiguous word. This is the "Subordinate Bias Effect" that has been reported in numerous reading experiments (Binder, 2003; Binder & Rayner, 1998; Kambe, Rayner & Duffy, 2001; Pacht & Rayner, 1993; Rayner, Cook, Juhasz, & Frazier, 2006; Rayner, Pacht & Duffy, 1994, Sereno, O'Donnell, & Rayner, 2006; Sereno, Pacht & Rayner, 1992).

The Subordinate Bias Effect is a well-established phenomenon under two conditions: (1) the homograph is strongly polarized, with subordinate meanings retrieved only about 10% of the time in word association tasks; (2) reading time for the homograph in subordinate context is compared to an unambiguous word matched to the homograph's form frequency—i.e., the sum of all meaning frequencies. When these conditions are *not* met, the results have been less consistent. For example, Wiley and Rayner (2000) did *not* find a Subordinate Bias Effect, using ambiguous words that were not strongly polarized and context passages that made use of titles for disambiguation. And Sereno et al. (2006, Experiments 2 and 3) actually found the *reverse* pattern when using a meaning-frequency control word: reading times were faster for highly polarized homographs in strong subordinate-biased contexts, compared to a control word that was matched in frequency with the subordinate meaning of the homograph. This finding seems to suggest that only the subordinate meaning of the homograph was accessed, but it is unclear why the homographs were faster than the control words—the authors themselves simply speculate and recommend further research. Sereno et al. (1992), who also failed to find the standard Subordinate Bias Effect, argued that a meaning-frequency control word is more appropriate than a form-matched control word, because the latter contrasts a high frequency (control) word with a low frequency word (the subordinate meaning of the homograph).

The issue of the appropriate control word is critical, although it is difficult to resolve because both word form frequency and word meaning frequency are likely to impact reading time. Furthermore, the fact that the Subordinate Bias Effect is so dependent on comparison against a high frequency control word raises the concern that the Subordinate Bias Effect does not reflect competition between meanings after all, but rather the increased time it takes to access and integrate a lower frequency word (as in Reichle, Pollatsek, & Rayner, 2006; Reichle, Rayner, & Pollatsek, 2003). Reichle et al. (2006) suggest that the Subordinate Bias Effect can be modeled in two ways. In their preferred account, slower reading times on the subordinate-biased homograph are due to competition from the dominant meaning. Because both meanings are activated and in competition, this is consistent with the Reordered Access model (Duffy, Kambe & Rayner, 2001; Duffy et al., 1988). Reichle et al. (2006) also consider an account in which slower reading times for the subordinate-biased homograph are due to its low frequency, compared to the high frequency control word. Such an account is consistent with selective activation of the subordinate meaning only, because it provides an explanation of the Subordinate Bias Effect without reference to activation of the dominant meaning.

During the last 15 years, Kellas and colleagues have advocated for a Context-Sensitive or Selective Access account in which the dominant meaning is not activated if the context is sufficiently constraining toward a subordinate meaning. Evidence from lexical decision, naming and self-paced reading studies has demonstrated that in strongly biasing contexts, reaction times to contextually appropriate items are facilitated, but reaction times to contextually inappropriate meanings are not (Kellas, Martin, Yehling, Herman, & Vu, 1995; Martin, Vu, Kellas & Metcalf, 1999; Kellas & Vu, 1999; Simpson, 1981; Vu & Kellas, 1999; Vu, Kellas, Metcalf & Herman, 2000; Vu, Kellas & Paul, 1998; Vu, Kellas, Petersen & Metcalf, 2003).

In short, the fate of the dominant meaning in a strong subordinate context is a theoretically important question that differentiates two possible accounts of the Subordinate Bias Effect, and more generally, distinguishes between the Reordered and Selective Access accounts of lexical ambiguity resolution. The issue is whether top-down contextual cues can override the strong relationship between the word-form of an ambiguous word and its dominant meaning. This issue applies to both reading and listening paradigms. In fact, much of the ground-breaking research used spoken homophones in a cross-modal paradigm, leading to the conclusion that multiple meanings are accessed, even in biasing context (e.g., Onifer & Swinney 1981; Swinney, 1979; Tabossi, Colombo & Job, 1987; Tabossi, 1993; Tanenhaus, Leiman, & Seidenberg, 1979).

More recently, Huettig and Altmann (2007) found evidence that the dominant homophone meaning is activated in a subordinate-biased context, using a variant of the visual world paradigm introduced by Tanenhaus, Spivey-Knowlton, Eberhard, and Sedivy (1995).

We take some time to review Huettig and Altmann's (2007) second experiment, both because of its similarity to the current set of studies and because it provides quite dramatic evidence of dominant meaning activation in subordinate context. Participants heard sentences containing polarized homophones, such as "pen" while viewing an array of four line drawings. The drawings appeared one second before sentence onset in all conditions. In the neutral condition, the sentence contexts were neutral to the meaning of the homophone, such as *The man got ready quickly, but then he checked the pen*. In the biased condition, the sentence contexts supported the subordinate meaning of the homophone, e.g., *The welder locked up carefully, but then he checked the pen.* In the neutral and biased conditions (25% of the trials), participants saw drawings depicting both meanings, along with two unrelated distracters. In the competitor condition, participants heard the subordinate-biased context sentence while a visual shape competitor (a sewing needle) replaced the dominant meaning (pen-writing) (for evidence that looks to visual shape competitors track lexical access, see Dahan and Tanenhaus, 2005; Huettig, Gaskell, & Quinlan, 2004).

At homophone onset (before lexical access of the homophone had begun), Huettig and Altmann (2007) found no differences in looks to any objects in the neutral condition. However, in the biased and competitor conditions, the listeners were already fixating the pen-enclosure drawing 45% and 49% of the time, respectively, indicating that they had used the sentence context to fixate on sentence-relevant drawings.

At homophone offset, both dominant and subordinate referents were fixated more than fillers in both the neutral and the biasing conditions. In the neutral condition, presumably both meanings of the homophone were accessed due to support from two sources: the spoken word form and the images of two potential referents in the visual display. It is not possible to know for sure that meaning activation for the homophone was influenced by the visual display in this condition, but it seems likely, especially for the subordinate meaning. In the biased condition, the combination of sentence context and the visual display apparently activated the subordinate meaning prior to any phonological cues from the spoken homophone. Nonetheless, it is striking that the spoken word-form of the homophone still prompted looks to the dominant, but contextually inappropriate, referent. Even more striking is the fact that the pattern for the competitor condition was very similar to that in the biased condition, even though the dominant referent was replaced with a shape competitor. Looks to the shape competitor for the dominant meaning can be taken as evidence that the dominant meaning was activated, despite the subordinate context and the lack of an appropriate visual referent. Thus, this experiment provides very strong evidence for dominant meaning activation, even when a subordinate-biased context has successfully focused attention on the subordinate meaning.

The Huettig and Altmann (2007) findings provide compelling evidence that the word-form of a polarized homophone will **always** activate the dominant meaning, regardless of the linguistic and visual context. This begs the question: does the linguistic context have **any** effect on the activation of the dominant meaning? According to Reordered Access, a subordinate-biased context can boost activation of the subordinate meaning, thereby making the dominant meaning and subordinate meaning more competitive. But this does not entail delaying and/or limiting activation of the dominant meaning. The Reordered Access model maintains that “prior disambiguating context does affect the access process by increasing the availability of the appropriate meaning without influencing the alternative meaning" (Duffy et al., 1988, p. 431). The same point has been made more recently: "The two meanings became activated independently. While context could speed activation of the intended meaning, it had no effect on the speed of activation of the unintended meaning" (Rayner, Binder & Duffy, 1999, p. 847). Thus, in subordinate-biasing contexts, activation of the dominant meaning should be unaffected, while the subordinate meaning should be activated earlier than usual. On the other hand, for Selective Access accounts, the activation of the meanings of an ambiguous word depends on several constraints: frequency, type of context, and strength of context; the combined influence of these variables determines the meaning accessed (Martin et al., 1999). Thus, the subordinate-biasing context would serve to both boost activation of the subordinate meaning and limit activation of the dominant meaning.

In the current experiments, we use a visual world paradigm similar to that of Huettig and Altmann (2007), and begin by establishing the extent of meaning activation for subordinate and dominant meanings of homophones in neutral context (Experiment 1). Then, we manipulate the linguistic context to determine how activations of both the subordinate and dominant meanings are affected (Experiment 2). As in Huettig and Altmann's competitor condition, we used visual displays that contained an actual referent for the subordinate meaning, a shape competitor for the dominant meaning, and two unrelated distractors. One major difference between our experiments and theirs is that we do not present the visual display until homophone onset, in order to prevent the visual display from influencing the initial stages of spoken word recognition.

Experiment 1

Experiment 1 explores dominance effects on the activation of multiple meanings of ambiguous words in an instructional eye-tracking during listening task. This is somewhat analogous to the neutral condition of Huettig and Altmann (2007), described above, but there are three important differences. First, instead of using a declarative sentence, we used interrogatives that directly engaged the listener ("Look at the flower/flour.") in the tradition of Dahan, Magnuson and Tanenhaus (2001). Second, we presented the visual stimuli coincident with the onset of the target word (a homophone in our experiments), rather than at trial onset, in order to limit the degree to which the visual context constrains lexical activation. Our goal in making these changes was to get a clearer picture of the time-course and extent of activation for the dominant and subordinate meanings, as reflected by fixation patterns in this paradigm, when meaning frequency is the only relevant factor.

Third, rather than presenting two meanings of the polarized homophones directly, one meaning was depicted using an actual referent picture and the other meaning was depicted by a visual shape competitor (Dahan & Tanenhaus, 2005, Huettig et al., 2004). For example, the dominant meaning of the homophone *flower/flour* was directly depicted using a picture of a flower, and the subordinate meaning was indirectly depicted using a pillow as a visual shape competitor for flour. On another trial, the subordinate meaning of *flower/flour* was depicted using a picture of flour, and a lollipop was used as a shape competitor for the dominant meaning, flower. Although an actual referent to the homophone was always in the visual display, residual activation of the alternative meaning of the homophone could be assessed by analyzing the looks received by the shape competitor. As in Dahan and Tanenhaus (2005), none of the shape competitors overlapped in phonology with the spoken referent names, so any activation of the shape competitor from the spoken input indicated activation of its homophone referent. The activation of multiple meanings of the ambiguous word was measured by comparing looks to the shape competitor picture on trials where the dominant or the subordinate actual item was pictured. A relative dominance effect would be found if pictures of dominant meanings of a homophone attracted more looks than pictures of subordinate meanings. Because we needed to compare the probability of looking at two different pictures, it was crucial to match the pictures on various dimensions, as described in our normative measures below.

Method

Participants

Thirty undergraduates at the University of Michigan participated in this experiment for partial course credit in an Introductory Psychology class. All participants in this and the following experiments were native speakers of English and had normal or corrected vision.

Materials

We collected word association norms for a set of heterographic and homographic homophones (details below) and chose the 14 homophones for which meaning dominance was most polarized. Each homophone had two distinct, imageable meanings (see Appendix A).

The auditory stimuli were recorded by a female speaker: “Look at the cross. Now look at the (homophone).” For each digital speech file, silence was added before the onset of the spoken instructions as needed (i.e., before “Look at…”), so that the onset of each critical homophone was 3000 ms from the beginning of the auditory stimulus.

For each meaning of each homophone, two critical pictures were selected. One depicted the referent of the homophone (Actual Referent), and one depicted an object that was similar in shape to the homophone referent (Shape Competitor). The norms used to assess shape similarity are described below.

Visual stimuli consisted of four pictures arranged on a white background with a fixation cross in the center for each critical trial. The critical pictures were all full-color realistic images selected from an online searchable database of images (Google, 2004). Actual Referent images were chosen so that the picture represented a typical instance or instances of the object, and such that the picture would not be identified with other possible labels. For example, a *stamp* with an unknown design was chosen so that the participants would not identify the stamp with its design, such as an "American flag". In the case of *letter*, the Actual Referent included multiple letters in order to prevent the picture to be labeled as the letter itself, such as "B". Shape Competitor images were selected so that the picture was as identifiable as the Actual Referent and would not be assigned a label that overlapped in phonology or semantics. The pictures appeared in the upper left, upper right, lower left, or lower right quadrant, arranged so that the Actual Referent appeared in each quadrant an equal number of times for every participant. The Shape Competitor also appeared in each quadrant an equal number of times for every participant. The two remaining quadrants contained filler pictures of objects with unambiguous names that did not begin with the same phonemes as the critical homophone and were not similar in shape to the critical pictures.

Each homophone was tested only once, with each auditory stimulus occurring with one of two visual display types: Dominant-Actual or Subordinate-Actual. In the Dominant-Actual display, participants viewed the Actual Referents of the dominant meaning of the homophones, together with the Shape Competitors of the subordinate meaning of the homophones. In the Subordinate-Actual display, participants viewed the Actual Referents of the subordinate meaning of the homophones, together with the Shape Competitors of the dominant meaning of the homophones. Display type was varied between participants because ~~there was a~~we were concerned that ~~possibility~~ that Shape Competitor ~~effects would not be large enough to create a comparison~~s would get relatively few looks, and we wanted to maximize statistical power for comparisons evaluating the hypothesis that Shape Competitors received more looks than would be expected by chance. Each participant was randomly assigned to one of the two display types.

In addition to the 14 critical homophone trials, 14 filler trials with unambiguous targets were constructed. Trials were presented in a fixed random order.

Norming

Word association norms. Meaning dominance frequencies were collected in a word association task. Twenty-seven participants provided the association norms and received partial course credit. No participants in this and any of the norming experiments participated in the primary experiment. Participants listened to a list of words and, for each word, typed the first related word that came to mind. The stimuli consisted of 148 heterographic and homographic homophones and 80 unambiguous fillers. We selected 14 homophones that elicited word association responses with at least a 19% difference between the dominant and subordinate meaning. Of these 14 homophones, on average, the dominant meaning gathered 79% of the total word association responses, and the subordinate meaning gathered 16% of the total responses. The remaining 5% of the responses had missing values or were unrelated to the two most common meanings of the homophone.

Picture agreement norms on Actual Referents. Picture agreement norms confirmed that there was no difference in labeling agreement for the pictures we chose to represent the Actual Referents of the subordinate and dominant meanings of the homophones. Forty-two participants were each presented with a sequence of 200 pictures on a computer screen. Two lists were created such that half of the homophone pictures were of the dominant meaning, and half of the homophone pictures were of the subordinate meaning. Each participant saw each homophone item once, either in the dominant or subordinate condition. Only one picture appeared on each screen, simultaneously with a box in which they were asked to type the name of the picture of the object represented. Fourteen were pictures of homophones, and 186 were filler pictures with unambiguous labels. Trials were coded as having correct agreement when the response included the homophone in any part of the answer, including misspelled words and plurality differences, but not including synonyms or other names. For example, if the intended label was flower, responses such as *purple flower*, *flower petals*, *flowers,* and *flowr* were accepted. However, responses such as *orchid*, *purple bloom,* and *bouquet* were not accepted. The agreement between the participants' responses and the intended labels was 85.5% for the dominant-biased condition and 81.2% for the subordinate-biased condition. A t-test indicated no differences between conditions ($t_2(26) = 0.76$, $p > .10$).

Picture norms on Shape Competitors. In choosing the pictures to represent the Shape Competitors, it was not crucial to select pictures with high name agreement, because the relevant factor was shape similarity to a prototypical object representing one of the homophone's meanings. Nonetheless, it would present a confound if a shape competitor picture was likely to be labeled with a name beginning with the same phonemes as the homophone in that particular trial. This is actually a potential weakness for Huettig and Altmann's (2007) competitor condition, described above, because they provided no norms on the shape competitors to ensure that they would not be given a label that overlapped in phonology with the homophone. We worried that, for example, the shape competitor 'needle' from their example sentence, would activate "pin"—a phonological competitor for "pen".

Thus, we collected picture naming data for the shape competitor pictures, similarly to the labeling agreement norms for the Actual Referent pictures. Twenty participants were presented with a sequence of 128 pictures on a computer screen. One list was created with 14 competitors of the dominant meanings and 14 competitors of the subordinate meanings of the homophone. One hundred filler pictures with unambiguous names were used. Each participant saw every Shape Competitor once, both in the dominant and subordinate conditions. Only one picture appeared on each screen, simultaneously with a box in which they were asked to type the name of the picture of the object represented. No responses for the Shape Competitor pictures indicated any phonologically similarity to the homophone to which the Shape Competitor belonged.

Picture similarity norms. Picture similarity norms indicated that the Shape Competitors were in fact similar in shape to the Actual Referents. Twenty-four participants were presented with a series of pictures with questions, such as “How similar in shape is this object to a flower?” Participants were asked to rate on a scale of 1 (not similar) to 7 (very similar) how similar the presented picture was to the object mentioned in the question. Participants’ judgments may also have been influenced by other perceptual variables, such as color and texture, but we explicitly avoided pictures with any conceptual or instrumental relationships to the homophones. In addition to the 28 Shape Competitor trials, there were 25 filler trials in which participants were asked to evaluate the shape similarity of a picture to a concept that we judged to be either related or unrelated in shape. Participants rated every Shape Competitor once. The mean ratings for shape-similarity were 4.84 and 5.76 for dominant and subordinate Shape Competitor, respectively. T-tests revealed that dominant Shape Competitors were judged less similar in shape to the actual objects than subordinate items, so any looks to dominant Shape Competitors can not be due to higher similarity of those items to the actual objects ($t_1(1,23) = 7.32$, $p < .001$; $t_2(1,26) = 3.50$, $p < .05$).

Picture saliency norms. Picture saliency norms were conducted to evaluate any difference in saliency among the critical pictures. These norms were collected for all 16 critical trials used in Experiment 2, however only the 14 trials relevant to Experiment 1 are reported here. Thirty-five participants were asked to view pictures silently on the computer screen while a head-mounted eye-tracker monitored their eye movements. Two display conditions were created such that half the participants saw the dominant Actual Referents and subordinate Shape competitor, and the other half saw the subordinate Actual Referents and the dominant Shape competitor. On each trial, four pictures appeared on the screen for 5 seconds, and a drift correction procedure was conducted between every trial. The four pictures were the same as the pictures from Experiment 1. The critical trials and 28 filler trials were presented in a random order.

The dwell time percentages for each object type in the Dominant-Actual display condition were the following: Actual Referent: 19.1%, Shape Competitor: 20.1%, Fillers: 18.7%. Subordinate-Actual display: Actual Referent: 21.2%, Shape Competitor: 18.9%, Fillers: 18.5%. For Shape competitors and Fillers, independent t-tests found no differences between the Dominant Actual and Subordinate Actual display conditions (Shape Competitor: $t_1(1,33) = 1.04$, $p > .10$, $t_2 < 1$; Filler: $t_1 < 1$, $t_2 < 1$). For Actual Referents, there was a marginal effect only by participants ($t_1(1,33) = -1.83$, $p < .10$, $t_2 < 1$), in which subordinate referents attracted more fixations. Independent t-tests found no advantage of Shape Competitors compared to Fillers in the Dominant Actual display ($t_1(1,52) = 1.17$, $p > .10$, $t_2 < 1$) nor in the Subordinate Actual display ($t_1 < 1$, $t_2 < 1$). Thus, there were no advantages in saliency for pictures representing the dominant meanings over pictures representing the subordinate meanings, nor for Shape Competitors over Filler objects.

Procedure and Equipment

The auditory sentences and their corresponding slides were presented in a fixed random order. There were four practice trials before the experimental trials began. Eye position was recorded as participants listened to the sentences, using an ISCAN© Head-mounted Eye Tracking System. The eye and scene cameras were mounted on a headgear, with a sampling rate of 120 Hz.

Participants were seated at approximately 24 inches from the screen. The visual angle from the fixation cross to the pictures was approximately 9 degrees. The auditory and visual stimuli were presented using E-Prime software. Participants heard these instructions:

> *At the beginning of each trial, you will see a cross in the center of the screen. Surrounding the cross, there will be four pictures. You will hear instructions that will ask you to look at the cross and then point to objects on the screen.*

Before the practice trials, a six-point calibration slide was presented. On each trial, participants were presented with a fixation slide simultaneously with auditory sentence instructions. At 3000 ms after sentence onset, the four-picture slide appeared simultaneously with the onset of the critical homophone. The experimenters used the scene camera screen to verify whether or not the participant was accurately pointing to the correct targets. Between each trial, there was an additional six-point calibration slide. If four out of six points were not accurately calibrated, recalibration was performed. The entire experiment lasted less than thirty minutes.

The data were collected and organized using PRZ analysis software provided by ISCAN©.

Results

As noted above, there were two critical pictures on each trial: the Actual Referent and the Shape Competitor. The data for one item were omitted from all analyses, because the subordinate meaning was inadvertently presented in the Dominant Actual display. Four eye movement measures were analyzed: (1) first run dwell time on each of the critical pictures and filler objects, (2) visual bias towards shape competitors, measured by log gaze probability ratios to Shape Competitor and Filler pictures from target word onset until 1000 ms after target onset, (3) the latency of the first look to the critical picture after target onset, and (4) the number of trials with at least one look to the Shape Competitor.

[Insert FIGURE 1]

Figure 1 presents the proportion of looks to all four types of critical pictures during each 100 ms interval after homophone onset, for both display conditions. From 0 to 399 ms, participants were not looking at any critical pictures 99% of the time. Beginning at 400 ms, participants started fixating the critical pictures. The dominant Actual Referents appear to have attracted more looks over time than the subordinate Actual Referents, revealing a relative dominance effect. Looks to Shape Competitors appear to increase at the same time as the Actual Referents, with dominant Shape Competitors attracting more looks than subordinate Shape Competitors. Looks to the subordinate Shape Competitors decrease starting around 700 ms.

First Run Dwell Time

First run dwell time was analyzed in order to evaluate initial processing time for each of the fixated objects (as in Arai, Van Gompel, and Scheepers, 2007). First run dwell time was defined as the first and all consecutive fixations on an object until another object or background was fixated. To maximize the likelihood that there would be at least one fixation on all four pictures for most trials, we searched for fixations during a large time window, 5 seconds following target onset. The mean first run dwell times for the critical objects in the Dominant-Actual display with standard errors were as follows: Actual Referent: 950(35), Shape Competitor: 174(15), Filler: 134(7). The means for the Subordinate-Actual display were as follows: Actual Referent: 872(38), Shape Competitor: 360(36), Filler: 164(12).

In order to determine whether the second meaning of the homophones was activated at above chance levels, first run dwell times to the Shape Competitors were compared to mean first run dwell times to the Filler objects. For each display condition, an independent t-test was performed. For the Dominant-Actual display, subordinate Shape Competitors had longer first run dwell times than Fillers ($t_1(1,28) = 2.30$, $p < .05$; $t_2(1,23) = 2.67$, $p < .05$). For the Subordinate-Actual display, dominant Shape Competitors had longer first run dwell times than Fillers ($t_1(1,27) = 4.70$, $p < .001$; $t_2(1,24) = 2.28$, $p < .05$). These findings suggest that both the dominant and subordinate meanings, represented by the Shape Competitors, were activated at levels higher than chance. This is not surprising, given the neutral linguistic context and the results of Huettig and Altmann (2007), but it demonstrates activation of the subordinate meaning of a homophone even when a subordinate referent is not viewed prior to homophone onset.

Display Condition effects on the first run dwell times to Actual Referents and Shape Competitors were analyzed using independent t-tests. There was no effect of display condition on Actual Referents ($t_1(1,28) < 1$; $t_2(1,24) = 1.11$, $p > .10$). However, Shape Competitors showed a significant effect of meaning dominance by participants, and marginally by items ($t_1(1,28) = 3.91$, $p < .001$; $t_2(1,24) = 2.01$, $p < .10$).

Visual Bias towards Shape Competitors

To evaluate the time course of activation of the second meaning of ambiguous words, visual bias towards the Shape Competitor compared to the Filler pictures was analyzed in 100 ms intervals from target word onset until 1 second after target onset. As per Arai et al. (2007), log gaze proportions were used in order to circumvent problems of interdependence between looks to pictures. If an Actual Referent is fixated 70% of the time in condition A and 50% in condition B, the Shape Competitor automatically has a lower chance of being fixated in the condition A than B, purely based on being paired with an object that attracts more fixations. Thus, it is not appropriate to compare absolute proportions to different pictures on the same trial. Log gaze proportions provide a measure of bias towards the Shape Competitor, independent of the proportion of fixations to the Actual Referent, providing an appropriate measure of higher-than-chance activation. Because Filler Objects should not attract fixations when the homophone is spoken, and only be fixated by chance, any bias towards Shape Competitors over Filler Objects would indicate preferential processing of the dominant meaning.

We used Arai et al. (2007)'s formula for log ratios to evaluate the strength of visual bias towards Shape Competitors:

$$\ln(P(\text{Shape Competitor})/P(\text{Filler Objects}))$$

P(Shape Competitor) is the likelihood of fixating the Shape Competitor during the 100 ms interval, and P(Filler Objects) is the likelihood of fixating a Filler Object during the 100 ms interval. Using the log of the ratio of likelihoods yields a number that is either 0, positive (indicating a Shape Competitor Visual Bias) or negative (indicating a Filler Object Visual Bias). Note that there are missing values for several log-ratio values due to zero values at the early bins: no ratio can be determined using zero as a denominator, nor a log value for zero. Figure 2 plots log gaze ratios in 100 ms intervals, relative to homophone onset. Due to missing values, statistics could be computed starting only from the 600 ms interval.

[Insert FIGURE 2]

For each display condition, one-way ANOVAs comparing the log-ratio to the test value 0 were performed within participants and within items for each 100 ms interval from 600 ms until 1000 ms after target onset. The degrees of freedom change for the different analyses based on the number of zero probabilities on a trial by participants or items. These differences in degrees of freedom across intervals affect the strength of the ANOVA F values, such that lower means can produce more significant F values if they have more degrees of freedom.

For the Dominant-Actual display condition, there was a visual bias towards the subordinate Shape Competitors at the 600 ms interval ($F_1(1,14) = 8.43$, $p <.05$; $F_2(1,12) = 7.60$, $p < .05$). This bias was significant at the 700 interval by items and marginal by participants ($F_1(1,16) = 4.18$, $p <.10$; $F_2(1,18) = 14.31$, $p < .01$), and was fully significant again at 800 ms ($F_1(1,24) = 10.73$, $p <.01$; $F_2(1,16) = 8.77$, $p < .01$). For the Subordinate-Actual display condition, there was a visual bias towards the dominant Shape Competitors at the 600 ms interval by participants, marginal by items ($F_1(1,16) = 11.94$, $p <.01$; $F_2(1,18) = 3.72$, $p < .10$), which was fully significant from 700 to 1000 ms after target onset (700 ms: $F_1(1,20) = 15.00$, $p <.01$; $F_2(1,24) = 7.21$, $p < .05$; 800 ms: $F_1(1,22) = 17.02$, $p <.001$; $F_2(1,20) = 16.73$, $p < .01$; at 900 ms: $F_1(1,20) = 33.29$, $p <.001$; $F_2(1,16) = 46.53$, $p < .001$). In sum, the activation of the second meaning, as indexed by the visual bias towards the Shape Competitor, compared to the filler pictures, was evident for both the dominant and subordinate meanings at the earliest measurable time frame, however the dominant meaning seems to have more robust activation that lasts longer than the subordinate meaning.

To determine whether the likelihood of fixating the Shape Competitors in a given interval depended on whether it represented the dominant meaning or the subordinate meaning, we performed t-tests on the log-ratios of Shape Competitors compared to Fillers at each 100 ms interval. Display Condition effects only appeared at 800 ms, where there was a stronger visual bias towards the dominant Shape Competitor than towards the subordinate Shape Competitor (800ms: $t_1(1,19) = 2.77$, $p < .05$, $t_2(1,14) = 3.01$, $p < .01$; 900ms: $t_1(1,17) = 4.00$, $p < .001$, $t_2(1,14) = 2.18$, $p < .10$).

These results show that multiple meanings of a word were activated after hearing the ambiguous word, because Shape Competitors attracted a higher proportion of fixations than filler objects. Even when there was a matching referent to the homophone on the visual display, alternative meanings of a word had an effect on eye movements, directing attention towards the Shape Competitor of the alternate meaning. Furthermore, relative dominance influenced the duration (and perhaps the degree) of activation of the Shape Competitors, such that dominant Shape Competitors were looked at comparatively more than the subordinate Shape Competitors.

Latency of First Fixation

The latency of the first look to a critical picture after homophone onset was examined as a function of each homophone's relative dominance in order to evaluate a more detailed correlation between relative meaning dominance and eye movements. Trials that had latencies of above 3 standard deviations were not included, which was 2.6% of trials. The average length of the spoken homophone was 527 ms, and the amount of time it takes to plan and execute an eye movement is approximately 200 ms. The mean latency of first looks to the Actual Referent pictures after homophone onset was 956 ms, i.e., on average, a fixation to an actual referent was planned within 250 ms of homophone offset. The mean latency of first looks to the Shape

Competitor pictures after homophone onset was 737 ms, indicating that many of these fixations were planned prior to homophone offset. The latency to Shape Competitors may have been faster than to Actual Referents because Shape Competitors did not require fixations, while Actual Referents were required to be fixated in order to complete the trial as directed. Thus, Shape Competitors, if fixated at all, were generally not fixated late in the trial. As shown in Figure 3, meaning dominance inversely affected latency of first look to the Actual Referent picture: as dominance increased, latency decreased (r(26) = -.52, p <.01) ($F_2(1,24) = 8.64$, p <.01). The analogous correlation was not found for Shape Competitor pictures, suggesting that the meaning dominance was more directly related to looking latency for the Actual Referent than for the Shape Competitor.

[Insert FIGURE 3]

Probability of Fixation

The proportion of trials in which participants made at least one look to a Shape Competitor within 1000 ms of homophone onset was 0.42 and 0.24 for dominant and subordinate Shape Competitor pictures, respectively. An independent t-test confirmed that were more trials with looks to the dominant Shape Competitors than the subordinate Shape Competitors ($t_1(1,28) = 3.16$, $p < .01$; $t_2(1,24) = 2.46$, $p < .05$). This was predicted by the relative dominance hypothesis, in which dominant meanings of an ambiguous word are more highly activated than subordinate meanings.

Discussion

In Experiment 1, as the spoken homophone unfolded in a neutral linguistic context, participants accessed multiple meanings, and relative activation of the two meanings was measured by observing the proportions of looks to pictures corresponding to each meaning of the homophone. One meaning's activation was measured by looks to a picture depicting an actual referent, and the alternative meaning's activation was measured by looks to a visual shape competitor of that meaning's prototypical referent. Recall that Huettig and Altmann (2007) also found activation of both subordinate and dominant meanings in neutral context, but it was unclear to what extent the fixation patterns were dependent upon visual preview of the potential referents. We find it particularly striking that, in our experiment, the subordinate meaning of the homograph was activated (based on above chance looks to the shape competitor) even when an actual referent for the dominant meaning was pictured.

The design of our experiment also allowed us to investigate the influence of meaning frequency on fixation patterns. Crucially, we found dominance effects in the proportion of looks to both Actual Referents and Shape Competitors. While neither dominance effect is particularly surprising given the ubiquity of frequency effects in neutral contexts, it was important to demonstrate that dominance effects could be found with Shape Competitors when an Actual Referent was simultaneously pictured. Even though there was a pictured target consistent with the spoken input, activation of other meanings of the homophone directed looks to other objects on the screen, namely the shape competitors of the alternative meaning.

Because the visual context was presented simultaneously with the spoken homophone, there was no previous visual or linguistic context to bias the meaning of the homophone. Thus, meaning frequency was the only available influence on initial spoken word recognition in this paradigm. Nonetheless, as the visual context was integrated with the spoken input, effects of the visual display on word recognition were observed. That is, initially, looks towards the actual referent and the shape competitor of the alternative meaning of the homophone increased in a similar fashion, but after 700 ms, the activation of the alternative meaning decreased, reflecting resolution of the homophone toward the pictured meaning.

Experiment 2

Whereas the primary focus in the first experiment was on meaning dominance effects, the primary focus in Experiment 2 was on sentence context effects. The Reordered Access and Selective Access accounts of ambiguity resolution differ in how a strongly subordinate-biasing context affects the pattern of activation of multiple meanings of homophones, so we manipulated the strength of the subordinate-biasing sentence context before the homophone was heard. Participants heard homophones in either neutral or subordinate-biased contexts (e.g., NEUTRAL: *Jenny looked at the table and was surprised to see the flower/flour*, BIASED: *The baker took out the necessary ingredients, like milk, eggs, and flour*). At homophone onset, four pictures appeared: a subordinate homophone referent (flour), a dominant meaning shape competitor (lollipop, for flower), and two unrelated pictures. The shape competitor was used to index subliminal activation of the dominant meaning.

Reordered Access theories would predict that the dominant meaning of the homophone will still be activated even under strong subordinate-biasing context because of the high frequency of the dominant meaning (Duffy et al., 1988, 2001). This theory would also predict changes in level of activation of the subordinate meaning across context conditions, but no change in the initial activation level of the dominant meaning. While the dominant meaning must be eventually be discarded because it is contextually inappropriate, its activation should not be affected by subordinate-biasing contexts. S*elective Access* theories would predict that activation of the dominant meaning is a function of contextual strength, so the dominant meaning should be strongly activated in the neutral context, but not activated at all in the strongly biased context (Martin et al., 1999).

By comparing both neutral and biasing contexts, we can measure the influence of subordinate-biased context on both the activation of the appropriate and the inappropriate meanings of the homophone. As in Experiment 1, none of the dominant shape competitors overlap in phonology with the spoken referent names, so any activation of the shape competitor from the spoken input indicates activation of the dominant meaning of the homophone. The activation of the dominant meaning of the homophone is measured by comparing looks to the shape competitor picture with looks to any of the filler items (by chance). If shape competitors of the dominant homophone meaning attract more looks than chance in either the neutral context, subordinate contexts, or both, multiple meanings have been accessed.

Method

Participants

Thirty undergraduates at the University of Michigan participated in this experiment for course credit in an Introductory Psychology class or were paid for participation. All participants were native speakers of English and had normal or corrected vision.

Materials

Sixteen homophones were selected with the criteria as in Experiment 1. The 14 homophones from Experiment 1 were included, and two additional homophones were added in order to increase statistical power (see Appendix B).

In contrast to Experiment 1, only the subordinate meaning of the homophone was ever pictured as the Actual Referent, and it always appeared with an object that was similar in shape to the dominant meaning of the homophone (Shape Competitor). The norms used to assess shape similarity are described below.

Visual stimuli consisted of four pictures arranged in a 3x3 grid on a white background with a fixation cross in the center for each critical trial. The critical pictures were all full-color realistic images selected from an online searchable database of images (Google, 2004). The pictures appeared in the upper left, upper right, lower left, or lower right area of the grid, arranged so that the Actual Referent appeared in each corner an equal number of times for every participant. The Shape Competitor also appeared in each corner an equal number of times for every participant. The two remaining corners contained filler pictures of objects with unambiguous names that did not begin with the same phonemes as the critical homophone and were not similar in shape to the critical pictures.

Two linguistic context conditions were created for each of the sixteen homophones (see Appendix C). In the Subordinate-Biased context condition, participants heard a sentence context that constrained the homophone toward its subordinate meaning (e.g., *The baker had agreed to make several pies for a large event today, so he started by taking out necessary ingredients, like milk, eggs, and flour*). No lexical associates were used in the sentence, in order to exclude bottom-up lexical priming as a factor in activation of either meaning of the homophone. In the Neutral context condition, participants heard a sentence context in which both meanings of the homophone were very plausible (e.g., *As Jenny walked into the house after school, she looked at the table and was surprised to see the flower/flour*). The norms for meaning bias of sentence contexts appear below. Context condition was varied between participants because ~~there was a possibility that~~ the probability of looks to the Shape Competitor ~~effects would not be large enough to create a comparison~~in the Subordinate context might be quite low, and we wanted to maximize statistical power for evaluating the hypothesis that the Shape Competitor was nonetheless activated at greater than chance levels. Each participant was randomly assigned to one of the two context conditions. The auditory stimuli were recorded by a female speaker.

In addition to the 16 critical homophone trials, 28 filler trials with unambiguous targets were constructed.

Norming

The picture agreement and similarity norms were run again for Experiment 2 in order to incorporate the 2 items which were not included in Experiment 1. In order to test the contextual strength of the sentences used in Experiment 2, meaning bias norms were also conducted.

Picture agreement norms on Shape Competitors. In order to ensure that the Shape Competitor pictures did not activate any lexical items beginning with the same phonemes as the actual homophones, we collected data from a picture naming agreement task. Twenty-three participants were presented a sequence of 132 pictures on a computer screen. The list was created such that Shape Competitors of the dominant meaning of the 16 homophone pictures were presented randomly with 116 filler pictures with unambiguous names. Each participant saw every Shape Competitor once. Only one picture appeared on each screen, simultaneously with a box in which they were asked to type the name of the picture of the object represented. No responses for the Shape Competitor pictures indicated any phonologically similarity to the actual homophone.

Picture similarity norms. Picture similarity norms indicated that the Shape Competitors were in fact similar in shape to the Actual Referents. We collected data from a picture similarity task. Twenty-three participants who participated in the picture naming norms were presented with a series of pictures with questions, such as “How similar in shape is this object to a flower?”

Participants were asked to rate on a scale of 1 (not similar) to 7 (very similar) how similar the presented picture was to the object mentioned in the question. The 16 Shape Competitor pictures of the dominant homophone meaning of were tested according to their similarity to the homophones, along with 58 filler ratings to unrelated objects, which varied in visual form similarity. The Shape Competitor pictures were presented along with a question asking how similar that object is to the actual homophone object. Participants rated every Shape Competitor once. The mean rating for shape-similarity was 5.25, which indicates high similarity of visual form to the actual dominant homophone referent.

Meaning bias norms. Meaning bias norms indicated that the Subordinate-Biased sentences indeed biased only the subordinate meaning of the homophone, and that the Neutral sentences did not favor one meaning of the homophone. We collected data from a sentence bias rating task. Twenty participants were presented with a series of auditory sentences with questions, such as “Was the sentence you just heard referring to a flower or flour?” Participants were asked to rate on a scale of 1 (dominant) to 9 (subordinate) the likelihood of two different interpretations of the object mentioned in the sentence. Participants rated every homophone twice, with all 16 Neutral sentences rated before the 16 Subordinate-Biased sentences, dispersed randomly among with 40 filler ratings to unrelated sentences. The mean ratings for the subordinate meaning were 8.85 and 4.98 for the Subordinate-Biased and Neutral sentences, respectively. These bias ratings were converted in the same manner as Martin et al. (1999) in order to test whether the biased and neutral distributions overlapped. The scale was converted to represent the strength of deviation from the center of the scale: 0 to represent ambiguity and 4 represented a strong bias. The contexts had the following scores: Biased: M = 3.846, SD = 0.386;

Neutral: M = -0.019; SD = 1.424. Compared to the strongly biasing contexts in Martin et al. (1999), the Subordinate-Biased contexts were similarly biased or stronger.

Picture saliency norms. Picture saliency norms were conducted to evaluate any difference in saliency among the critical pictures. These norms were collected for all 16 critical trials. The procedure for the saliency norms is reported above in Experiment 1. Only data from the relevant Subordinate-Actual display is reported here. The dwell time percentages for each critical picture were 21.0%, 18.8%, and 18.8% for the Actual Referents, Shape Competitors, and Fillers, respectively. An independent t-test found no advantage in saliency for Shape Competitors over Filler objects ($t_1 < 1$, $t_2 < 1$).

Procedure and Equipment

Experiment 2 differs from Experiment 1 in the eye-tracking system used. Experiment 2 employs an Eyelink II head-mounted binocular eye tracking device. As in Experiment 1, the eye cameras were mounted on headgear, but Experiment 2 used a sampling rate of 500 Hz. Also in contrast to Experiment 1, the order of the auditory sentences and their corresponding slides was randomized for each participant.

Participants were seated at approximately 24 inches from the screen. The distance from the fixation cross to the center of the pictures was approximately 7.5 degrees. The auditory and visual stimuli were presented using SR Research Experiment Builder software. Participants read these instructions:

> *In this experiment, you will hear a sentence. At the end of the sentence, you will see four objects on the screen. Your task is to click on the object that matches the last word of the sentence you just heard and drag it to the center of the screen. For example, if you heard "The cat was scared of the dog, so it*

ran under the table", you would click on the TABLE and drag it to the center of the screen. You will also have a comprehension question after every sentence. Please say your answer (YES or NO) out loud.

Before the experiment began, the experimenter performed a calibration procedure. Before each trial, a drift correction procedure was performed. On each trial, participants looked at a fixation cross while listening to the sentence. The pictures appeared simultaneously at target word onset. The entire experiment lasted fewer than thirty minutes.

The data were collected and organized using SR Research Experiment Builder and Data viewer software.

Results

The participants responded correctly to the comprehension questions 92.9% of the time.

As in Experiment 1, there were two critical pictures on each trial, the Actual Referent and the Shape Competitor. The three eye movement measures analyzed include the following: (1) Average proportion of looks to critical items from target word onset until 1000 ms after target onset, (2) first run dwell time on each of the critical pictures, and (3) visual bias towards shape competitors, measured by log gaze probability ratios to shape competitor and filler pictures from target word onset until 1000 ms after target onset.

[Insert FIGURE 4]

Proportion of Fixations over Time

Figure 4 presents the proportion of looks to all four types of critical pictures during each 100 ms interval after homophone onset, for both Context Conditions. The effects of context appear to be quite large, with Subordinate-Biased Context both increasing fixations to the Actual Referent and decreasing fixations to the Shape Competitor for the dominant meaning. Clearly, the dominant meaning was strongly activated in the Neutral Context, as evidenced by many fixations on the Shape Competitor. Less clear, is whether the dominant meaning was still partially activated in the Subordinate-Biased Context.

The proportion of looks to critical objects seems to have risen more ~~quickly~~ slowly in Experiment 1 (700ms) than in Experiment 2 (400ms). Several factors may have contributed to this difference in timing, and it is most likely that a combination of factors~~, rather than a single factor, that drives~~ caused these differences. First, differences in the display types between the two experiments can explain some of the timing difference. In Experiment 1, the pictured objects were located in one of the four large quadrants ~~on~~ of the screen, but ~~were not adjusted to have a~~varied in specific size ~~or~~ and location within the quadrants. In contrast, in Experiment 2, ~~the same~~a 3x3 grid in the center of the screen was used on every trial, ~~such that~~with a picture in each corner of the grid~~,~~. The size of each picture was adjusted to be as large as possible, while still fitting within the boundaries of the appropriate square. ~~the pictures were displayed with the same size and shape.~~ Thus, the ~~shape,~~ location and size of the objects was more constrained in Experiment 2, whereas the pictures tended to be larger, more irregular, and farther from the fixation cross in Experiment 1~~, so the uniformity of the objects may have played a role in decreasing fixation time~~. We think this difference in the visual layout of the screen may have made it easier in Experiment 2 to quickly assess the content of each picture and plan a saccade to the appropriate picture. Secondly, ~~strategic processing of~~ the more constraining sentence contexts in Experiment 2 may have contributed to differences in time course. Even the Neutral sentences in Experiment 2 semantically constrained the interpretation of the homophone prior to homophone onset, compared to unvarying spoken instructions in Experiment 2. This may have lead to faster lexical access times, which in turn would lead to earlier fixations on the pictures.

(~~However~~In contrast, in both experiments, predictive processing *due to the visual display* is not likely because the pictures did not appear until homophone onset.) Lastly, differences in tasks, instructions and equipment between the two experiments may have also played a role. In particular, Experiment 1 employed a pointing task, while Experiment 2 required participants to use the computer mouse, which may have made the participants more tuned to the mouse pointer and other objects on the screen.

To evaluate the time course of the influence of biasing context, we analyzed the proportion of looks to each critical picture in 100 ms intervals from target word onset. First, we contrasted looks to the Actual Referent during Subordinate-Biased and Neutral Contexts using independent t-tests. Starting at 300 ms, the Subordinate-Biased Context increased looks to the Actual Referents compared to the Neutral Context by participants (300ms: $t_1(1,28) = 2.97$, $p < .01$; $t_2(1,30) = 1.83$, $p < .10$).

The context also influenced the probability of looks to the Shape Competitors. Starting at 500 ms, there were fewer fixations to the Shape Competitor in the Subordinate-Biased Context than in the Neutral Context by participants, and at 600 ms for both participants and items (500ms: $t_1(1,28) = -2.56$, $p < .05$; $t_2(1,30) = -1.43$, $p > .10$; 600ms: $t_1(1,28) = -4.34$, $p < .001$; $t_2(1,30) = -2.20$, $p <.05$). Together, these findings indicate that at early time intervals, the Subordinate-Biased Context both increased activation of the subordinate meaning and decreased activation of the dominate meaning, relative to a Neutral Context.

First Run Dwell Time

First run dwell time was analyzed in order to evaluate initial processing time for each of the fixated objects. The mean first run dwell times for the critical objects in the Neutral Context condition with standard errors were as follows: Actual Referent: 590(13), Shape Competitor:

246(6), Filler: 205(3). The means for the Subordinate-Biased Context condition were as follows: Actual Referent: 706(15), Shape Competitor: 228(9), Filler: 192(3).

In order to determine whether the dominant meaning of the homophone was activated at above chance levels, first run dwell times on the Shape Competitors were compared to mean first run dwell times on the unrelated filler objects. For each contextual bias condition, independent t-tests were performed. In the Neutral Context condition, Shape Competitors had longer first run dwell times than fillers, as expected ($t_1(43) = 6.26$, $p < .001$; $t_2(46) = 6.49$, $p < .001$). Interestingly, this effect also occurred in the Subordinate-Biased Context condition: Shape Competitors had longer first run dwell times than fillers ($t_1(43) = 5.29$, $p < .001$; $t_2(46) = 2.93$, $p < .01$). These findings suggest that the dominant meaning, represented by the Shape Competitor, was activated at levels higher than chance, even during the Subordinate-Biased Context.

Contextual bias effects on the first run dwell times to Actual Referents and Shape Competitors were analyzed using t-tests. There was an effect of context type on Actual Referents ($t_1(28) = 3.20$, $p < .01$; $t_2(30) = 4.14$, $p < .001$), such that the Actual Referent in the Subordinate-Biased condition was fixated longer than in the Neutral Context. This effect confirms that the Subordinate-Biasing Context boosted activation of the subordinate meaning. There was however no context effect on Shape Competitors ($t_1(28) = 1.10$, $p > .10$; $t_2(30) = 1.66$, $p > .10$).

Visual Bias of Shape Competitors

As another test of whether the dominant homophone meaning was activated in the Subordinate-Biased Context, we compared the observed proportion of looks to the proportion that would be expected on the basis of chance alone. To evaluate this activation, we used log gaze ratios as a measure of visual bias to the Shape Competitors compared to Filler objects. Log-gaze ratios provide a measure of bias towards the dominant meaning compared to filler objects that is independent from the level of activation of the subordinate meaning. If Shape Competitors are activated more than Filler objects, this would be evidence for higher activation than expected by chance. Figure 5 plots the time course of log gaze ratios for each context condition. Due to missing values, statistics could be computed starting only from the 300 ms interval.

[Insert FIGURE 5]

One way ANOVAS compared the log gaze ratios to 0 across participants and items for each 100 ms interval from 300 ms until 1000 ms after target onset. In the Neutral Context, there was a visual bias towards Shape Competitors compared to Filler objects starting at 500 ms, significant only by participants, not by items ($F_1(1,26) = 16.17$, $p <.001$; $F_2(1,30) = 3.23$, $p < .10$), and continuing from 600 until 1000 ms by both participants and items (600 ms: $F_1(1,26) = 40.26$, $p <.001$; $F_2(1,30) = 14.24$, $p < .01$; 700 ms: $F1(1,26) = 50.45$, $p <.001$; $F2(1,26) = 38.15$, $p < .001$; 800 ms: $F_1(1,26) = 23.79$, $p <.001$; $F_2(1,28) = 8.48$, $p < .01$; 900 ms: $F_1(1,24) = 10.82$, $p <.01$; $F_2(1,28) = 24.80$, $p < .001$). More importantly, in the Subordinate-Biased Context, there was still a visual bias towards the Shape Competitors compared to Filler objects, that was significant at 500 ms by participants ($F_1(1,28) = 11.11$, $p <.01$; $F_2(1,26) = 3.13$, $p < .10$), and by both participants and items at 600 and 700 ms (600 ms: $F_1(1,28) = 15.14$, $p <.01$; $F_2(1,26) = 4.34$, $p < .05$; 700 ms: $F_1(1,26) = 17.78$, $p <.001$; $F_2(1,26) = 5.11$, $p < .05$). Dominant meaning activation is predicted by all theories in the Neutral Context, however evidence of dominant meaning activation during the strong Subordinate-Biased Context was only predicted by the Reordered Access theory.

To determine whether the Subordinate-Biased Context affected the level of activation of the dominant meaning, as represented by the Shape Competitor, the log ratio of bias towards the dominant Shape Competitor was compared across context conditions for each 100 ms interval.

At 700 ms after homophone onset, one-tailed t-tests revealed a larger bias in the Neutral than the Subordinate-Biasing Context ($t_1(1,26) = 1.84$, $p<.05$; $t_2(1, 18) = 1.97$, $p<.05$).[i] Assuming that this effect reflects early lexical processing, and not post-lexical processing, this difference indicates that context did influence the activation level of the dominant meaning. This finding is problematic for a strict version of Reordered Access that assumes that a subordinate-biased context has an effect only on the subordinate meaning, by increasing its initial activation, and leaves the dominant meaning activation unaffected. This finding, however, is consistent with the Selective Access view that strong subordinate-biasing context both increases activation of the subordinate meaning and limits activation of the dominant meaning

Discussion

There are three important findings reported here. First, context influenced the proportion of fixations on the subordinate Actual Referent, starting at 300ms after homophone onset. This finding is consistent with all accounts of the Subordinate Bias Effect, as well as both Reordered and Selective Access. Second, the dominant Shape Competitor attracted more fixations than expected by chance, even in the Subordinate-Biased Context condition. This effect is predicted by competition-based accounts of the Subordinate Bias Effect, Reordered Access, and is consistent with the Huettig and Altmann (2007) findings, but is not consistent with Selective Access accounts.

Third, context influenced the proportion of fixations on the dominant Shape Competitor, beginning 500ms after homophone onset, according to the raw proportion of fixations over time.

[i] A one-tailed t-test is appropriate here because subordinate-biasing context is predicted to decrease activation of the dominant meaning, according to Selective Access, while Reordered Access predicts no effect of context on the dominant meaning. A more conservative two-tailed test revealed a marginal context effect on the dominant meaning, by both participants and items ($t1(1,26) = 1.84$, $p<.10$; $t2(1, 18) = 1.97$, $p<.10$). However, the two-tailed t-test was fully significant when we excluded the 3 items whose subordinate-biased and neutral contexts differed by less than 30% in the meaning bias norms of Experiment 2 ($t1(1,25) = 2.55$, $p<.05$; $t2(1, 18) = 3.13$, $p<.01$).

Using a more stringent test (log ratios), context influenced the amount of bias towards the dominant Shape Competitor, beginning 700ms after homophone onset. The theoretical importance of this finding depends upon whether it reflects contextual modulation over initial access of the dominant meaning, as would be expected under Selective Access, or rapid use of context to select the appropriate meaning, as would be expected under Reordered Access. Average homophone duration was 527 ms, and the amount of time it takes to plan and execute an eye movement is approximately 200 ms, so the linguistic context began to influence looks to the pictured objects prior to homophone offset. Of course, spoken word recognition can occur mid-word in some cases (Marslen-Wilson, 1975; Marslen-Wilson & Tyler, 1975), so the fact that our context effects begin prior to homophone offset is no guarantee that they reflect initial lexical access rather than post-access processes.

One factor that seems to support the Reordered Access account is that the context effects emerged about 200 ms earlier for the contextually supported Subordinate Actual Referent than they did for the contextually unsupported Dominant Shape Competitor. Reordered Access maintains that, in a subordinate-biased context compared to a neutral context, access to the subordinate meaning will be faster. Initial access to the dominant meaning will be unaffected, but once context is used to select the subordinate meaning, the dominant meaning will become less activated. In our experiment, if looks to the Actual Referent and the Shape Competitor are equally sensitive to activation of the subordinate and dominant meanings, respectively, a different time-course for context effects would indeed be predicted by Reordered Access. Unfortunately, because only the subordinate meaning is actually pictured while the dominant meaning is represented by a shape competitor, the implications of this time-course difference are unclear. It is also unclear whether the later context effects for the Shape Competitor are actually late enough to reflect post-access processing.

Another way to gauge the theoretical implications of the contextual modulation of the dominant meaning in our experiment is to compare the time-course of our results with well-known cross-modal priming studies. (It is more difficult to compare the time-course of our results with reading studies because the perception of word form and the temporal dynamics of lexical activation are quite different in the written and spoken modalities.) The classic experiments that initially established multiple meaning activation presented the target word at homophone *offset* (Swinney, 1979; Tanenhaus et al., 1979). To the extent that the paradigms are comparable, our experiments tapped lexical processing at a slightly earlier time-point than these experiments, and certainly earlier than cross-modal experiments that delayed presentation of the target word until 200 ms or more after homophone offset, demonstrating that, by that time, a single referent had been selected after initially activating multiple candidates (e.g., Seidenberg, Tanenhaus, Leiman & Bienkowski, 1982).

Another point of comparison is provided by the more recent visual world experiments investigating lexical activation. For example, Allopenna, Magnuson and Tanenhaus (1998) found more fixations to unambiguous referents and phonological cohorts than controls from 300-700 ms after the critical word. Similarly, Dahan et al. (2001) found more fixations to unambiguous referents and phonological cohorts than controls from 200-500 ms after the critical word. These effects occurred before the offset of the spoken target, with eye movements planned almost immediately after target onset. However, in both cases, the spoken input was disambiguated earlier than in our current experiments, which could affect how early the saccades were planned. Also, the pictures were on the screen for several seconds prior to pronunciation of the critical word, which could conceivably allow strategic processing of the visual input, increasing lexical activation prior to integration of the spoken input. At a minimum, free viewing of the pictures before hearing the target word would facilitate saccade planning.

In sum, we can not completely rule out the possibility that the context effects on the dominant meaning reflect post-access use of context, but taken together with the broader literature, it is most likely that the context modulated the initial activation of the dominant meaning. If so, these findings provide evidence against any theory of lexical ambiguity resolution that maintains that the dominant meaning is always accessed simply based on the strong form-meaning mapping, and not modulated by sentential context. Thus, competition-based accounts of the Subordinate Bias effect, as well as a strict version of Reordered Access in which only activation of the contextually appropriate meaning is influenced by context, cannot provide an account of this finding.

In short, our data support a version of Reordered Access in which the activation of each of a homophone's meanings is modulated by context very early during lexical access. A strong subordinate bias may both increase the activation of the subordinate meaning and decrease activation of the dominant meaning. For balanced homophones, context may sometimes be strong enough to selectively activate a single meaning. However, for polarized homophones, the dominant meaning is likely to be somewhat activated, even in strongly subordinate-biased contexts, based solely on the strength of its form-meaning mapping. Although context can have a great influence on activation of each of the homophone meanings, activation of a strongly dominant meaning probably cannot be completely overridden. This account is quite similar to the Reordered Access account of Duffy et al. (1998, 2001).

General Discussion

In Experiment 1, using neutral imperative sentence contexts, both the pictured referent meaning of the homophone and the alternative shape competitor meaning of the homophone competed for attention following the spoken homophone. Importantly, we found dominance effects on looks to Shape Competitors when an Actual Referent was simultaneously pictured. Dominant meanings were activated more strongly than the subordinate meanings, as seen in the high number of looks to the dominant Shape Competitors. Secondly, although subordinate meaning Shape Competitors received fewer overall looks than the dominant meaning Shape Competitors, they nonetheless received above-chance attention, despite the presence of an Actual Referent for the dominant meaning. Both effects are somewhat surprising, given that shape competitors had no connection to the spoken homophone, except that they were visual competitors of the alternate meaning. As such, our results add to the growing body of shape competitor findings in the visual world paradigm indicating that shape competitors provide an unobtrusive but sensitive index of lexical activation (Dahan & Tanenhaus, 2005; Huettig & Altmann, 2007; Huettig et al., 2004).

In Experiment 2, we demonstrated that top-down processing from sentential context can influence the pattern of activation of multiple meanings of a homophone, such that subordinate-biasing context boosts activation of the subordinate meaning of the homophone. More importantly, analyses of looks to shape competitors designating the dominant meaning of the homophone revealed that the subordinate-biasing context decreased activation of the dominant meaning, although the dominant meaning was still activated more than would be expected by chance. This provides evidence that multiple access of homophone meanings still occurs, even when the biasing sentential and visual context only allows one interpretation of the homophone, which is consistent with the results of Huettig and Altmann (2007), previous reading studies showing the Subordinate Bias Effect even during strongly biased contexts, and Reordered Access (Binder, 2003; Binder & Rayner, 1998; Kambe et al., 2001; Pacht & Rayner, 1993; Rayner et al., 2006; Rayner et al., 1994, Sereno et al., 2006; Sereno et al., 1992). Multiple access, however, is inconsistent with the predictions of Selective Access models, where the Subordinate Bias Effect should be eliminated in strongly biasing subordinate contexts. As discussed above, both our normative data and the large, immediate effects of contextual bias suggest that our subordinate-biased contexts were indeed strongly biasing.

In contrast, the finding that the subordinate-biasing context decreases activation of the dominant meaning is not consistent with a strict version of Reordered Access that assumes that contextually inappropriate meanings are not influenced by disambiguating context (Duffy et al., 1988; 2001). This finding is, however, consistent with Selective Access accounts, where frequency, type of context and strength of context can influence homophone meaning activation (Martin et al., 1999). Neither a strict version of Reordered Access nor Selective Access is capable of accounting for all our findings in the current study. A more appropriate approach may be a version of Reordered Access in which both frequency and strength of context can constrain activation of each homophone meaning, but neither factor is able to completely dominate patterns of lexical activation.

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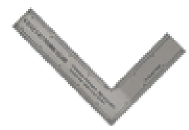
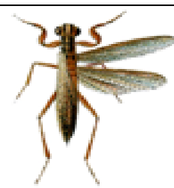
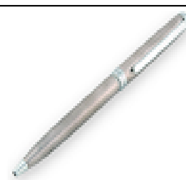
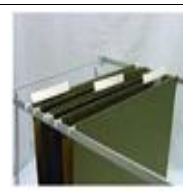
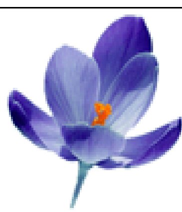
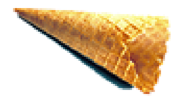
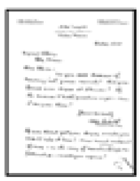
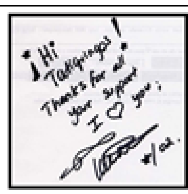
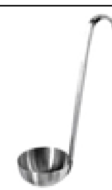
Appendix A.

Critical Stimuli for Experiment 1

Critical Homophone	**Dominant Actual Referent**	**Dominant Shape Competitor**	**Subordinate Actual Referent**	**Subordinate Shape Competitor**
bow	 hunting bow	 hanger	 bowtie	 candy
check	 money check	 cutting board	 check symbol	 carpenter square
fairy	 fairy woman	 insect	 ferry boat	 sushi boat
file	 nail file	 ink pen	 office file	 accordion
flower	 flower blossom	 lollipop	 wheat flour	 pillow

Critical Homophone	Dominant Actual Referent	Dominant Shape Competitor	Subordinate Actual Referent	Subordinate Shape Competitor
glasses	 reading glasses	 handcuffs	 drinking glasses	 candles
horn	 French horn	 Shell	 animal horn	 ice cream cone
letter	 written letter	 playing card	 alphabet letter	 church cross
nails	 hand nails	 lipstick	 hammer nails	 pencils
note	 written note	 framed painting	 music note	 ladle

Critical Homophone	Dominant Actual Referent	Dominant Shape Competitor	Subordinate Actual Referent	Subordinate Shape Competitor
nut	 nut in shell	 brain	 tool nut	 hexagonal boxes
ring	 wedding ring	 inner tube	 boxing ring	 sandbox
stamp	 letter stamp	 painting	 ink stamp	 joystick
tank	 army tank	 slide projector	 water tank	 pill

Appendix B

Additional Stimuli for Experiment 2

Critical Homophone	**Dominant Actual Referent**	**Dominant Shape Competitor**	**Subordinate Actual Referent**
hose	watering hose	 snake	 digging hoes
trunk	car trunk	 present	 elephant trunk

Appendix C

Sentence Stimuli for Experiment 2

Item	Condition	Sentence
bow	Biased	When the girls at the slumber party decided to play dress-up, Katie put make-up on Monica, and Jessica put up Lisa's hair with a bow.
bow	Neutral	There was a blackout tonight, so there was no chance that Jamie would be able to find the bow.
check	Biased	Normally, Alice gets A plusses on her papers, but today she found out that the teacher marked it only with a check.
check	Neutral	Mr. White was working on the case all morning and did not realize that on the front page there was a check.
ferry	Biased	The travelers could not bring their car to the island because they didn't have enough cash to pay for their car to be loaded onto the ferry.
ferry	Neutral	During last Tuesday's art class, Lee's teacher was impressed by his detailed drawing of a ferry.
file	Biased	At the end of the work day, the manicurist cleaned up the salon and put everything back in its place, the cotton swabs, the polish, and the file.
file	Neutral	Andrea wondered how her sister ever got any work done, because she did not do anything except sit and occupy herself with a file.
flour	Biased	The baker had agreed to make several pies for large event today, so he started by taking out necessary ingredients, like milk, eggs, and flour.
flour	Neutral	As Jenny walked into the house after school, she looked at the table and was surprised to see the flour.
glasses	Biased	The restaurant's dishwashers had a scheme that worked very efficiently: first they would wash the plates, then the silverware, and finally the glasses.
glasses	Neutral	Amanda was on the phone and wasn't able to supervise her little brother, who ended up dropping the glasses.
hoes	Biased	Kim wanted to plant daisies in the yard, so she asked the boys to start preparing the soil with the hoes.
hoes	Neutral	It was spring cleaning time, and George always had a hard time throwing old items away, like the hoes.
horn	Biased	The environmentalist was especially protective of a specific species of rhinoceros that people often kill for its horn.
horn	Neutral	Charlie was looking through his closet for a set of screwdrivers, but ended up only finding a horn.
letter	Biased	The kindergartener was usually good at writing her name on the chalkboard, but today she mistakenly added an extra letter.
letter	Neutral	In lecture this morning, Daniel heard that a lot of confusions can occur just because of one letter.
nails	Biased	The father was about to fix the door on the shed, and remembered to bring a wrench but forgot to bring nails.
nails	Neutral	The homeowner was trying to fix her porch, but she was annoyed to find some dirt on her nails.
note	Biased	The pianist had had the opportunity to study the sheet music carefully, but when playing the piece she still missed one note.
note	Neutral	The director believed Julie's story that she had been so absent-minded in class that she didn't see the note.

nut	Biased	The builder was very organized with his tools, so he knew exactly which compartment in his toolbox contained the right nut.
nut	Neutral	Trevor felt something funny in his pocket, so he stood up, put his hand in his pocket, and found a nut.
ring	Biased	The wrestler was nervous about the next fight, so he meditated a bit before climbing into the ring.
ring	Neutral	Morgan worked for a magazine and was delighted to accept the assignment to photograph the ring.
stamp	Biased	The woman wanted to make a personalized greeting card for her nephew, so she took out her ink pad and created a design using a stamp.
stamp	Neutral	Allison was in a rush on Tuesday, and her desk was so messy that she did not find the stamp.
tank	Biased	The company needed to store a large amount of liquid in their facilities, so they decide to install an above-ground tank.
tank	Neutral	It was hard to see through the fog, but it was easy to notice that the object in the distance was a tank.
trunk	Biased	Daisy was the largest circus animal of them all, and entertained the audience by picking up barrels with her trunk.
trunk	Neutral	Misty had a very strange dream, in which she was standing on a boat in the middle of a jungle, and she had a trunk.

Figure Captions

Figure 1. Time course of probability of fixations on critical pictures and fillers at each 100 ms interval from homophone target onset for combined Dominant-Actual (represented with squares) and Subordinate-Actual (represented with triangles) display conditions. The first interval is 0-99 ms after target onset.

Figure 2. Visual bias towards Shape Competitors as indicated by log gaze ratios, by Dominant-Actual and Subordinate-Actual display conditions.

Figure 3. Regression of average latency of first look to the Actual Referent picture from trial onset with relative meaning dominance. Shorter latencies were observed for more dominant meanings.

Figure 4. All data from both contextual bias conditions are summarized here. For each contextual bias condition, we show the proportion of trials within a 100 ms interval with fixations on the Actual Referent, the Shape Competitor, or the average of the filler objects. The first time interval is 0 – 99 ms after homophone onset.

Figure 5. Average log gaze ratios for each context type in 100 ms time intervals. The first interval is 0-99 ms after target onset.