

Semantic asymmetries are modulated by phonological asymmetries: Evidence from the disambiguation of homophonic versus heterophonic homographs

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ABSTRACT

The present study investigated cerebral asymmetries in accessing multiple meanings of two types of homographs: homophonic homographs (e.g., *bank*) and heterophonic homographs (e.g., *tear*). Participants read homographs preceded by either a biasing or a non-biasing sentential context and performed a lexical decision on lateralized targets presented 150 ms after onset of the sentence-final ambiguous prime. Targets were either related to the dominant or the subordinate meaning of the preceding homograph or were unrelated to it. In the case of homophonic homographs – our results converge with previous findings: both activation and selection processes are faster in the LH than in the RH. Importantly, however, in the case of heterophonic homographs – opposite asymmetries were found. These results suggest that semantic asymmetries are modulated by phonology. They are discussed in the context of a model of functional architecture of reading in the two hemispheres in which orthography, phonology and semantics are fully interconnected in the LH, whereas in the RH, orthography and phonology are not directly connected, such that phonological processes are mediated by semantics.

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1. Introduction

Readers frequently encounter words that have more than one distinct meaning. For example, the homograph *bank* is associated with a financial institution and a riverside. Ambiguity resolution studies have shown that both lexical and contextual factors bias our interpretation (e.g., Duffy, Morris, & Rayner, 1988; Peleg, Giora, & Fein, 2001, 2004; Titone, 1998). First, our previous experience with the ambiguous word may render one meaning more accessible if, for example, it is more frequently encountered than the other meaning. Thus, for most English speakers, the money related meaning of *bank* is the more salient/dominant/frequent meaning. Second, the immediate context may bias our interpretation towards one of the meanings, so that when we read ‘*Bill stole from...*’ we expect a place one can steal from, and when we read: ‘*Bill fished from...*’ we expect a place one can fish from.

Neuropsychological studies show that although the left hemisphere (LH) is dominant for language, the right hemisphere (RH) also plays an important role in ambiguity resolution. For example, not just unilateral LH damage, but also unilateral RH damage leads to deficits in ambiguity resolution (Grindrod & Baum, 2003). Similarly, imaging studies reveal bilateral activation during ambiguity resolution (Mason & Just, 2007). However, despite decades of intensive research, the unique contribution of each hemisphere

to lexical access in general and to the resolution of homographs in particular remains to be elucidated.

One way to investigate asymmetries in meaning activation is by employing the divided visual field (DVF) technique. The interpretation of DVF studies rests on the assumption that responses to stimuli presented briefly to one visual field reflect mainly the processing of that stimulus by the contra-lateral hemisphere, so that information presented in the RVF is processed mainly by the LH and visa versa (for theoretical and electrophysiological support for this assumption, see Banich, 2003; Berardi & Fiorentini, 1997; Coulson, Federmeier, Van Petten, & Kutas, 2005). Indeed, decades of studies employing this technique have found robust and highly replicable hemispheric processing asymmetries, attesting to the effectiveness of the procedure.

Research using the DVF technique has led to the conclusion that the hemispheres differ significantly in the way they deal with lexical and contextual factors during ambiguity resolution. According to the received view, in the LH, all meanings are immediately activated and shortly afterwards, one meaning is selected on the basis of frequency and/or contextual information. The RH, on the other hand, activates all meanings more slowly and maintains these meanings irrespective of context or frequency.

Within this “standard model”, the functioning of the LH is maximized: it has the ability to immediately activate both salient and less-salient meanings and then to use both lexical and contextual information in order to select a single appropriate meaning; As a result, in the absence of contextual bias, it quickly selects the sali-

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ent, more frequent meaning (e.g., Burgess & Simpson, 1988), while in the presence of a biasing prior context, it quickly selects the contextually appropriate meaning (e.g., Faust & Chiarello, 1998; Faust & Gernsbacher, 1996). The RH abilities, however, are minimized: first, activation of the less-salient meaning is slower (e.g., Burgess & Simpson, 1988). In addition, it is viewed as less able to use lexical and/or contextual information for selection. As a result, it maintains alternate meanings regardless of their frequency or contextual appropriateness (e.g., Burgess & Simpson, 1988; Faust & Chiarello, 1998; Faust & Gernsbacher, 1996).

A number of attempts have been made to account for this pattern of asymmetries. The coarse coding hypothesis postulates that the cerebral hemispheres differ in their breadth of semantic activation, with the LH activating a narrow, focused semantic field and the RH weakly activating a broader semantic field (e.g., Beeman, 1998; Jung-Beeman, 2005). As a result, meaning activation in the RH is relatively sustained and non-specific, whereas meaning activation in the LH is faster and restricted to more frequent or closely-associated meanings. According to the “message-blind RH” model (e.g., Faust, 1998) the LH is sensitive to sentence level context, while the RH primarily processes word level meaning and is therefore less able to use sentential information for selection. Finally, it was proposed that the RH is simply slower (Burgess & Lund, 1998). Because activation processes are slower, selection processes start later. As a result, alternative meanings are maintained for a longer period of time in the RH than in the LH. Taken together, current models of hemispheric differences in ambiguity resolution converge on a proposal that LH language processing is relatively more focused and faster than RH language processing, and takes place at higher (e.g., the sentence message) levels of analysis.

However, the idea that the RH is insensitive to higher-level, contextual processes seems at odds with neuropsychological studies reporting discourse-level deficits after RH damage (e.g., Brownell, Potter, Bihle, & Gardner, 1986), as well as the findings that patients with damage to either hemisphere display deficits in their ability to exploit sentence-level information to determine the appropriate meaning of homographs (e.g., Grindrod & Baum, 2003). Further, in contrast to the message-blind model, recent behavioral and ERP studies suggest that context-sensitivity characterizes both hemispheres (e.g., Coulson et al., 2005; Federmeier & Kutas, 1999; Peleg & Eviatar, 2008). We, therefore suggest an alternative explanation for asymmetries in meaning activation from written words. Our explanation relates to the different ways in which orthographic phonological and semantic processes interact in the two hemispheres. Thus, rather than assuming asymmetries at higher levels of analysis we propose asymmetries at lower (e.g., phonological) levels of analysis.

Generally speaking, there are two ways to access meaning from print: visually (from orthography directly to meaning) and phonologically (from orthography to phonology to meaning). Previous studies suggest that the visual route exist in both hemispheres, whereas the phonological route is available only to the LH (e.g., Lavidor & Ellis, 2003; Smolka & Eviatar, 2006; Zaidel & Peters, 1981). On the basis of these findings, we propose a simple model in which both hemispheres exploit orthographic, phonological, and semantic information in the processing of written words. However, in the LH, orthographic, phonological, and semantic representations are fully interconnected, while there are no direct connections between phonological and orthographic units in the RH. The model is illustrated in Fig. 1. We make no other assumptions about the nature of these representations in the two hemispheres. Indeed, we claim that this single difference in hemispheric functional architecture results in hemisphere asymmetries in the disambiguation of homographs in particular, and more broadly, in the processing of written words.

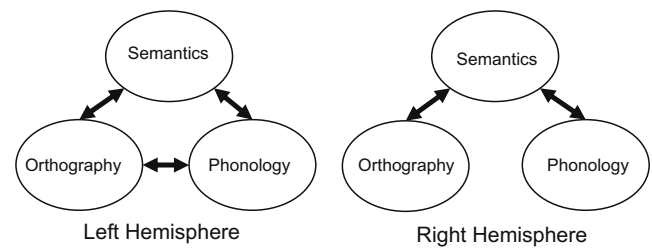


Fig. 1. The functional architecture of reading in the two hemispheres.

Previous studies examined *homophonic homographs* – multiple meanings associated with a single orthographic and phonological representation (e.g., *bank*). The unvoveled Hebrew orthography offers an opportunity to examine other types of homographs as well. In Hebrew, letters represent mostly consonants, and vowels can optionally be superimposed on consonants as diacritical marks. Since the vowel marks are usually omitted, Hebrew readers frequently encounter not only homophonic homographs (*bank*), but also *heterophonic homographs* – a single orthographic representation associated with multiple phonological codes each associated with a different meaning (e.g., *tear*).

Both types of homographs have one orthographic representation associated with multiple meanings. They are different however, in terms of the relationship between orthography and phonology. According to our proposed model (Fig. 1), when orthographic and phonological representations are unambiguously related (as in the case of homophonic homographs like *bank* or unambiguous words), meaning activation is faster in the LH, because all related meanings are *immediately* boosted by both visual and phonological sources of information. However, when a single orthographic representation is associated with multiple phonological representations, (As in the case of heterophonic homographs like *tear*) meanings may be more difficult to activate in the LH due to the competition between the different phonological alternatives.

In order to contrast the received view with our proposal, we examined the disambiguation of homophonic versus heterophonic homographs in the two hemispheres: if hemispheric differences in processing homophonic homographs are due to lexical and/or contextual asymmetries, then a similar pattern should be observed with heterophonic homographs. If, however, hemispheric differences in processing homophonic homographs are due to phonological asymmetries, then opposite asymmetries should be observed in the case of heterophonic homographs.

In our previous study (Peleg & Eviatar, 2008), a DVF technique was employed in conjunction with the lexical-priming paradigm. Participants were asked to focus on the center of the screen and to silently read sentences that ended with either homophonic or heterophonic homographs. The sentences were either biased toward one interpretation or unbiased. Subjects were asked to perform a lexical decision task on targets presented 250 ms after offset of the final homographs. Targets were presented to the left visual field (LVF) or the right visual field (RVF) and were either related to the dominant or the subordinate meaning of the ambiguous prime, or unrelated. Magnitude of priming was calculated by subtracting reaction time (RT) to related targets from RT to unrelated targets.

In that study, the patterns of priming between homophonic and heterophonic homographs did not differ. Performance asymmetry was found in the absence of a biasing context: dominant-related targets were exclusively facilitated in the RVF/LH, whereas both dominant- and subordinate-related targets were facilitated in the LVF/RH. Performance symmetry was found in the presence of a

biasing context: dominant-related targets were exclusively activated in dominant-biasing contexts, whereas both dominant- and subordinate-related targets were facilitated in subordinate-biasing contexts.

We suspected that while the stimulus onset asynchrony (SOA) of 250 ms used in Peleg and Eviatar (2008) was sensitive to both lexical and contextual processes, it was not sensitive enough to phonological processes which may have occurred earlier. The purpose of the present study was therefore to obtain priming effects of homophonic versus heterophonic homographs in the two hemispheres by using an earlier, 150 ms SOA.

2. Method

2.1. Participants

Forty undergraduate students (23 females), aged 21–34 (mean age 23.8 SD 2.6) participated in the study. They were all healthy, right handed, native speakers of Hebrew with normal vision.

2.2. Stimuli

Materials are the same as those used in our previous study, where a 250 SOA was employed. These include a total 112 noun-noun polarized Hebrew homographs (56 homophonic and 56 heterophonic) which were used as primes. Homographs were selected on the basis of the following pretests: (1) A booklet containing homographs and their paraphrased meanings was presented to 50 subjects, who were instructed to circle the most frequent sense. The dominant meaning of a homograph was defined as the meaning chosen by at least 65% of subjects. (2) The validity of this selection was then tested by asking 50 different subjects to write the first association that came to their minds when reading the homographs. Only those homographs whose frequency judgment coincided with the additional test were used in the experiment. Overall, the selected homograph corpus was polarized with the salient/dominant meaning being chosen with a mean of 84% (homophones: 83% heterophones: 85%).

For each homograph, two target words were selected: one related to the dominant meaning and the other to the subordinate meaning. Unrelated targets were constructed by randomly re-pairing related primes and targets. Thus each homograph was paired with two related and two unrelated target words. To insure similar semantic relatedness in the case of related targets, and to establish that unrelated target words were indeed unrelated, 36 different subjects were instructed to rate the degree to which each target is associatively related to the compatible meaning of the homograph on a 5-point scale (where five represented a very strong association and one represented a very weak association). In this pretest, presentation of word pairs was counterbalanced by using four stimulus lists, each of which contained homograph-dominant pairs, homograph-subordinate pairs, and homograph-unrelated pairs. Thus, the same homograph primes appeared in each of the lists, each time paired with a different target word (two related and two unrelated). The means of those ratings were 4.4 for the

dominant meanings (homophones: 4.4; heterophones: 4.4) and 4.35 for the subordinate meanings (homophones: 4.4 heterophones: 4.3), and no reliable difference was found between them (all $ps > .3$). The mean for unrelated pairs was 1.9. Related pairs were always rated significantly higher than unrelated pairs. Dominant and subordinate targets were also compared in terms of length (number of letters). The means were 4.2 (homophones: 4.2; heterophones: 4.2) and 4.25 (homophones: 4.3 heterophones: 4.2), respectively, and did not differ ($p > .7$). Given the lack of frequency norms in Hebrew, we asked 36 additional subjects to perform a simple lexical decision task on all of the target words. The mean times for dominant and subordinate targets were 697 (homophones: 701 heterophones: 693) and 691 (homophones: 694 heterophones: 688), respectively. Latencies from this pretest revealed no reliable differences among the targets ($p > .3$).

Finally, for each homograph, three sentence contexts were constructed, each preceding the final homograph: an unbiased (i.e., ambiguous) context, one biased toward the dominant meaning, and another biased toward the subordinate meaning. To ensure similar degree of contextual bias, the relatedness of the sentential context and its final homograph was rated by 36 new subjects on a 5-point scale ranging from very related (5) to very unrelated (1). Presentation of contexts and primes were counterbalanced by creating three stimulus lists which contained homograph-dominant contexts, homograph-subordinate contexts, and homograph-unbiased contexts. Thus, the same homograph primes appeared in each of the lists, each time embedded in a different sentential context. The means of those ratings were 4.65 for the dominant-biased context (homophones: 4.69 heterophones: 4.61); 4.42 for the subordinate-biased context (homophones: 4.48 heterophones: 4.38); and 3.15 for the unbiased context (homophones: 3.16 heterophones: 3.14). An analysis of variance revealed no significant difference between dominant and subordinate-biased contexts (all $ps > .2$). Biased contexts were rated significantly higher than unbiased contexts (all $ps < 0.001$). Translated examples of the stimuli are shown in Table 1.

2.3. Apparatus

Stimulus presentation and responses were controlled and recorded by a Dell GX-260 PC P4-1800-14H. An adjustable chin-rest kept subjects at a fixed viewing distance from the computer screen (57 cm). Stimuli, constructed from characters presented in "Arial" font (size 20), were colored white and displayed on a gray colored screen. A closed-circuit video camera was mounted directly over the screen to monitor participants' eye fixation.

2.4. Experimental design and procedures

The experiment used a 2 (homograph type: homophonic or heterophonic) \times 3 (context type: biasing toward the dominant or the subordinate meaning or unbiased) \times 2 (target dominance: dominant or subordinate) \times 2 (target relatedness: related or unrelated) \times 2 (target location: LVF or RVF) within subjects design. There were 2688 experimental permutations for the target words

Table 1
Translated examples of stimuli.

Homograph type	Sentence context	Homograph	Pronunciation	Target words
Homophonic homograph	Unbiased: they looked at the Dominant: the buyers signed the Subordinate: the Children of Israel listened to the	חוזת Contract Seer	/XOZE/	Dominant – document Subordinate – prophet
Heterophonic homograph	Unbiased: the young man looked for the Dominant: the students were asked to buy the Subordinate: the bride made an appointment with the	ספר Book Barber	/SEFER//SAPAR/	Dominant – reading Subordinate – hair

(56 × 2 types of homographs × 3 types of sentential context × 2 target words × 2 prime-target relations × 2 VF presentations). Twenty four sub-lists were created such that all factors were counterbalanced across items. Each sub-list contained 112 experimental sentences (ending in homographs) which were paired with word targets and 112 sentence fillers that were paired with non-word targets (224 trials in total). These 24 sub-lists were grouped into four lists (each composed of 6 sub-lists). Each homograph appeared only once per sub-list (6 times total in the experiment, and the six presentations appeared in different conditions). Within each list there were 14 trials per condition. Each subject completed one of the four lists. The four lists were counterbalanced across groups of 10 subjects. Trials within each list were presented in random order, with randomization controlled by the computer and the order of lists was counterbalanced across subjects. In order to complete their assigned lists, each participant completed three experimental sessions (two sub-lists per session). The testing sessions lasted approximately 60 min (20 min for each list with a 10–20 min break between them). The sessions were administered with an interval of 1–3 weeks between them to avoid carry-over repetition effects.

Participants were seated 57 cm from the computer screen and placed their heads in the head and chin rest. All target stimuli were presented such that their innermost boundary, whether to the right or left of center, was exactly 2° of visual angle from the central fixation marker. Fixation was monitored via a closed-circuit video camera focused on the participant's eyes. The output from this camera was fed into another monitor at the experimenter's control station. Each session comprised 28 practice trials presented in one block, 224 experimental trials and fillers presented in blocks of 28, with a rest period between blocks, a 10 min break, and a second set of 224 experimental trials and fillers presented in the same manner.

At the start of each trial, subjects were presented with a central fixation marker for 650 ms. The offset of the marker was followed by a 100 ms pause, and the sentential context (i.e. the sentence without the final homograph) was then presented in the same position (center of the screen) for 1500 ms (a period which had been previously identified as comfortable for reading any of the sentences presented in the experiment). The offset of the sentence was followed successively by a 200 ms blank period and a central fixation marker for 300 ms. The prime (homograph) was then presented in the same central position for 150 ms. At 0 ms ISI (150 ms SOA), the target string was presented for 150 ms to the LVF or RVF for a lexical decision response.

Subjects made lexical decision responses by pressing the up/down arrows with their right index finger for word/nonword responses. They were instructed to maintain gaze on the central fixation marker and to make responses based on what they can see from the periphery as quickly and accurately as possible. The data collected for each subject included RT for target words and error rates for all conditions.

3. Results

Three subjects were replaced because they did not complete the three sessions. Two items were deleted due to an error rate greater than 50% in one or more conditions, such that overall results are based on 110 items (55 homophonic and 55 heterophonic). A 3 × 2 × 2 × 2 × 2 ANOVA was conducted for both RT data and error data across subjects (F_1) and items (F_2) with Type of Sentential Context (dominant-consistent, subordinate-consistent or unbiased), Type of Homograph (homophonic or heterophonic), Target Dominance (dominant or subordinate), Target Relatedness (related or unrelated) and Location of Target (RVF or LVF) as factors. Cutoff

response times of 200 ms for anticipations, and 2000 ms for late responses were used (2.6% of the trials were excluded based on this criterion). Analyses of RTs were based on participants' mean RT to correct responses (an additional 13.9% of trials were excluded due to incorrect response). Mean RT, SDs, and error rate in all conditions are presented in Table 2.

The main effect of Visual Field was significant in the item analysis for both RT ($F_2(1, 108) = 7.06, p < .01, MSE = 10607.2$) and errors ($F_2(1, 108) = 8.98, p < .004, MSE = 93.2$) and showed the same tendency in the subject analysis, indicating that targets were responded to more quickly and accurately when they were presented to the RVF/LH. The main effect of Target Relatedness was significant in both analyses for both RT ($F_1(1, 39) = 117.98, p < .0001, MSE = 8590.79; F_2(1, 108) = 49.72, p < .0001, MSE = 26821.9$) and errors ($F_1(1, 39) = 116.61, p < .0001, MSE = 201.4; F_2(1, 08) = 53.91, p < .0001, MSE = 316.7$), indicating that related targets were more rapidly and accurately responded to than unrelated targets. The main effect of Target Dominance was also significant in both analyses for both RT ($F_1(1, 39) = 56.88, p < .0001, MSE = 7575.29; F_2(1, 108) = 14.88, p = .0002, MSE = 31478.2$) and errors ($F_1(1, 39) = 77.21, p < .0001, MSE = 98.1; F_2(1, 108) = 17.36, p < .0001, MSE = 317.5$), indicating that dominant targets were more rapidly and accurately responded to than subordinate targets. In addition, for RT, the main effect of homograph type was significant in the subject analysis ($F_1(1, 39) = 6.99, p < .02, MSE = 3057.78$), indicating that reaction time to target words following heterophonic homographs were faster than to targets presented after homophonic homographs.

Importantly, the hypothesized five-way interaction between Context Type, Homograph Type, Visual Field, Target Dominance, and Target Relatedness was significant for RT ($F_1(2, 78) = 7.40, p < 0.002, MSE = 3060.93; F_2(2, 216) = 3.27, p = 0.04, MSE = 8695.2$), but not for errors. This interaction was further examined by testing the Homograph Type, Visual Field, Target Dominance, and Target Relatedness separately for each Context Condition.¹

3.1. Unbiasing (ambiguous) context

The 4-way interaction between Homograph Type, Visual Field, Target Relatedness, and Target Dominance was significant in the subject analysis ($F_1(1, 39) = 4.86, p < 0.04, MSE = 4844.9$) and was marginally significant in the item analysis ($F_2(1, 108) = 2.80, p = 0.09; MSE = 3060.9$). We computed degree of priming by subtracting RT for related targets from RT for unrelated targets in each condition. The top panel of Fig. 2 shows the magnitude of priming to targets presented after heterophonic and homophonic homographs in the two visual fields (LVF/RH-left panel, RVF/LH-right panel). It is evident from these graphs that for LVF target presentation, only responses to dominant targets were significantly facilitated relative to the unrelated conditions, irrespective of homograph type (Homophonic homographs: *by subjects*: $t(39) = 3.80, p < 0.0004$; *by items*: $t(54) = 3.80, p = 0.0004$. Hetero-

¹ Several lower level interactions were also significant. For RT, there was a significant Visual Field × Context Type interaction in both analyses ($F_1(2, 78) = 4.06, p < 0.03, MSE = 9344.38; F_2(2, 216) = 4.63, p = 0.02, MSE = 8255.4$), as well as a significant Target Dominance × Target Relatedness interaction in the subject analysis ($F_1(1, 39) = 4.21, p < 0.05, MSE = 6116.3$). The two way interaction between Target Relatedness and Context Type was significant in the item analysis for both RT ($F_2(2, 216) = 30.80, p = 0.0001, MSE = 7083.6$) and errors ($F_2(2, 216) = 26.29, p = 0.0001, MSE = 49.6$). The three way interaction between context type, target dominance, and target relatedness was significant for both RT ($F_1(2, 78) = 23.04, p < 0.0001, MSE = 5268.78; F_2(2, 216) = 21.54, p = 0.0001, MSE = 6877.7$) and errors ($F_1(2, 78) = 34.24, p < 0.0001, MSE = 51.80; F_2(2, 216) = 26.07, p = 0.0001, MSE = 49.5$). In addition, for errors, a significant 3-way interaction between homograph type, target dominance, and target relatedness was found in the subject analysis ($F_1(1, 39) = 5.68, p < 0.03, MSE = 79.13$).

Table 2

Mean correct RT (in ms) and error rates (in%) as a function of visual field, sentence context, and target type, presented separately for each homograph type.

Visual field	LVF/RHHH			RVF/LH		
	Dominant biased	Unbiased	Subordinate biased	Dominant biased	Unbiased	Subordinate biased
A. Heterophonic homographs						
Target type						
Dominant						
Related	750.3 (110.9) 7%	761.7 (118) 10.4%	772.2 (118.9) 11.8%	742.7 (106.7) 6.1%	749.1 (123.5) 7%	806.9 (149.1) 10.7%
Unrelated	802.6 (134.5) 16.8%	802.6(139.8) 17.7%	841.1 (143) 16.4%	809.6 (146.8) 17.3%	783.5 (134.8) 15%	803.9 (143.7) 14.6%
Subordinate						
Related	835.2 (153.8) 16.3%	805.2 (149.5) 15.2%	778 (131.6) 7.5%	836.9 (152.6) 15.5%	771.7 (123.1) 13.2%	762.2 (130.2) 7.7%
Unrelated	834.5 (170.1) 19.6%	839.1 (147.1) 18.6%	828.8 (139.4) 18.2%	831.6 (146.7) 17%	783.9 (139.7) 17.1%	843.1 (156.3) 15.9%
B. Homophonic homographs						
Target type						
Dominant						
Related	731.8 (100.7) 7.1%	759.6 (110.4) 9.5%	784.2 (124.5) 12.1%	729.3 (110.5) 4.6%	746.8 (109.2) 7.9%	794.1 (145.5) 8.4%
Unrelated	830.2 (134.7) 15.3%	836.1 (172.4) 16.1%	831 (131) 14.8%	806.6 (136.8) 14.8%	790.3 (145.2) 15.2%	830.7 (164.4) 14.6%
Subordinate						
Related	832.9 (165.4) 17.8%	821.6 (150.3) 14.6%	770.8 (118.4) 9.5%	825.9 (167.4) 16.1%	769.9 (133) 12.7%	765.9 (137.2) 6.4%
Unrelated	850.4 (148.9) 20.5%	844.2 (141.5) 24.3%	863.2 (147.1) 20.4%	844.2 (141.5) 22%	828.8 (157) 19.6%	864.6 (140.6) 20.9%

Standard deviations (in ms) are presented in parenthesis.

phonic homographs: *by subjects*: $t(39) = 2.28, p < 0.03$; *by items*: $t(54) = 2.07, p < 0.05$.), while subordinate targets were not significantly facilitated ($p > .13$).

In contrast, for RVF target presentation, we see a different pattern of responses for the two types of homographs: in the case of homophonic homographs, responses to targets related to both

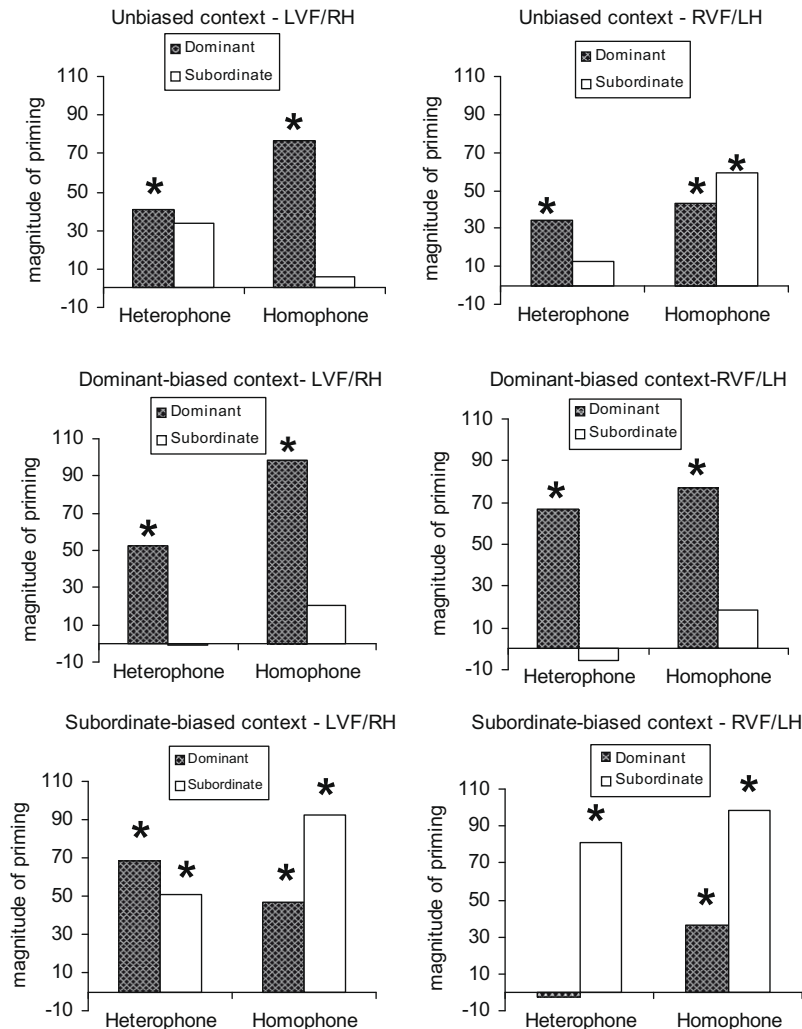


Fig. 2. Magnitude of priming in ms (RT-unrelated – RT-related) for target words, presented separately for each visual field (LVF/RH-left panel, RVF/LH-right panel) and for each context condition: unbiased (top panel), dominant-biased (middle panel); or subordinate-biased (bottom panel). Note: *Significant, $p < 0.5$.

the dominant and the subordinate meaning were significantly facilitated relative to the unrelated conditions (Dominant, *by subjects*: $t(39) = 4.02$, $p = 0.0003$; *by items*: $t(54) = 2.56$, $p < 0.02$; Subordinate, *by subjects*: $t(39) = 2.91$, $p < .006$; *by items*: $t(54) = 2.86$, $p = .006$). On the other hand, for heterophonic homographs, targets related to the dominant meaning were significantly facilitated only when analyzed *by subjects* ($t(39) = 2.67$, $p < .02$), while priming for subordinate targets was not significantly different from 0 ($p > .36$).

These results suggest that when homophonic homographs are embedded in an unbiassing (ambiguous) context, only the dominant meaning is activated in the LVF/RH, while both meanings are activated in the RVF/LH. In contrast, when heterophonic homographs are presented in an unbiassing context, only the dominant meaning is activated, regardless of target location (LVF or RVF).

3.2. Dominant biasing contexts

The Homograph Type \times Target Dominance \times Target Relatedness \times Visual Field ANOVA revealed a significant interaction of Target Dominance \times Target Relatedness ($F(1, 39) = 32.59$, $p < 0.0001$, $MSE = 5392.9$; $F(1, 216) = 13.82$, $p = .0003$, $MSE = 15268.4$). As mentioned earlier, the magnitude of semantic priming was calculated by subtracting RT for related targets from RT for unrelated targets.

The middle panel of Fig. 2 shows the magnitude of priming to targets presented after heterophonic and homophonic homographs in the two visual fields (LVF/RH-left panel, RVF/LH-right panel). It is evident from these graphs that responses to targets related to the contextually appropriate, dominant meaning of the final homograph were significantly facilitated, irrespective of homograph type (homophonic or heterophonic) or target location (LVF or RVF). (For homophonic homographs: in the LVF: *by subjects*: $t(39) = 5.35$, $p < .0001$; *by items*: $t(54) = 5.98$, $p < .0001$. In the RVF: *by subjects*: $t(39) = 6.21$, $p < .0001$, *by items*: $t(54) = 4.88$, $p < .0001$. For heterophonic homographs: in the LVF: *by subjects*: $t(39) = 3.80$, $p = .0005$; *by items*: $t(54) = 3.84$, $p = .0003$. In the RVF: *by subjects*: $t(39) = 3.97$, $p = .0003$, *by items*: $t(54) = 2.98$, $p < .005$.) Conversely, responses to subordinate targets were not significantly facilitated ($p > .13$).

3.3. Subordinate-biasing contexts

The 4-way interaction between Homograph Type, Visual Field Target Relatedness and Target Dominance was marginally significant in the item analysis ($F(2, 108) = 3.50$, $p = 0.06$; $MSE = 9959.3$). The 3-way interaction of Visual Field \times Target Dominance \times Target Relatedness was significant in the subject analysis ($F(1, 39) = 4.90$, $p < 0.03$, $MSE = 7136.8$).

The bottom panel of Fig. 2 shows the magnitude of priming to targets presented after heterophonic and homophonic homographs in the two visual fields. For LVF target presentation (left panel), responses to dominant and subordinate targets were significantly facilitated relative to the unrelated conditions, irrespective of homograph type (homophonic homographs: *by subjects*: Dominant: $t(39) = 2.81$, $p < 0.008$; Subordinate: $t(39) = 5.16$, $p < 0.0001$; *by items*: Dominant: $t(54) = 1.67$, $p < 0.1$ (marginal); Subordinate: $t(54) = 3.98$, $p = 0.0002$. heterophonic homographs: *by subjects*: Dominant: $t(39) = 3.81$, $p = 0.0005$; Subordinate: $t(39) = 2.52$, $p < 0.02$; *by items*: Dominant: $t(54) = 3.12$, $p < 0.003$; Subordinate: $t(54) = 2.66$, $p < 0.02$).

In contrast, for RVF target presentation (right panel), again, we see a different pattern of responses for the two types of homographs: in the case of homophonic homographs, responses to targets related to both the dominant and the subordinate meaning were significantly facilitated relative to the unrelated conditions (*by subjects*: Dominant: $t(39) = 2.41$, $p < 0.03$; Subordinate:

$t(39) = 5.44$, $p < 0.0001$; *by items*: Dominant: $t(54) = 1.91$, $p < 0.07$ (marginal); Subordinate: $t(54) = 3.67$, $p = 0.0006$). Alternatively, for heterophonic homographs, targets related to the contextually appropriate subordinate meaning were significantly facilitated (*by subjects*: $t(39) = 3.83$, $p = 0.0004$; *by items*: $t(54) = 4.01$, $p < 0.0002$), while priming for dominant but contextually inappropriate targets was not significantly different from 0 ($p > .8$).

These results indicate that when homophonic homographs are embedded in a subordinate-biased context, both meanings are activated irrespective of target location (LVF or RVF). In contrast, responses to targets presented after heterophonic homographs are modulated by visual field of presentation. In the LVF/RH both meanings are activated, while in the RVF/LH, the contextually appropriate meaning is activated exclusively, 150 ms. after homograph presentation.

4. General discussion

Previous DVF studies demonstrated asymmetries in processing homographs such as *bank*: in the LH, all meanings are immediately activated, and shortly afterwards one meaning is selected on the basis of frequency and/or contextual information. In contrast, the RH activates all meanings more slowly and maintains these meanings irrespective of contextual information or frequency. On the basis of such findings, current hemispheric models of ambiguity resolution have converged on the proposal that LH language processing is relatively more focused, faster, and takes place at higher levels of analysis than RH language processing.

We propose an alternative explanation for these reported asymmetries in activating the meanings of written words. According to our proposal, in the LH, orthographic, phonological, and semantic representations are interconnected. As a result activation of meanings in the LH is boosted by both visual and phonological sources of information. In contrast, in the RH, orthographic and phonological representations are not directly connected. As a result, meanings are initially activated on the basis of orthography.

Because, in the LH, meanings are immediately activated not only via orthography but also via phonology, it is usually faster and more accurate. This advantage, however, depends on the ability of the network to quickly associate the orthographic representation of a given word with its phonological representation. This depends on the relationship between these two types of representations: when orthographic and phonological representations are unambiguously related, (as in the case of homophonic homographs like *bank*), all related meanings are immediately boosted by both visual and phonological sources of information. As a result, meaning activation is faster in the LH. However, when a single orthographic representation is associated with multiple phonological representations, (As in the case of heterophonic homographs like *tear*) meanings may be more difficult to activate in the LH due to the competition between the different phonological alternatives. Thus, in contrast to the received view, we predicted opposite asymmetries in the case of heterophonic homographs.

In order to contrast the received view with our proposal, we examined the disambiguation of homophonic versus heterophonic homographs in the two hemispheres: if hemispheric differences in processing homophonic homographs are due to higher-level semantic asymmetries, then a similar pattern should be observed with heterophonic homographs. If, however, hemispheric differences in processing homophonic homographs are due to lower-level phonological asymmetries, then opposite asymmetries should be observed in the case of heterophonic homographs.

Overall, our results support our view that asymmetries in homograph resolution are qualified by the phonological status of the homograph. As predicted by our model, in the case of homo-

phonic homographs, our results are consistent with the received view: both activation and selection processes are faster in the LH than in the RH. Importantly, however, in the case of heterophonic homographs – opposite asymmetries were found.

4.1. When context was kept neutral

In a neutral, non-biasing context, our results regarding homophonic homographs replicated previous results (e.g., Burgess & Simpson, 1988): in the LH, both meanings were immediately available (at 150 SOA). However, 100 ms. later, only the dominant meaning remained active (see Peleg & Eviatar, 2008). In the RH, the less-salient meaning was activated more slowly so that 150 ms. after the onset of the ambiguous prime, only salient/dominant meanings were significantly activated. Shortly afterwards (at 250 SOA), however, the less-salient meaning was available alongside the salient one (Peleg & Eviatar, 2008). Thus, consistent with previous proposals, in the case of homophonic homographs, both activation and selection processes are faster in the LH.

Importantly, however, heterophonic homographs induce a different pattern of results. In contrast to the received view, our results suggest that it may be harder for the LH to activate the less-salient meaning, so that 150 ms after encountering the homograph, the LH activated only the salient meaning and the same pattern was obtained 100 ms later (at 250 SOA), as shown in Peleg & Eviatar, 2008.² In the RH, congruent with previous proposals, dominant meanings were activated before subordinate meanings. Thus, 150 ms after the prime only the dominant meaning is significantly activated for both types of homographs, and 250 ms after the prime, both meanings are activated for both types of homographs (Peleg & Eviatar, 2008).

4.2. When context is biased towards the dominant meaning

In a context biasing towards the salient meaning, this meaning is activated exclusively, regardless of SOA, location of target (LVF or RVF), or the phonological status of the homograph. This indicates that the RH is able to select the contextually appropriate meaning when this meaning is salient and is supported by contextual information.

4.3. When context is biased toward the subordinate meaning

In a context biasing towards the less-salient meaning, we see a different pattern of results in the two visual fields and for the two types of homographs. For homophonic homographs, both meanings (the dominant contextually inappropriate meaning and the subordinate appropriate meaning) were activated initially (at 150 SOA) in both hemispheres and remained active 100 ms later (Peleg & Eviatar, 2008). Heterophones, however, were processed differently: 150 ms after the onset of the ambiguous word, the LH activated the contextually appropriate subordinate meaning exclusively, while the RH activated both meanings. Interestingly, however, at 250 SOA (Peleg & Eviatar, 2008), both meanings were available in both hemispheres.

Taken together, our results demonstrate that semantic asymmetries in ambiguity resolution are modulated by the phonological status of the homograph. In the case of homophonic homographs – our results converge with the received view. Both activation and selection processes are faster in the LH than in the RH. Importantly,

however, in the case of heterophonic homographs – opposite asymmetries are found: in neutral contexts, less-salient, subordinate meanings are more difficult to access in the LH than in the RH. In addition, when context is biased towards the less-salient meaning, activation of the salient but contextually inappropriate meaning is slower in the LH than in the RH. These results cannot be explained unless phonological factors are taken into account. Thus, our model not only explains existing data based on homonyms, but can also account for opposite asymmetries in the disambiguation of heterophonic homographs.

According to our model, meaning activation depends on both contextual (e.g., prior semantic information) and experiential (e.g., frequency of occurrence) processes. Both processes occur in both hemispheres. However, in the LH frequency effects depend not only on the relation between orthography and meaning, but also on the relation between orthographic and phonological representations. In the case of polarized heterophonic homographs, frequency effects are more pronounced in the LH, because they constrain not only semantic processes but also phonological processes. As a result, when a biasing context is not provided, less-frequent, subordinate meanings are more difficult to activate.

Phonological ambiguity in the LH also leads to ordered (rather than simultaneous) meaning activation. In the absence of phonological ambiguity (homophonic homographs), both meanings are immediately activated when context is kept neutral or when it is biased towards the subordinate meaning. But, when phonology is ambiguous (as is the case of heterophonic homographs), activation is ordered according to frequency or prior contextual information: in a neutral, non-biasing context, the dominant meaning is activated first. However, when contextual information is biased towards the subordinate meaning, this order is reversed, such that the less-salient but contextually appropriate meaning is activated before the salient more frequent meaning.

The overall picture that emerges from the present results is that hemispheric processes may be more similar than assumed earlier. It seems that both hemispheres have access to the same sources of information (orthographic, phonological, lexical, and contextual); however, as a result of the two functional architectures (see Fig. 1), these may be used differently, and at different temporal stages. Although our pattern of results may reflect additional asymmetries (as for example suggested by Federmeier & Kutas, 1999), we propose that RH processing reflects a different pattern of interaction between orthographic, phonological, and semantic information, rather than, as suggested by other models, lower sensitivity to lexical and contextual constraints. This view of RH abilities converges with many neuropsychological studies showing RH involvement in comprehending the full meaning of words, phrases, and text (e.g., Coulson & Williams, 2005; Eviatar & Just, 2006; Federmeier & Kutas, 1999; Giora, Zaidel, Soroker, Batori, & Kasher, 2000; Mashal, Faust, & Hendler, 2005; McDonald, 1996, 1999).

Beyond hemispheric differences, our results have important implications for general models of ambiguity resolution and reading. Contrary to the predictions of the direct-access (context-sensitive) model (e.g., Vu, Kellas, & Paul, 1998), suggesting that a strong context can selectively activate one meaning, regardless of salience, we show that *both* context and salience influence the retrieval of word meanings. Importantly, in agreement with hybrid models such as the Graded Salience Hypothesis (e.g., Giora, 1997, 2003; Peleg, Giora, & Fein, 2008; Peleg et al., 2001, 2004), we show that context can enhance activation of the contextually appropriate meaning, but it cannot inhibit the contextually inappropriate meaning, if it is salient.

Thus, even when context is strongly biased towards the subordinate less-salient meaning, salient, dominant meanings are still activated: in the case of homophonic homographs both meanings were activated immediately (150 SOA) and remained active

² It may be claimed that these results reflect even earlier selection processes for heterophonic homographs. However, new results from our lab (Peleg & Eviatar, in preparation) indicate that given enough time (1000 ms SOA) the subordinate meaning of heterophonic homographs is also activated in the LH, while, similarly to the 250 SOA condition, only dominant meanings are activated for homophonic homographs.

100 ms. later, regardless of location (LVF or RVF) of target. Interestingly, even in the case of heterophonic homographs, in which the contextually appropriate meaning is activated exclusively in the LH (150 SOA), 100 ms later (250 SOA) the salient but contextually inappropriate meaning also becomes available regardless of context (Peleg & Eviatar, 2008).

In addition, our model has implications for one of the main controversies in the reading literature; namely, the role phonology plays in silent reading. One class of models suggests that printed words activate orthographic codes that are directly related to meanings in semantic memory. An alternative class of models asserts that access to meaning is always mediated by phonology (for a review, see Frost, 1998; Van Orden & Kloos, 2005). According to our model, both hemispheres activate phonological representations of written words. However, as a result of the two functional architectures (see Fig. 1), this information may be used differently, and at different temporal stages. Specifically, because in the RH orthography and phonology are indirectly connected, we predicted that phonological effects will be *more* pronounced in the LH than in the RH during *earlier* stages of word processing.

As predicted by our model, we show that in terms of *significant* priming effects, similar patterns were obtained for both types of homographs in the LVF/RH, while different priming for homophonic and heterophonic homographs were found in the RVF/LH. This converges with previous studies showing that the LH is more influenced by the phonological aspects of a written word (e.g., Lavidor & Ellis, 2003; Zaidel, 1982; Zaidel & Peters, 1981), whereas lexical processing in the RH is more sensitive to the visual form of a written word (e.g., Lavidor & Ellis, 2003; Marsolek, Kosslyn, & Squire, 1992; Marsolek, Schacter, & Nicholas, 1996; Smolka & Eviatar, 2006).

Nevertheless, inspection of the actual magnitude of the priming effects for the two types of homographs in the LVF/RH (as shown in Fig. 2) suggest that, 150 ms after homograph presentation, the RH may also be sensitive to the phonological status of the homograph. For example, when context was kept neutral, subordinate meanings were not significantly primed. However, heterophones resulted in larger priming differences than homophones (top-panel). Similarly, in the subordinate-biasing context (bottom panel), both meanings were significantly primed. But, the pattern of result suggests differences in the effect of salience on priming magnitude. Importantly, however, in both context conditions, these homophonic /heterophonic differences in the RH, if real (non significant in all but one marginal condition), are exactly in the opposite direction than in the LH. Taken together our results suggest that the RH may be initially less sensitive to homophonic/heterophonic differences, but not completely immune. Further research is needed in order to fully understand the way phonology interacts with lexical and contextual information in the RH.

In sum, the results of the present study support the conclusion that the two hemispheres both exploit phonological, lexical and contextual information in the processing of written words. However, as a result of the two functional architectures (see Fig. 1) these processes exert their influence at different temporal stages (and possibly in a different manner). We propose that RH word processing reflects a different pattern of interaction between orthographic, phonological, and semantic information, rather than, as suggested by other models, lower sensitivity to lexical and/or contextual constraints.

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