Laterality: Asymmetries of Body, Brain and Cognition

ISSN: 1357-650X (Print) 1464-0678 (Online) Journal homepage: http://www.tandfonline.com/loi/plat20

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To cite this article: Orna Peleg & Zohar Eviatar (2015): Controlled semantic processes within and between the two cerebral hemispheres, Laterality: Asymmetries of Body, Brain and Cognition, DOI: 10.1080/1357650X.2015.1092547

To link to this article: http://dx.doi.org/10.1080/1357650X.2015.1092547

Published online: 09 Oct 2015.

LATERALITY: ASYMMETRIES OF BODY, BRAIN AND COGNITION, 2015
http://dx.doi.org/10.1080/1357650X.2015.1092547

Routledge
Taylor & Francis Group

Controlled semantic processes within and between the two cerebral hemispheres

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ABSTRACT
To test the separate and combined abilities of the two cerebral hemispheres to perform controlled semantic selection and integration processes, Hebrew readers saw pairs of words and had to decide whether the two words were semantically related. The first word in each pair was presented centrally. The second word was presented in the left, right, or central visual field (LVF, RVF, and CVF). We compared response latencies for related pairs in two conditions: In the ambiguous condition, the first word was a homograph (either homophonic or heterophonic) and the second word was related to either its dominant or subordinate meaning. In the unambiguous condition, homographs were replaced with unambiguous control words. Irrespective of VF or homograph type, response times for ambiguous pairs were significantly longer than for unambiguous pairs only when targets were related to the subordinate meaning of the homograph. In the left hemisphere (RVF/LH), this ambiguity effect was larger for heterophones than for homophones, whereas in the right hemisphere (LVF/RH), similar patterns were observed for both types of homographs. Finally, performance patterns in the CVF revealed the same patterns as those in the RVF/LH, and were different from those in the LVF/RH. The implications of these results are discussed.

ARTICLE HISTORY Received 6 June 2015; Accepted 4 September 2015

KEYWORDS Hemisphere; language; reading; ambiguity resolution

Introduction

It is now commonly accepted that both hemispheres process the meanings of words, but they do so in qualitatively different ways (e.g., Coulson & Williams, 2005; Eviatar & Just, 2006; Faust & Chiarello, 1998; Federmeier & Kutas, 1999; Giora, Zaidel, Soroker, Batori, & Kasher, 2000; Harpaz, Levkovitz, & Lavidor, 2009; Jung-Beeman, 2005; Mashal, Faust, & Hendler, 2005; Titone, 1998). Nevertheless, the exact nature of these asymmetries is still under investigation.

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One way to assess hemispheric differences in semantic processing is by using the divided visual field (DVF) technique. This technique takes advantage of the fact that stimuli presented in the left side of the visual field are initially processed by the right hemisphere (RH) and vice versa. Although information presented in this manner can be later transmitted to both hemispheres, the interpretation of DVF paradigms rests on the assumption that responses to stimuli presented briefly to one visual field reflect mainly the processing of that stimulus by the contralateral hemisphere, so that responses to targets in the right visual field (RVF) reflect left hemisphere (LH) processes, and responses to targets in the left visual field (LVF) reflect processes in the RH (for theoretical and electrophysiological support for this assumption, see Banich, 2003; Berardi & Fiorentini, 1997; Coulson, Federmeier, Van Petten, & Kutas, 2005).

Studies using the DVF technique have led to the conclusion that whereas both hemispheres are able to activate meanings in response to words, they differ in their ability to carry out meaning selection and suppression. According to this received view, after initial broad automatic activation, the LH quickly selects closely related meanings, by inhibiting distantly related or contextually inconsistent information. In contrast, the RH maintains activation of multiple meanings including those that are less related or contextually inconsistent (e.g., Beeman, 1998; Burgess & Simpson, 1988; Faust & Chiarello, 1998; Faust & Gernsbacher, 1996).

For example, Burgess and Simpson (1988) investigated the activation and selection of ambiguous word meanings. In this study, participants were presented with ambiguous word primes (homophonic homographs like *bank*) and after 35 or 750 ms, they performed lexical decisions on target words related to the dominant (money) or subordinate (river) meaning of the ambiguous prime. The ambiguous primes were presented centrally (to both hemispheres). The targets were presented either in the LVF (to the RH) or in the RVF (to the LH). In short delays (35 ms Stimulus Onset Asynchrony (SOA)) both the dominant and the subordinate meanings of the ambiguous prime were available in the LH, while only the dominant meaning was available in the RH. In contrast, in longer delays (750 ms SOA), only the dominant meaning remained active in the LH, while both dominant and subordinate meanings were available in the RH. Thus, 750 ms after encountering the ambiguous word, the LH maintained the dominant meaning and suppressed the subordinate one, while the RH maintained both meanings, irrespective of meaning dominance.

Similarly, Faust and Chiarello (1998) have shown that sentential information can be used to suppress contextually inappropriate meanings in the LH but not in the RH. In this study, participants read sentences that were either biased towards the dominant (He could not wait for even a *second*) or subordinate (She stood in line and was *second*) meaning of their final ambiguous word (*second*), and performed lexical decisions on lateralized target words, presented 900 ms following the onset of the sentential prime. Targets were either related to the dominant meaning (time) or the subordinate meaning (number), or were unrelated words (sound). Results revealed that in the RVF/LH, priming was restricted to targets related to the contextually compatible meaning. In contrast, in the LVF/RH, related targets were primed regardless of context.

Taken together, these studies suggest that when readers encounter an ambiguous word, in the LH, multiple meanings are automatically activated but shortly afterwards one meaning is selected on the basis of frequency or contextual appropriateness. In the RH, on the other hand, multiple meanings are activated more slowly and remain active, irrespective of frequency or contextual information. Thus, according to the received view, post-access controlled selection processes occur in the LH but not in the RH.

However, in a series of DVF priming experiments, we have recently demonstrated that this hypothesis is too strong, and that *both* hemispheres utilize contextual and lexical sources of information during ambiguity resolution (e.g., Peleg & Eviatar, 2008, 2009, 2012; Peleg, Markus, & Eviatar, 2012). More importantly, we posit that differences in the functional connectivity between orthographic, phonological, and semantic representations underlie asymmetries in the time course of meaning activation and selection. In these studies, we investigated hemispheric asymmetries in accessing and maintaining multiple meanings of two types of Hebrew homographs: *Homophonic Homographs* (*e.g., bank*)—a single orthographic and phonological representation associated with multiple meanings, and *Heterophonic Homographs* (e.g., *tear*—/tɪər/ /tɛər/)—a single orthographic representation associated with multiple phonological codes, each associated with a different meaning. (It is important to note that Hebrew uses an abjad writing system, in which letters represent consonants and vowels are represented as diacritics mostly below and within the letters. Most written materials do not include the vowel diacritics, resulting in many words spelled the same but sounding different).

Participants read sentences that ended in either a homophonic or a heterophonic homograph, and performed a lexical decision task on targets presented laterally, either to the LH or to the RH, 150, 250, or 1000 ms after the onset of the final homograph. Sentential contexts were either biased towards one of the meanings of the final homograph, or unbiased. Targets were either related to one of the meanings of the ambiguous prime, or unrelated. Overall, dominant or contextually appropriate meanings were more likely to be activated and maintained in both hemispheres. The activation and maintenance of subordinate or contextually inappropriate meanings, however, differed as a function of VF presentation, homograph type, and context. Accordingly, in the case of *homophonic homographs* (*bank*), presented without a biasing context, selection processes were faster in the LH than in the RH. Specifically, in the LH, both meanings were activated immediately (150 ms SOA). However, shortly afterwards (250 ms SOA), the dominant, more salient meaning remained active, while the subordinate less salient one decayed (on degree of salience, see Giora, 1997, 2003). In contrast, in the RH, only dominant meanings were activated immediately (150 ms SOA). Less-salient meanings were activated more slowly, and were therefore available only at a later point in time (250 ms SOA). Importantly, at an even later point in time (1000 ms SOA) the dominant meaning was still active, while the subordinate meaning was not. Thus, at the 1000 ms SOA, the RH showed the same pattern as manifested by the LH at the 250 ms SOA.

In contrast, in the case of *heterophonic homographs* (*tear*), presented in a subordinately biased context, selection processes were faster in the RH than in the LH. Specifically, in the RH, although contexts were strongly biased towards the less-salient meaning, both meanings (the contextually appropriate and inappropriate) were activated immediately (150 ms SOA) and remained active 100 ms later on (250 ms SOA). However, at 1000 ms SOA, only the contextually appropriate meaning remained active, whereas the inappropriate one was not. In contrast, in the LH, contextually inappropriate meanings were activated more slowly (250 ms SOA), and were still available at a later point in time (1000 ms SOA). Thus, in this case, at the 1000 ms SOA, the LH mirrored the pattern manifested by the RH at the 250 ms SOA.

These reverse asymmetries were interpreted as supporting the hypothesis that hemispheric differences in the links between orthographic, phonological, and semantic codes underlie asymmetries in the time course of meaning activation and selection. According to this Dual Hemispheric Reading Model, in the LH, orthographic, phonological, and semantic representations are fully interconnected, whereas in the RH, there is no direct link between orthographic and phonological codes (Peleg & Eviatar, 2009, 2012; Peleg et al., 2012).

Accordingly, when orthographic and phonological representations are unambiguously related, as in the case of homophonic homographs (*bank*), direct orthographic–phonological links in the LH may boost activation of subordinate and/or contextually inappropriate meanings due to the shared phonological representation. And because multiple meanings are activated faster in the LH than in the RH, selection processes—the moment at which the less-frequent or the contextually inappropriate meaning is rendered inactive through attentional withdrawal, suppression, or decay—may start earlier as well. However, when orthographic and phonological representations are ambiguously related, as in the case of heterophonic homographs, direct orthographic–phonological links in the LH may slow down activation of subordinate and/or contextually inappropriate meanings due to the competition between different phonological alternatives. Because these meanings get activated later in the LH than in the RH, selection processes, in this hemisphere, may start later as well.

Importantly, despite these asymmetries in the time course of ambiguity resolution, our previous findings suggest that in contrast to the received view, *both* hemispheres may use lexical and contextual cues to suppress subordinate or contextually inappropriate word meanings.

The present study

The present study aimed to further test the separate and combined abilities of the two cerebral hemispheres to actively select word meanings, by examining the processing of homophonic and heterophonic homographs in the context of an explicit semantic judgment task combined with a DVF method. To emphasize controlled selection, integration, and revision processes, we presented the disambiguating information after rather than before the presentation of the homograph, and used a relatively long SOA (750 ms). Hemispheric differences were assessed by comparing lateral (RVF/LH with LVF/RH) presentations. Hemispheric interactions were examined by comparing central with unilateral (RVF/LH or LVF/RH) stimulus presentations.

Thus, in the study, Hebrew readers saw pairs of words and had to decide whether the two words (presented successively) were semantically related (Yes/No). The first word in each pair was presented centrally to both hemispheres. The second word was presented either laterally to one hemisphere (either to the RVF/LH or to the LVF/RH), or centrally (in the central visual field (CVF)) to both hemispheres. We compared response latencies to related pairs ("Yes" responses) in two conditions: an ambiguous condition (e.g., bank-money or bank-river) and an unambiguous condition (e.g., purse-money or boat-river). In the ambiguous condition, the first word in each pair was a homograph (e.g., bank) and the second word was related either to its dominant (e.g., money) or subordinate (e.g., river) meaning. In the unambiguous condition, homographs (e.g., bank) were replaced with unambiguous control words (purse or boat). The ambiguity effect is the difference between these conditions, and may reveal the automatic excitation of the alternative (contextually inappropriate) meaning of the homograph.

If the LH actively selects dominant meanings, while the RH passively activates and maintains both dominant and subordinate meanings, as assumed by the received view (e.g., Burgess & Simpson, 1988), then, in the RH, ambiguous pairs (bank-money or bank-river) should be more difficult to process in comparison to unambiguous pairs (purse-money or boat-river), irrespective of frequency. In other words, dominant conditions (bank-money vs. purse-money) and subordinate conditions (bank-river vs. boat-river) should yield similar ambiguity effects (slower and less-accurate responses to ambiguous pairs in comparison to unambiguous pairs). In contrast, in the LH, the ambiguity effect is expected to be modulated by frequency: In the subordinate condition, ambiguous pairs (bank-river) are expected to be more difficult to process than unambiguous pairs (boat-river), whereas in the dominant condition, no difference is expected between ambiguous (bank-money) and unambiguous (purse-money) pairs. However, if both hemispheres can select dominant meanings (within 750 ms), as suggested by our previous results (e.g., Peleg & Eviatar, 2012), then subordinate conditions (bank-river vs. boat-river) should yield larger ambiguity effects than dominant conditions (bank-money vs. purse-money) in both hemispheres.

A further goal of the present study was to directly test our Dual Hemispheric Reading Model (Peleg & Eviatar, 2009, 2012) by contrasting homophonic homographs (bank) with heterophonic homographs (tear). If direct orthographic–phonological links exist in the LH, but not in the RH, as assumed by our proposal (Peleg & Eviatar, 2009, 2012), then differences between homophones and heterophones should be more pronounced in the LH than in the RH. Specifically, we predicted that subordinate conditions in the LH would yield larger ambiguity effects in heterophones (*tear*-fabric) than in homophones (*bank*-river). This is because replacing the initial dominant interpretation with the subordinate meaning may be facilitated in the case of homophones, due to the shared phonological representation, whereas in the case of heterophones, subordinate conditions require both semantic and phonological revisions.

Finally, comparison of performance when stimuli are presented in the peripheral visual fields to performance when stimuli are presented centrally can reveal patterns of *metacontrol*: What is the hemispheric division of labour when processing unlateralized stimuli (Eviatar, Hellige, & Zaidel, 1997; Luh & Levy, 1995). Thus, if both hemispheres make differential contributions to meaning comprehension during natural reading, then lateral presentations should elicit different response patterns than central presentations. However, if meaning apprehension is controlled by one hemisphere, then the performance under bilateral, central viewing should be similar to the performance of that hemisphere, and different from the performance of the other hemisphere.

Method

Participants

Forty undergraduate students (mean age = 25.6, SD = 2.96, 5 males) participated in the study. They were all healthy, right handed, native speakers of Hebrew with normal or corrected vision, without neurological diseases, psychiatric disorders, or language disabilities. Handedness was assessed with the Edinburgh Handedness Questionnaire (Oldfield, 1971), with 80 as the cut-off point.

Stimuli

A total of 156 noun–noun polarized Hebrew homographs (78 homophonic and 78 heterophonic) were used as primes. Each homograph (e.g., bank) was paired with two target words: one related to the dominant meaning (e.g., bank-money) and the other to the subordinate meaning (e.g., bank-river). Unambiguous control pairs were created by replacing homographs with unambiguous control words (e.g., purse-money or boat-river). A battery of pre-tests ensured that the different conditions were balanced in terms of polarity, semantic relatedness, frequency, and length.

Polarity pre-tests

In order to determine the order of meaning salience for each homograph, and the distance in salience between the first two meanings (polarity), two pre-tests were performed. In the first pre-test, 20 participants were presented with homographs and their paraphrased meanings and were instructed to indicate the relative frequency of each of the meanings on a 10-point frequency scale ranging from 1 (never encountered) to 10 (highly frequent). In the second pre-test, 20 different participants were presented with the homograph and were instructed to write down their first association of that word. On the next screen the different meanings of the homograph were presented and participants had to ascribe their association to the most appropriate meaning. The salience of each meaning was computed based on the combined score from the two pre-tests and the two most salient meanings of each homograph were selected. Homographs were excluded if one or both of the two most salient meanings was not a noun, or if they had more than two similarly salient meanings. The difference between the salience of the two selected meanings served as the polarity index, which was balanced across Homophones and Heterophones: Homophopnes: $M = 3.67$ SD = 2.18, Heterophones: $M = 3.96$ SD = 2.39; $p > .43$.

Semantic relatedness pre-test

In order to balance the strength of semantic relatedness across ambiguous and unambiguous pairs this pre-test presented each homograph or unambiguous word with four related target words, on which 20 participants made a semantic relatedness judgement on a 10-point relatedness scale ranging from 1 (completely unrelated) to 10 (very strongly related). Semantic relatedness was defined as either a categorical or associative relation. For homographs two of these target words were related to its dominant meaning and two were related to the subordinate meaning. The words with the highest score were selected for related pairs and semantic relatedness scores were balanced across all conditions: (a) Homophones-dominant targets: $M = 9.12$, SD = 0.77, Heterophones-dominant targets: $M = 9.15$, SD = 0.77; $p > .79$, (b) Homophones-subordinate targets: $M = 8.90$, SD = 0.94, Heterophones-subordinate targets: $M = 8.74$, SD = 0.96; $p > .31$, (c) Homophones unambiguous controls-dominant targets: $M = 9.16$, SD = 0.98, Heterophones unambiguous controls-dominant targets: $M = 8.94$, SD = 0.77; $p > .18$, (d) Homophones unambiguous controls-subordinate targets: $M = 9.01$, SD = 1.02, Heterophones unambiguous controls-subordinate targets: $M = 8.94$, SD = 1.00; $p > .65$. Inspection of the final stimuli used in this experiment reveals that most pairs were related due to both feature overlap and associative strength.

Frequency pre-test

Since in Hebrew there is no extensive database for word frequency that includes all the words used in this experiment, a pre-test tested subjective frequency (overall word-form dominance). Ninety judges were asked to rate all words selected in previous pre-tests (homographs, unambiguous controls, and targets) on a 10-point frequency scale ranging from 1 (never encountered) to 10 (highly frequent). The average rates on the frequency scale did not vary across conditions: (a) Homophones: $M = 7.19$ SD = 0.98, Heterophones: $M = 7.32$ SD = 0.93; $p > .38$, (b) Homophones-dominant unambiguous controls: $M = 7.15$ SD = 1.39, Heterophones-dominant unambiguous controls: $M = 7.35$ SD = 1.32; $p > .27$, (c) Homophones-subordinate unambiguous controls: $M = 7.24$ SD = 1.23, Heterophones-subordinate unambiguous controls 7.14 SD = 1.54; $p > .59$, (d) Homophones-dominant targets: $M = 7.19$ SD = 1.13, Heterophones-dominant targets: $M = 7.20$ SD = 1.11; $p > .93$, (e) Homophones-subordinate targets: $M = 7.31$ SD = 1.06, Heterophones-subordinate targets: $M = 7.16$ $S = 1.05$; $p > .36$.

Finally, the different conditions were also balanced in terms of word length (number of letters): (a) Homophones: $M = 3.76$ SD = 0.97, Heterophones: $M = 3.59$ SD = 0.84; $p > 0.27$, (b) Homophones-dominant unambiguous controls: $M = 4.66$ SD = 0.95, Heterophones-dominant unambiguous controls: $M = 4.62$ SD = 1.04. $p > .74$, (c) Homophones-subordinate unambiguous controls: $M = 4.44$ SD = 0.87, Heterophones-subordinate unambiguous controls: 4.58 SD = 1.04; $p > .38$, (d) Homophones-dominant targets: $M = 4.47$ SD = 1.11, Heterophones-dominant targets: $M = 4.51$ SD = 1.08; $p > .32$, (e) Homophones-subordinate targets: $M = 4.51$ SD = 1.11, Heterophones-subordinate targets: $M = 4.74$ $S = 1.23$; $p > .18$.

Apparatus

Stimulus presentation and responses were controlled and recorded by a HP Z400 PC, using the E-Prime experiment software suit. An adjustable chin-rest kept participants at a fixed viewing distance of 57 cm from the computer screen. A 19" CRT monitor was used for presenting the stimuli at a resolution of 1024 × 768 pixels. Stimuli, constructed from characters presented in David font (size 18), were coloured black and displayed on a grey coloured screen.

Experimental design & procedure

The experiment used a 2 (homograph type: homophonic or heterophonic) × 2 (target dominance: dominant or subordinate) × 2 (pair condition: ambiguous or unambiguous) × 3 (target location: (CVF, LVF, or RVF) within participants design. There were 1872 experimental permutations for the target words (78 × 2 types of homographs × 2 target words × 2 pair conditions × 3 VF presentations). Six lists were created such that all factors were counterbalanced across items and participants. Cell means are based on 26 experimental trials per condition per participant. Each list contained 312 experimental pairs that were semantically related and 312 semantically unrelated pairs that served as fillers (624 trials in total) Participants were randomly assigned to two experimental lists. Each target appeared only once per list (each participant saw each item pair twice, and the two presentations appeared in different conditions). Trials within each list were presented in random order, with randomization controlled by the computer and the order of lists was counterbalanced across participants. The testing sessions lasted approximately 90 min (30 min for each list with a 20–30-minute break between them).

Participants were seated 57 cm from the computer screen and placed their heads in the head and chin-rest. Unilateral stimuli were presented such that their innermost boundary, whether to the right or left of centre, was exactly 2° of visual angle from the central fixation marker, with a maximum of 2.5° of visual angle. Each session began with 24 practice trials presented in one block, and comprised 624 experimental trials and fillers presented in blocks of 24 with a rest period between blocks, a ten-minute break, and a second set of 624 experimental trials and fillers presented in the same manner.

At the start of each trial, participants were presented with a central fixation marker for 400 ms. The offset of the marker was followed by a 100 ms pause, and the first word (either a homograph or an unambiguous control) was then presented, in the same position (centre of the screen) for 150 ms. At 600 ms ISI (750 ms SOA), the second word (the target) was presented for 150 ms to the CVF, LVF, or RVF for a semantic decision response.

Participants made semantic decision responses by pressing the up/down arrows with their right index finger for related/unrelated responses. They were instructed to retain their gaze on the central fixation marker and to make responses as quickly and accurately as possible. The data collected for each subject included RT for target words and error rates for all conditions.

Results

Participants whose overall accuracy score was lower than 75% were excluded ($N = 3$). In addition, pairs of words for which the overall (i.e., for both related and unrelated pairs) accuracy of response was less than 75% were excluded ($N = 6$, 3 heterophones and 3 homophones). Response times (RTs) of errors were deleted, as were RTs that were 3.5 SD away from the participants' overall mean RT.

The RT and error scores to related pairs (correct 'yes' responses) were analysed using a linear mixed effects (LME) model (Baayen, Davidson, & Bates, 2008). This computation allows the testing of hypotheses while taking into account the variance due to participants and to items simultaneously. Our major hypothesis relates to the difference in RTs to pairs in which the first word was ambiguous (a homograph) versus matched pairs (in terms of the targets) in which the first word was unambiguous. This is the effect of ambiguity.

Thus, the model was constructed for the analysis with the effects of Phonology (type of homograph: homophonic or heterophonic), Target Dominance (whether the second word was related to the dominant (DOM) or subordinate (SUB) meaning of the homograph), Ambiguity (whether the prime was a homograph or a matched unambiguous word), and Visual Field (CVF, RVF, or LVF) as fixed factors, and the effects of Item, and Subject as random factors. Because of the small number of males in the sample, for both RT and errors, we first compared a model in which sex was used as an intercept for the random effects of Subject, with a model in which sex was not included. These did not differ from each other ($p > .9$). Therefore, we used the simpler models in which sex is not included as a parameter.

RT analyses

The analysis of RT revealed that a model with the fixed factors Ambiguity, Phonology, Frequency, and Visual Field, in a 4-way interaction and the random factors of Item and Subject results in the best fit for the data ($\chi^2(2) = 6.48$, $p < .05$, relative to all the 3-way models). Within this model, the 4-way interaction between Ambiguity, Frequency, Phonology, and Visual Field was significant $F(2, 26373.5) = 3.24$, $p < .05$. Importantly, an examination of raw RTs for *unambiguous conditions* revealed no significant interactions between Phonology, Frequency, and VF. Given that our hypothesis is specific to the ambiguity effect, this is the analysis we focus on. The estimated effects of ambiguity are illustrated in Figure 1. Each value represents the difference in RT between ambiguous and unambiguous pairs (computed over subjects and items simultaneously).

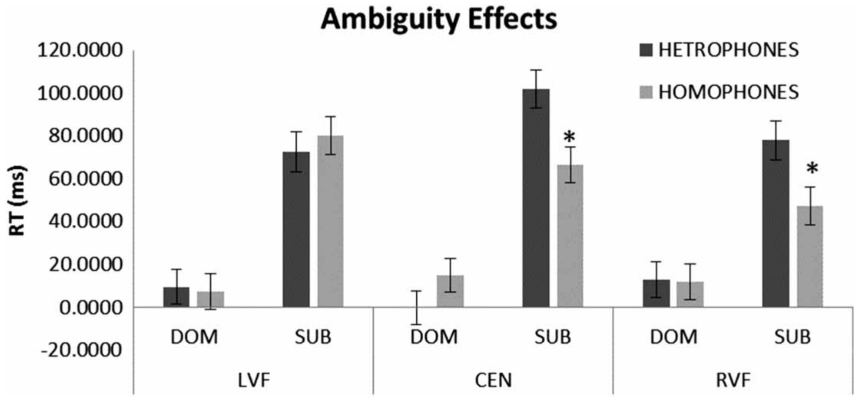

Figure 1. Ambiguity effects (differences between ambiguous and unambiguous pairs) as a function of Homograph Type (homophones vs. heterophones) Target Location (LVF/CEN/RVF), and Target Dominance (dominant vs. subordinate conditions). DOM = dominant condition; SUB = subordinate condition; * = $p < .05$.

In order to follow up the 4-way interaction, we computed the simple main effect of Ambiguity in each condition. This tests whether the difference between the ambiguous and unambiguous conditions is different from zero. As can be seen in Figure 1, this difference was only significant when the second word was related to the less frequent (SUB) meaning of the ambiguous word, in all of the visual fields, for both types of homographs. The statistics for these comparisons are listed in panel A of Table 1. In addition, in order to compare these effects in homophones and heterophones, we computed the interaction between Ambiguity and Phonology in each VF by Frequency condition, within the previously described LME model. The statistics for these interactions are listed in panel B of Table 1. The results show that the effects of Ambiguity were different for homophones and heterophones only in the CVF and RVF when the second word was related to the subordinate meaning of the homograph. It can be seen in Figure 1 and in panel A of Table 1 that in both cases, heterophones resulted in larger differences between ambiguous and unambiguous pairs than homophones. In the LVF, ambiguity effects for heterophones and homophones did not differ from each other.

In terms of metacontrol, the LME analyses revealed that when the model included CVF and RVF, the 4-way interaction was not significant ($p > .37$), whereas when the model included CVF and LVF, the 4-way interaction was significant ($p < .05$). Thus, performance patterns in the central visual field reveal the same patterns as those in the RVF (LH), and are different from those in the LVF (RH). This pattern suggests that the LH is dominant for our task, and that performance in the CVF reflects mainly LH processing.

Table 1. (a) Ambiguity effects (differences between ambiguous and unambiguous pairs) as a function of Homograph Type (homophones vs. heterophones), Target Dominance (dominant vs. subordinate conditions) and Target Location (LVF/ CVF/ RVF). (b) Ambiguity by phonology interaction as a function of Target Dominance and Target Location.

(a) Simple main effect of ambiguity

LVF				*CVF*				*RVF*			
DOM		*SUB*		*DOM*		*SUB*		*DOM*		*SUB*	
HET	*HOM*	*HET*	*HOM*	*HET*	*HOM*	*HET*	*HOM*	*HET*	*HOM*	*HET*	*HOM*
$z = 1.16$ $p > .9$	$z = 0.86$ $p > .9$	$\mathbf{z = 7.93}$ $\mathbf{p < .001}$	$\mathbf{z = 8.91}$ $\mathbf{p < .001}$	$z = -0.05$ $p > .9$	$z = 1.86$ $p = .54$	$\mathbf{z = 11.65}$ $\mathbf{p < .001}$	$\mathbf{z = 7.90}$ $\mathbf{p < .001}$	$z = 1.58$ $p > .7$	$z = 1.41$, $p > .8$	$\mathbf{z = 8.57}$ $\mathbf{p < .001}$	$\mathbf{z = 5.27}$ $\mathbf{p < .001}$

(b) Ambiguity by phonology interaction

LVF		*CVF*		*RVF*	
DOM	*SUB*	*DOM*	*SUB*	*DOM*	*SUB*
$X^2_{(1)} = 0.04$ $p > .8$	$X^2_{(1)} = 0.34$ $p > .55$	$X^2_{(1)} = 1.84$ $p > .17$	$X^2_{(1)} = 8.47$ $\mathbf{p < .005}$	$X^2_{(1)} = .01$ $p > .9$	$X^2_{(1)} = \mathbf{5.72}$ $\mathbf{p < .05}$

Note: DOM, dominant; SUB, subordinate; HET, heterophones; HOM, homophones. Values in bold are statistically significant at an alpha of .05.

Error analyses

The analysis of error scores using the binomial distribution family revealed that the three-way model best fits the data ($\chi^2(7) = 39.77$, $p < .001$, relative to the next-best two-way model). Follow-up analyses revealed that the significant 3-way interaction is between Phonology, Ambiguity, and Frequency, $F(1,33099) = 34.15$, $p < .0001$. Similar to the RT results, the effect of Ambiguity was much larger when the target word was related to the subordinate, less-frequent meaning of the homograph, and this effect was larger for heterophones than for homophones.

Discussion

To examine controlled semantic processes both within and between the two cerebral hemispheres, Hebrew readers were asked to decide whether two words, presented one after the other, were semantically related or unrelated. The first word was presented centrally to both hemispheres, the second word was presented either laterally (to the LH or to the RH) or centrally (to both hemispheres). We compared semantically related pairs under two conditions: An ambiguous condition (e.g., bank-money or bank-river) and an unambiguous condition (e.g., purse-money or boat-river). The ambiguity effect is the difference between these two conditions, and reveals the automatic excitation of the alternative (contextually inappropriate) meaning of the homograph.

Irrespective of VF or homograph type, RTs for ambiguous pairs were significantly longer than for unambiguous pairs only when targets were related to the subordinate meaning of the homograph. The fact that dominant conditions (bank-money vs. purse-money) did not reveal an ambiguity effect indicates that by the time participants encountered the target (750 ms SOA) only the dominant meaning of the homograph remained active in both hemispheres. This clearly suggests that both hemispheres are sensitive to lexical information (e.g., degree of meaning salience) so as to actively select dominant word meanings.

Furthermore, although the dominant meaning was selected before the target was presented, both hemispheres were able to judge subordinate pairs (bank-river) as semantically related. That is, both hemispheres were able to revise their initial (dominant) interpretation of the homograph, in response to the subordinate target, as indicated by their “better than chance” ability to judge subordinate pairs (bank-river) as semantically related (d′ is significantly different from zero). This revision process, in both hemispheres, is further demonstrated by the fact that judging subordinate targets (river) as semantically related to their preceding homographs (bank) took significantly longer compared to their unambiguous controls (boat).

Taken together, the results of this study suggest that, in contrast to the received view (e.g., Burgess & Simpson, 1988), both hemispheres are able to perform controlled semantic processes such as meaning selection, integration, and revision. These results converge with recent ERP studies indicating that the RH is able to recruit controlled semantic mechanisms, especially when explicit semantic judgements are required (Kandhadai & Federmeier, 2010; Meyer & Federmeier, 2007).

A further goal of the present study was to directly test our Dual Hemispheric Reading Model (Peleg & Eviatar, 2009, 2012), assuming full interconnectedness of orthographic, phonological, and semantic representations in the LH, but only partial connections in the RH, where orthographic and phonological representations are not directly connected. To accomplish this, two types of Hebrew homographs were included in the study: homophonic homographs (bank) and heterophonic homographs (tear). In both cases, a single orthographic representation is associated with multiple meanings. They are different, however, in terms of their phonology. In the case of homophones, the orthographic representation is associated with a single phonological code (which is also associated with multiple meanings). In contrast, in the case of heterophones, the orthographic representation is associated with two different phonological codes, each associated with a different meaning. As predicted by our model, homophonic and heterophonic homographs, which diverge on how their meanings are related to phonology, were processed differently in the LH, whereas, in the RH, similar patterns were obtained for both types of homographs.

Specifically we show that although subordinate conditions yielded longer RTs in ambiguous (bank-river) than unambiguous (boat-river) conditions, irrespective of VF and homograph type, this ambiguity effect was larger for heterophones than for homophones only in the LH. These results further support the assumption that while orthographic–semantic connections exist in both hemispheres, direct orthographic–phonological connections exist only in the LH (For a similar view see Halderman, & Chiarello, 2005; Lavidor & Ellis, 2003; Zaidel & Peters, 1981).

A final aim of this study was to assess hemispheric interactions by examining the extent to which both hemispheres contribute to the performance of the participants under natural (central) reading conditions. To accomplish this, targets were presented either laterally or centrally. If both hemispheres contribute, then centrally presented targets should be processed differently than laterally presented targets. However, if only one hemisphere contributes, then centrally presented targets should be processed similarly to targets presented to that hemisphere and differently from targets presented to the other hemisphere. In the present study, performance patterns in the CVF were similar to those in the RVF (LH), and different from those in the LVF (RH). Thus, although both hemispheres were able to actively select, reactivate, and integrate meanings (as implied by our unilateral conditions), performance under typical (central) reading conditions is controlled by the LH. It is possible, however, that this LH dominance is restricted to semantic processes at the lexical level. Future studies should examine the extent to which the RH contributes to automatic versus controlled semantic processes during higher-level sentence and/or discourse comprehension.

Funding

This research was supported by grant 624/12 from the Israel Science Foundation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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