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Visual simulations in the two cerebral hemispheres during first and second language comprehension

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ABSTRACT

Embodied theories of language processing hold that language is understood by mentally simulating the state-of-affairs described by the linguistic content. That is, the same mental representations that are activated when we experience real events are also activated in response to verbally described events. Language comprehension, therefore, involves not only the activation of linguistic representations, but also the activation of different types of modal representations (e.g., visual representations) associated with the described objects and events (e.g., Anderson, 2003; Barsalou, 2008; Glenberg, 2015).

Based on this embodied assumption, Barsalou and colleagues (Barsalou, Santos, Simmons, & Wilson, 2008) proposed a hybrid model, in which meanings are represented in two separate systems: a linguistic system that uses word association to represent meaning, and a simulation system that uses non-verbal sensorimotor knowledge. Importanlty, the model assumes that these two systems are connected, such that during language comprhension, lexical representations in the linguistic system (e.g., the writtten form of the word “dog”) evoke sensorimotor representations in the simulation system (e.g., the visual image of a dog).

Substantial evidence supports an embodied view of language comprehension (for a review see Barsalou, 2008), however, most findings come from research on L1 processing. As opposed to an L1, the acquisition of an L2 later in life, in a formal manner, outside of the environment where it is naturally and constantly spoken, is far less associated with real life experiences, and its use is relatively limited. Under such circumstances, the links between lexical representations in the linguistic system and sensorimotor representations in the simulation system may be weaker. Thus, it is possible that one of the fundamental differences between L1 and L2 comprehension reside in the ability of bilinguals to spontaneously construct a rich and detailed mental simulation of the situations conveyed by the linguistic content.

Therefore, the first aim of the current work was to examine whether late bilinguals who learned their L2 formally in an un-immersive environment can activate sensorimotor representations of described objects during L2 comprehension. In particular, this study investigated the extent to which perceptual visual information is activated during L2 reading, in comparison to L1 reading. If the manner of language acquisition and use indeed affects the ability to construct perceptual simulations during language comprehension, then non-verbal

visual information associated with the linguistic content will be activated more extensively during L1 processing, than during L2 processing.

The second aim of this study was to examine the neural mechanisms that support the construction of these visual simulations during reading, specifically, focusing on the relative contribution of each hemisphere to this process. Previous studies, which have examined hemispheric asymmetries in both language and visual processing, have demonstrated a left hemisphere (LH) advantage in language processing and a right hemisphere (RH) advantage in visual processing (Corballis, 2003; Hugdahl, 2000). However, only a few studies examined asymmetries in the activation of visual knowledge during language comprehension, and these focused only on L1 processing (e.g., Lincoln, Long & Baynes, 2007). Thus, the current study examined the combined and separate ability of the two cerebral hemispheres to activate perceptual visual knowledge during L1 and L2 reading. If the LH specializes in language processing and the RH specializes in non-verbal visual processing, then visual simulation processes should be more pronounced in the RH than in the LH. Furthermore, if L1 comprehension involves visual simulations and L2 comprehension relies mainly on linguistic knowledge, then the RH should be more involved in L1 than in L2 processing.

To test these assumptions, two sets of experiments were conducted. In all experiments, participants were native Hebrew speakers (L1-Hebrew) that have lived their entire lives in the L1 environment (Israel), and learned their L2-English after the age 6 in a formal school setting. These participants performed the two experimental tasks in their L1-Hebrew and in their L2-English. The first task - the sentence picture verification task (Zwaan, Stanfield & Yaxley, 2002) – tested their ability to activate the implied visual shape of mentioned objects during sentence reading (Exp. 1 and 3). The second task - semantic relatedness judgment of word-pairs (Zwaan & Yaxley, 2003a) – tested their ability to activate the typical spatial location of mentioned objects during word reading (Exp. 2 and 4). In the first set (Exp. 1 and 2), target stimuli (as described below) were presented in the central visual field (CVF) to both hemispheres. In the second set (Exp. 3 and 4), the same stimuli were presented either in the right visual field (RVF) to the LH, or in the left visual field (LVF) to the RH.

Exp. 1 and 3 utilized the sentence picture verification task. In this task, participants read sentences describing an object in a certain location (e.g., “The boy saw the balloon in the air/package”). The sentences were presented either in the L1-Hebrew (L1 block) or in the L2-English (L2 block). After each sentence, a picture of an object (e.g., balloon) was presented and participants had to decide whether or not the pictured object had been mentioned in the preceding sentence. On critical trials, the pictured object was indeed mentioned in the sentence. However, its shape could have either matched or mismatched the shape implied by the sentence. For example, the sentence: “The boy saw the balloon in the air” implies the shape of an inflated balloon. Thus, after this sentence, a picture of an inflated balloon was presented in the match condition, and a picture of a deflated balloon was presented in the mismatch condition (and vice versa in the sentence: “The boy saw the balloon in the package”). Faster responses in the match, relative to the mismatch condition (i.e., the shape effect), indicate that implied visual knowledge about the shape of objects is spontaneously activated during sentence comprehension. Exp. 1 examined the activation of visual shape information when target pictures were presented in the CVF to both hemispheres. Exp. 3 examined the activation of visual shape information when target pictures were presented either in the RVF to the LH or in the LVF to the RH.

Exp. 2 and 4 utilized the semantic judgment task. In this task, participants were asked to decide whether two words, presented one above the other on a screen, are semantically related or not. Word-pairs were presented either in the L1-Hebrew (L1 block) or in the L2-English (L2 block). All critical word-pairs denoted objects with strong semantic relation, which their referents consist of a typical spatial-vertical relation, such that one object is usually located above the other object (e.g., car-road). These word-pairs were presented in two spatial conditions. In the match condition, the spatial arrangement of the two words on the screen matched the typical spatial relation of their referents (e.g., “car” was displayed above “road”). In the mismatch condition, the visual spatial arrangement of the two words did not match the typical spatial relation of their referents (e.g., “road” was displayed above “car”). Faster responses in the match, relative to the mismatch condition (i.e. the spatial effect), indicate that visual knowledge about the typical spatial location of objects is spontaneously activated during word comprehension. Exp. 2 examined the activation of visual spatial information when target word-pairs were presented in the CVF to both hemispheres. Exp. 4 examined the activation of visual spatial information when target word-pairs were presented in the RVF to the LH or in the LVF to the RH.

The specific predictions were as follow: (a) in the first set of experiments (central presentation), we predicted that, among these type of bilinguals, L2 processing will produce weaker visual simulations than L1 processing, assumingly because of the relatively formal fashion by which they have learned and used their L2. Thus, visual effects in both tasks (i.e., the shape and spatial effects) were expected to be significantly reduced in the L2, relative to the L1; (b) in the second set of experiments (lateral presentation), we predicted that during word and sentence reading in both languages, visual knowledge would be activated in both hemispheres, since visual mechanisms exist in both. However, we predicted that this knowledge would be activated more extensively in the RH, due to its advantage in processing non-verbal visual information. Namely, visual effects in both languages were expected to be stronger in the RH, than in the LH.

In line with the first prediction, in the first set, visual effects were found only during L1 reading (and, as detailed below, only in the sentence picture verification task). In Exp. 1 (the sentence picture verification task) a significant interaction between the shape condition (match/mismatch) and the language condition (L1/L2) was demonstrated, such that the shape effect was significantly evident only in the L1, whereas in the L2 the match and the mismatch conditions hardly differed. These findings indicate that this type of bilinguals construct visual simulations in their L1, but not in their L2. Namely, while the comprehension of a naturally acquired L1 involves simulations processes, the comprehension of a formally learned L2 is mainly supported by linguistic processes.

Interestingly, the shape effect in both languages was modulated by the order of the language blocks (L1 after L2/L2 after L1). Specifically, in the L1, the shape effect was smaller when the L1 block was performed immediately after the L2 block. Conversely, in the L2, the shape effect was larger when the L2 block was performed immediately after the L1 block. Thus, the specific processing pattern employed in each language in the first block (simulation-based processing in the L1-Hebrew/linguistic-based processing in the L2-English), influenced the processing of the other language in the second block.

Moreover, the current findings also demonstrated that visual effects were modulated by the task. While the sentence picture verification task (Exp. 1) produced a significant visual effect in the L1, the semantic judgment task (Exp. 2) did not yield significant visual effects, neither in the L1 nor in the L2. This finding suggests that the degree of involvement of the simulation system, even in the L1, may be modulated by various factors such as the nature of the task (sentence picture verification/semantic judgment), the type of stimuli (with pictures/without pictures), or the visual property that is being tested (shape/spatial location).

In sum, the results obtained from the first set of experiments suggest a difference between L1 and L2 processing, such that visual simulations during language comprehension occur only in the L1. Moreover, even in the case of an L1, visual simulations were observed only in the sentence picture verification task and only when the L1 experiment was performed before the L2 experiment. These results can be explained by embodied theories of language processing, which distinguish between comprehension processes that merely employ the linguistic system and deeper comprehension processes that employ the simulation system as well (Barsalou et al., 2008). Accordingly, an L2 that is learned formally, does not establish strong links between these two systems, and thus, relies primarily on the linguistic system. On the other hand, a naturally learned L1 is characterized by a strong connection between the two systems, and therefore enables both types of processing – shallower processing that employs only the linguistic system (Glaser, 1992), and deeper processing that includes the activation of perceptual visual representations in the simulation system (Solomon & Barsalau, 2004).

In line with the second prediction, in the second set of experiments (lateral presentation), the visual shape effect was more robust when the stimuli were presented in the LVF directly to the RH. Like in Set A, visual effects were observed only in the sentence picture verification task (Exp. 3). In this experiment, a marginally significant interaction was observed between the shape condition (match/mismatch) and the visual field condition (RVF/LVF), such that regardless of the language involved, the shape effect was significant only when the target stimuli were presented in the LVF to the RH. This finding indicates that perceptual visual knowledge is more strongly activated in the RH than in the LH, assumingly due to the advantage of the RH in visual processing (Corballis, 2003; Hugdahl, 2000).

Although the three-way interaction between the shape condition (match/mismatch), visual field condition (RVF/LVF), and language condition (L1-Hebrew/L2-English) was not significant, planned comparisons conducted separately for each language showed that the difference between the two hemispheres, in terms of the shape effect, was more pronounced in the L2-English than in the L1-Hebrew. Specifically, in the L1-Hebrew, a similar pattern of results was obtained in both hemispheres - responses were faster in the match than in the mismatch condition, but this difference did not reach significance. However, in the L2-English, a significant shape effect was obtained in the RH, whereas, in the LH, the effect was not evident at all. This, together with the results of Exp. 1 (central presentation), suggests that the two hemispheres may be differently engaged during L1 and L2 sentence processing.

To explore this possibility, additional analyses were conducted, in which performance patterns (i.e., the shape effect) that were observed under CVF presentation were compared with those observed under LVF or RVF presentations. These comparisons revealed that both hemispheres are involved in natural L1 and L2 reading. However, the two languages differ in the degree to which each hemisphere is involved. In the L1, the pattern of the shape effect obtained in the CVF (a significant effect) was different than the pattern obtained in both the LVF/RH and the RVF/LH (in both cases the effect was not significant). This indicates that during natural L1 reading, both hemispheres additively contribute to the shape effect, and hence, reading processes in the L1 are more balanced in terms of hemispheric involvement. However, in the L2, the pattern of the shape effect obtained in the CVF was more similar to the pattern obtained in the RVF/LH (in both cases the shape effect was not significant) and different from that obtained in the LVF/RH (a significant effect). This indicates that natural L2 reading relies mainly on the LH (linguistic-based processing). Thus, although L2 sentence reading can significantly evoke visual knowledge in the RH, this knowledge does not affect L2 reading under normal (central) conditions.

In sum, the results obtained from the second set of experiments suggest greater RH involvement in visual simulation processes, irrespective of the target language. These findings are consistent with the claim that the RH is more involved in visual processing, while the LH is more involved in linguistic processing. Additionally, the comparison between the results obtained in the central visual field to those obtained in the peripheral visual fields, revealed a different pattern of hemispheric interaction in each language, such that L1 reading relies more equally on both hemispheres, whereas L2 reading relies primarily on the LH.

Taken together, the present study demonstrated a relationship between the manner of language acquisition, the pattern of hemispheric involvement, and the ability to evoke visual simulations during language comprehension. In particular, in the case of an L1, which is acquired in a natural and experiential fashion, processing relies on both hemispheres, and therefore involves not only linguistic representations, but also non-verbal visual representations. However, in the case of an L2, which is acquired in a formal and un-immersive fashion, processing relies mainly on the LH, and therefore involves only linguistic representations.

These differences may have critical implications on the nature of comprehension in each language, because simulation-based comprehension is assumed to involve deep conceptual information, which enable higher-level processing functions, whereas linguistic-based comprehension is assumed to be relatively shallow, because it relies on superficial low-level processing strategies, which may not be sufficient for some tasks (Solomon & Barsalau, 2004; Barsalau et al., 2008). The current study presents evidence for L1-L2 differences in hemispheric processing and simulation abilities. Further studies are needed in order to establish a causal relationship between simulation abilities and language comprehension abilities in both the L1 and the L2.

1. GENERAL INTRODUCTION

A fundamental question in cognitive science concerns the role of sensory, motor, and affective information in representing conceptual knowledge, and its involvement in language processing (Bedny & Caramazza, 2011; Glenberg, 2015; Mahon & Caramazza, 2008; Zwaan, 2004). On the one hand, completely disembodied theories assume that knowledge consists of abstract, symbolic, amodal representations that are qualitatively distinct and separable from sensory, motor and affective experiences (Collins & Loftus, 1975; Fodor, 1975; Gentner, 2010; Landauer & Dumais, 1997; Mahon, 2015). On the other hand, theories of embodied cognition postulate that knowledge consists of modal representations stored in modality-specific brain regions. Accordingly, high-level cognitive processes, such as language comprehension, are grounded in low-level neural mechanisms of perception, action, and emotion. In this view, language comprehension involves not only the activation of linguistic representations, but also the activation of sensory, motor, and affective representations associated with the described objects and events (Anderson, 2003; Barsalou, 1999; 2008; Barsalou, Santos, Simmons, & Wilson, 2008; Paivio, 1990; 2010; 2014; Zwaan & Madden, 2005).

Substantial evidence supports an embodied view of language processing (e.g., Barsalou, 2008; Pulvermüller, 2005; Zwaan & Madden, 2005), however, most findings come from research on first language (L1) comprehension. The question regarding the embodiment of a second language (L2) is relatively unexplored (for reviews see Adams, 2016; Kühne & Gianelli, 2019; Monaco, Jost, Gygax & Annoni, 2019). Thus, the first aim of the current study was to investigate the extent to which L2 comprehension involves the activation of modality-specific representations. In particular, it aimed to investigate the extent to which perceptual (visual) information is spontaneously activated during L2 comprehension, in comparison to L1. A second aim was to investigate the neural mechanisms that support the construction of these visual simulations, specifically focusing on the separate and combined abilities of the two cerebral hemispheres to activate visual properties of verbally described situations during L1 and L2 comprehension.

To accomplish these aims, two sets of experiments were conducted - Set A and Set B. These two sets are introduced, described, and discussed in the next two sections (Sections 2 and 3). Set A focuses on the embodiment of an L2, in comparison to an L1. Therefore, Section 2, initially reviews what is currently known about the involvement of sensory, motor, and affective information in L2 processing, and then describes and discusses the first set of experiments. Set B focuses on the involvement of the two cerebral hemispheres in embodied language comprehension. Therefore, Section 3 initially reviews previous findings regarding the relative contribution of the two hemispheres to language comprehension in general, and to embodiment effects in particular, and then describes and discusses the second set of experiments. However, before these two sections can be discussed in detail, a general introduction section is provided, in which I present the main assumptions underlying theories of embodied language processing as well as evidence supporting them; and discuss the influence of life-experience and language proficiency on embodied language comprehension.

1.1. Embodied cognition and language comprehension

Embodied theories of language processing assume that language is understood by mentally simulating the described situation (Barsalou, 1999; 2008; Bergen, 2015; Zwaan, 2004; Zwaan & Madden, 2005). That is, the same sensory, motor, and affective representations that are activated in response to real objects and events, are also activated in response to verbally described objects and events. Although these theories may take a strong form assuming that conceptual processing is completely dependent on sensorimotor mechanisms (e.g., Gallese & Lakoff, 2005), or a weak form assuming only partial dependence (e.g., Meteyard, Cuadrado, Bahrami & Vigliocco, 2012), they all predict the activation of sensorimotor representations during the comprehension of words, sentences, and discourse units.

For example, the dual coding theory (Paivio, 1990; 2010; 2014), postulates that concepts (e.g., dog) are represented in two functionally independent but interconnected systems – a verbal system that represents concepts using linguistic symbols (e.g., the word "dog"); and a non-verbal system that represents concepts using mental imagery (e.g., the image of a dog). Both verbal and non-verbal representations come in different modalities (e.g., the visual and auditory form of the word "dog" in the verbal system; and the image and the sound of a dog in the non-verbal system) and can be activated separately or together, depending on task demands. However, while verbal codes are arbitrary symbols (i.e., different languages use distinct words to label the same referent), non-verbal codes are analogous to the objects and events that they denote and are therefore intrinsically meaningful. Importantly, intra-system associative connections allow associative processing of meaning by internal spreading of activation within each system, and inter-systems referential connections allow the verbal and the non-verbal systems to process information together.

During language comprehension, these referential connections permit verbal representations (e.g., the visual form of the word "dog") to activate non-verbal representations (e.g., the image of a dog) to establish meaning.

The language and situated simulation theory (Barsalou et al., 2008) holds a similar view. Accordingly, the representation and processing of concepts rely on both linguistic forms, stored in the brain’s language system, and on situated simulations, generated in the brain’s modal systems. It is assumed that during perception, action, and introspection, the brain captures modal states, and then later attempts to reactivate and simulate these real-life states to represent concepts during comprehension. Importantly, it is also assumed that experiential knowledge about things is simulated in the context of relevant situations, resulting in the construction of situated simulations. Thus, during language comprehension, linguistic forms and situated simulations interact in varying mixtures to produce meaning. For example, the word “bird” activates other words, which co-occur with “bird” in natural language, within the linguistic system. In addition, it evokes sensorimotor simulation, which consist of experiential knowledge about birds, in the simulation system. Finally, this theory postulates that while linguistic-based comprehension is relatively shallow, because it relies on superficial processing strategies (i.e., word association) that can be sufficient only for some tasks, situated simulations result in deep conceptual processing that forms the bases for high-level comprehension processes such as the generation of predictions and inferences.

Along similar lines, Zwaan (2004) have proposed that words and grammar serve as a set of cues that activate and combine experiential traces in the mental simulation of the described objects and events. Zwaan and Madden (2005) have further emphasized that language comprehenders construct rich and detailed simulations that also include implied, extrinsic, and less-typical features that change as a function of the described situation.

For example, Stanfield and Zwaan (2001) demonstrated that during sentence comprehension readers activate the specific spatial orientation (e.g., vertical or horizontal) of described objects (e.g., pencil), even when this information is not explicitly stated, but merely implied by their location in the described situation (e.g., drawer or cup). They showed that when readers comprehended the sentence “John puts the pencil in the drawer”, they simulated a horizontally oriented pencil. However, on comprehending the sentence “John puts the pencil in the cup” they simulated a vertically oriented pencil.

Similarly, De Koning, Wassenburg, Bos, and Van der Schoot (2017a) demonstrated that readers simulate the sentence-implied size of objects. They showed that while the sentence “The man got the present out of his pocket” evokes a visual simulation of a small present, the sentence “The man got the present out of his trunk” evokes a visual simulation of a big present. These findings suggest that implied perceptual features, which are determined by the verbally described situation, are activated and integrated into the simulation.

Indeed, according to the embodied view, simulation-based meaning representations are flexible and dynamic, rather than fixed, because they are comprised of distributed modality-specific features (Kiefer & Pulvermuller, 2012; Martin, 2007). These features can become more or less active depending on contextual constrains, such as the described situation, the individual experience of language comprehenders, and the task’s goal (Connell & Lynott, 2014; Hoenig, Sim, Bochev, Herrnberger & Kiefer, 2008; Lebois, Wilson-Mendenhall & Barsalou, 2015; Yee & Thompson-Schill, 2016; Zwaan & Madden, 2005).

Thus, as mentioned above, when a specific context is given (e.g., "the pencil is in the deawer"), the simulation is highly specific (e.g., a horizontally oriented pencil). Moreover, comprehenders may construct a specific simulation early in a sentence and modify it when additional information is integrated. For example, when readers comprehend sentences in which the specific shape of the mentioned object (e.g., egg) is implied initially by its location (e.g., refrigirator) and then by the final verb (e.g., dropped), they update the visual shape representaion of the object (e.g., whole egg vs. broken egg) as a function of the unfolding context (Sato, Schafer & Bergen, 2013). Yet, in cases of under specification or in the absence of linguistic context, as in the processing of isolated words, it is assumed that the nature of conceptual representation is mostly determined by default expectations, which are shaped by experiential, cultural, and environmental circumstances (Zwaan & Madden, 2005). For example, Lachmair, Dudschig, De Filippis, De la Vega and Kaup (2011) showed that words presented without context automatically activate their typical spatial location (e.g., the word “roof” activate the upper part of the visual field which is the spatial location typically associated with this entity). In addition, Willems, Hagoort and Casasanto (2010) observed that the long-term body experience of right- and left-handers in performing manual actions, results in distinct patterns of brain activation (i.e., left vs. right pre-motor cortex, respectively) during the processing of manual action verbs (e.g., throw), demonstrating experience-based neural differences in conceptual representation.

In sum, embodied accounts argue that conceptual representation is directly related to sensory, motor, and affective experiences, and that the representation of a concept in a certain linguistic context, by a specific individual, within a particular task, results in a distinct mental simulation that consists of merely the relevant and available multimodal features associated with the concept. Therefore, under different conditions, the same concept is expected to be represented differently.

1.2. Evidence for multimodal simulations during language comprehension

As detailed below, an extensive body of evidence supports an embodied view of language comprehension. First, numerous findings from neuroimaging studies indicate that language processing is accompanied by the activation of modality-specific brain regions (e.g., Pulvermüller, 2013; Willems & Casasanto, 2011). These studies have demonstrated that the same cortical areas which are crucial for online processing of specific sensory (e.g., González, Barros-Loscertales, Pulvermüller, Meseguer, Sanjuán, Belloch & Ávila, 2006; Simmons, Ramjee, Beauchamp, McRae, Martin & Barsalou, 2007; Kiefer, Sim, Herrnberger, Grothe & Hoenig, 2008), motor (e.g., Hauk, Johnsrude & Pulvermüller, 2004; Tettamanti, Buccino, Saccuman, Gallese, Danna, Scifo, Fazio, Rizzolatti, Cappa & Perani, 2005) and affective (e.g., Citron, 2012) information, are also active during language comprehension. For example, Hauk et al. (2004) showed that the comprehension of action-related words (e.g., lick, pick, kick) activated cortical motor regions that are also involved in the execution of these same actions. Likewise, González et al. (2006) showed that reading odor-related words (e.g., cinnamon) activated the primary olfactory cortex involved in odor processing.

Second, evidence from behavioral studies further indicate that language users mentally simulate perceptual (e.g., Brunyé, Ditman, Mahoney, Walters & Taylor, 2010; Rey, Riou, Vallet & Versace, 2017), action-related (e.g., Glenberg & Kaschak, 2002; Scorolli & Borghi, 2007), and emotion-related (e.g., Havas, Glenberg & Rinck, 2007) features of the linguistic content. For instance, Brunyé et al. (2010) demonstrated that the implied auditory characteristics of sentences are simulated during reading. They found that readers were faster to correctly categorize a sound as ‘real’ (i.e., occurring in the world) rather than ‘fake’ (i.e., computer generated), when the sound (e.g., a truck engine) had been implied by a preceding sentence (e.g., “The engine clattered as the truck driver warmed up his rig”).

In addition, Scorolli and Borghi (2007) showed that motor information regarding the specific body-effector involved in performing the described action is activated during sentence reading. They found that readers responded faster on a sensibility judgment task (i.e., whether or not a sentence make sense), when motor responses were made by the same effector (e.g., leg) implied by the sentence (e.g., “to kick the ball”), relative to an incongruent condition, in which the effectors were different. Along similar lines, Glenberg and Kaschak

(2002) showed that language comprehenders activate motor information regarding the specific motion direction of the action implied by the sentence. They found that readers responded faster on a sensibility judgment task, when the movement direction of the required motor response (e.g., moving the hand away from the body) matched the one implied by the sentence (e.g., “close the drawer”), rather than mismatched (e.g., “open the drawer”).

In particular, a significant number of studies have demonstrated effects of visual simulations during language comprehension. These studies have shown that language comprehenders spontaneously activate information regarding various visual features of described objects and scenes, such as distance (e.g., Morrow & Clark, 1988; Winter & Bergen, 2012), orientation (e.g., Stanfield & Zwaan, 2001; Wassenburg & Zwaan, 2010), motion direction (e.g., Zwaan, Madden, Yaxley & Aveyard, 2004; Kaschak, Madden, Therriault, Yaxley, Aveyard, Blanchard & Zwaan, 2005; Meteyard, Bahrami & Vigliocco, 2007), size (e.g., De Koning et al., 2017a), color (e.g., Mannaert, Dijkstra & Zwaan, 2017; Simmons et al., 2007), shape (e.g., Zwaan, Stanfield & Yaxley, 2002), and spatial location (e.g., Zwaan & Yaxley, 2003a). The current study focused on the latter two visual features. Thus, next I present the existing findings regarding the activation of perceptual visual simulations of shape and spatial location during the comprehension of words and sentences.

1.2.1. *Visual simulations of shape*

Numerous findings indicate that language users simulate the visual shape of verbally described objects (e.g., Flores d'Arcais, Schreuder & Glazenborg, 1985; Kellenbach, Wijers & Mulder, 2000; Lam, Dijkstra & Rueschemeyer, 2015; Pecher, Zeelenberg & Raaijmakers, 1998; Schreuder, d'Arcais & Glazenborg, 1984; Solomon & Barsalou, 2001; Zwaan et al., 2002). For instance, in an event related potentials (ERP) study, Kellenbach et al. (2000) demonstrated perceptual priming effects for prime-target word pairs that their referents share a similar shape (e.g., pizza-coin). These researchers observed that the amplitude of the N400 component, considered to reflect semantic processing, was significantly attenuated in response to target words (e.g., coin) that were processed immediately after a shape-related prime word (e.g., pizza), indicating that visual shape features are accessed during lexical semantic processing.

Furthermore, Solomon and Barsalou (2001) demonstrated that the specific form of physical properties denoted by concreate nouns (e.g., mane), is accessed during lexical processing. They used a property verification task (i.e., whether or not a property is a physical part of a larger entity), with one word denoting a concrete concept (e.g., horse) and another word denoting a physical property (e.g., mane). It was found that verifying a property on a target-trial (e.g., pony-mane) was faster after verifying a similar property with the same form in another concept (e.g., horse-mane), than after verifying a similar property with a different form in another concept (e.g., lion-mane). These findings suggest that the perceptual visual representation of property-concepts is influenced by the context of the larger entity in which they appear, and that the visual context determines the activation of specific form features of the concept during lexical processing.

Finally, using a sentence picture verification task, several studies have shown that understanding the meaning of a word in a sentence involves the activation of contextually relevant visual shape information (e.g., Madden & Zwaan, 2006; Zwaan et al, 2002; Zwaan & Pecher, 2012). For instance, in Zwaan et al. (2002) participants read sentences describing objects in particular locations (e.g., “The ranger saw the eagle in the sky” vs. “The ranger saw the eagle in the nest”). Importantly, the shape of the object (e.g., eagle) changed as a function of its described location (e.g., sky vs. nest), but was not explicitly mentioned in the sentence. For example, the sentence “The ranger saw the eagle in the sky” implies an eagle with its wings stretched out, whereas the sentence “The ranger saw the eagle in the nest” implies an eagle with folded wings. To investigate whether comprehenders spontaneously activate such subtle perceptual details, after each sentence, participants were asked to decide whether or not a depicted object (e.g., a picture of an eagle) was mentioned in the preceding sentence (e.g., “The ranger saw the eagle in the nest”). In all critical trials, the pictured object was indeed mentioned in the sentence, however, its shape could have either matched or mismatched the shape implied by the sentence. Thus, in the match condition, the sentence “The ranger saw the eagle in the nest” was paired with a picture of an eagle with folded wings, whereas in the mismatch condition the same sentence was paired with a picture of an eagle with its wings stretched out.

Zwaan et al. (2002) assumed that sentence comprehension involves the construction of a mental simulation, in which specific and context-based visual shape representations are activated and integrated. These were expected to facilitate the visual processing of the subsequent picture in the match, relative to the mismatch condition. Indeed, they found that responses to pictures were faster when the shape of the pictured object matched the shape implied by the sentence, suggesting that implied information about objects’ shape is spontaneously activated during sentence comprehension.

This visual shape effect has been replicated and extended in numerous studies (e.g., Coppens, Gootjes & Zwaan, 2012; De Koning, Wassenburg, Bos & van der Schoot, 2017b; Engelen, Bouwmeester, De Bruin, & Zwaan, 2011; Hirschfeld, Zwitserlood, & Dobel, 2011; Kaup , Yaxley, Madden, Zwaan, & Lüdtke, 2007; Madden & Zwaan, 2006; Pecher, van Dantzig, Zwaan & Zeelenberg, 2009; Peleg, Ozer, Norma & Segal, 2018; Sato et al., 2013; Zwaan & Pecher, 2012). For example, the shape effect (i.e., faster responses in the match than in the mismatch condition) was also demonstrated when participants were asked to name the object in the picture, a task that does not require linking the picture to the sentence, suggesting that visual shape simulations are automatically constructed during sentence processing, regardless of task requirements (Zwaan et al., 2002; Madden & Zwaan, 2006). Moreover, in a magnetoencephalography (MEG) study, Hirschfeld et al. (2011) demonstrated that the shape effect occurs as early as 120 ms after picture presentation and affects brain activity in occipital areas responsible for early visual processing.

In addition, Pecher et al. (2009) showed that the performance in a recall task (i.e., whether or not a pictured object had been mentioned in one of the sentences presented in a previous study phase) was better in the match, compared to the mismatch condition, both immediately after reading the complete list of sentences, and after a 45 minutes delay, indicating that details of perceptual simulations are retained over longer periods. Coppens et al. (2010) further showed that sentence processing was affected by the shape condition of a pictured object presented 15 minutes before reading.

Taken together, these findings indicate that readers spontaneously activate and maintain visual shape representations of verbally described objects even when this information is not explicitly stated, but merely implied by the described situation.

1.2.2. *Visual simulations of spatial location*

Other evidence indicates that language comprehension involves the activation of visual information about the spatial location of described objects (Bergen, Lindsay, Matlock & Narayanan, 2007; Dudschig, Souman, Lachmair, De la Vega & Kaup, 2013; Estes, Verges, & Barsalou, 2008; Estes, Verges & Adelman, 2015; Louwerse, 2008; Ostarek & Vigliocco, 2017; Richardson, Spivey, Barsalou & McRae, 2003; Spivey & Geng, 2001; Zwaan & Yaxley, 2003a). For example, Dudschig et al. (2013) used a lexical decision task on visually presented words referring to entities with a typical spatial location (i.e., up vs. down; e.g., sun vs. worm). In that task, participants had to respond by moving their eyes to a target (i.e., word/non-word) that was located either in an upper or lower screen position. They found that eye movments were faster when the visual target (i.e., word) was located in a screen position (e.g., upper or lower) compatible with the typical spatial location of the word's referent in the real world, indicating that during word reading visual spatial properties of mentioned entities are spontaniously activated, even if the words do not explicitly convey spatial information in their meaning.

Furthermore, it was demonstrated that words (Estes et al., 2008) and sentences (Bergern et al., 2007) denoting objects that are typically seen high in the visual field (e.g., "head"; "The ceiling cracked") hindered the visual identification of targets (i.e., a letter; a geometric shape) appearing at the top of the display, whereas words and sentences denoting objects that are typically seen in the lower visual field (e.g., "foot"; "The cellar flooded") hindered the visual identification of targets presented at the bottom of the screen. These findings indicate that reading words and sentences that denote objects activates visual simulations of the typical spatial location associated with each object.

In particular, using a semantic judgment task on concrete word-pairs, Zwaan and Yaxley (2003a) showed that readers activate perceptual visual knowledge about the typical spatial relations of referred object-pairs during lexical processing. They presented semantically related word-pairs, which their referents consist of typical vertical relations (e.g., flame-candle). Critically, the two words were displayed one above the other on the screen, however, their visual spatial arrangement could have either matched (e.g., the word "flame" was presented above the word "candle") or mismatched (e.g., the word "candle" was presented above the word "flame") the typical spatial relation of their referents. In each trial, participants were asked to decide whether or not the two words were semantically related.

It was assumed that because parts of objects (e.g., elbow) are typically not seen in isolation, their meaning representation is derived from the physical context in which they are usually seen (e.g., an elbow is part of an arm, which is part of the human body). Therefore, the visual spatial positions of the two referents relative to each other or to a larger entity, were predicted to be part of the activated conceptual representations during lexical processing. Thus, semantic judgments were expected to be facilitated when the words were presented consistently with the positions of their referents.

Indeed, Zwaan and Yaxley (2003a) found that responses on the semantic judgment task were significantly faster when the location of the words on the screen matched, rather than mismatched, the typical spatial locations of their referents (i.e. when the word "flame" was presented above the word "candle"; for similar results see Louwerse, 2008). Notably, this visual spatial effect disappeared when the words were presented horizontally, ruling out that the effect was caused by the order in which the words were read. These findings further suggest that comprehenders activate visual spatial information during lexical processing, even when this information is neither explicitly mentioned, nor necessary to perform the task (Zwaan & Madden, 2005).

Importantly, all the above-mentioned studies focused on L1 processing. Given that most people know more than one language (e.g., Grosjean, 2010), it is important to examine how embodied theories can be extended to non-native L2 processing. Therefore, the current study investigated the extent to which L2 comprehension involves the activation of perceptual visual representations. In particular, this study used the sentence picture verification task (Zwaan et al. 2002) and the semantic judgment task (Zwaan & Yaxley, 2003a), described above, to investigate whether L2 comprehension involves visual simulations of shape and spatial location. Next, I present findings concerning the influence of life-experience and language proficiency on embodied language processing in the context of L1 comprehension and discuss their potential consequences on the processing of an L2 in terms of embodiment.

1.3. The influence of experience and proficiency on the embodiment of language

Hebbian learning theories, which describe changes in the neuronal level resulting from learning processes, postulate that the co-occurrence of two neural processes connects them over time (Hebb, 1949; Wennekers, Garagnani, & Pulvermüller, 2006). Accordingly, theories of embodied language processing assume that neural networks associated with language processing and those associated with the processing of real-life experiences become strongly linked over time, because they are frequently activated together during language acquisition and use (Pulvermüller, 1999; 2013; Zwaan & Madden, 2005).

Therefore, it is likely to assume that the existence and strength of the links between language networks and sensorimotor networks may depend on the extent to which language users simultaneously activate linguistic and sensorimotor representations as well as on the nature and scope of their language and sensorimotor experiences. Thus, it could be that if individuals have not had the opportunity to acquire a certain level of linguistic or sensorimotor skills, these links may be weak or may not exist, and language processing may be less embodied (e.g., Peleg et al., 2018).

Consistent with this assumption, several studies have demonstrated that the accumulating life experience of an individual, reflected for example in one's age (Dijkstra, Yaxley, Madden, & Zwaan, 2004; Madden & Dijkstra, 2010) or in one's sensorimotor experiences and skills (Beilock, Lyons, Mattarella-Micke, Nusbaum & Small, 2008; Holt & Beilock, 2006; Hoenig, Müller, Herrnberger, Sim, Spitzer, Ehret & Kiefer, 2011; Willems et al., 2010), modulate the activation of embodied representations during L1 processing. For instance, it was found that older language users exhibited larger shape effects in the sentence picture verification task, relative to younger language users (Dijkstra et al., 2004; Madden & Dijkstra, 2010), suggesting that older adults construct stronger and richer mental simulations than younger adults, assumingly due to their greater experience both in life and in language use.

Further findings suggest that activating perceptual visual representations during sentence reading depends on the specific motor experience in interacting with the objects and performing the actions described by language. For example, using the sentence picture verification task, Holt and Beilock (2006) showed that the shape effect for sentences describing sport-specific scenarios (e.g., "The trainer saw the offensive *lineman* protect the ball"; "The fan saw the *hockey net* after the player slid into it") was evident only in expert athletes of the specific sport (i.e., football vs. ice-hockey), indicating that only expert sport players, as opposed to novice players, activated embodied visual representations of sport-specific objects and body-positions that they read about.

In addition, Beilock et al. (2008) further showed that sport-related motor experience enhanced action-related language understanding by recruiting a spesific motor-related cortex region, normally devoted to higher-level action selection and implementation, even when readers had no intention to perform a real action. In a similar vein, Hoenig et al. (2011) showed that only in professional musicians, auditory-related cortex regions were activated to a greater extent during the conceptual processing of visually presented musical instruments, relative to other non-musical objects, suggesting that the links between visual and auditory features of musical concepts are stronger among those who have repeatedly experienced both type of information simultaneously.

Two other studies have examined whether developing reading skills modulate the activation of perceptual and motor knowledge during L1 processing, yielding inconsistent findings. Engelen et al. (2011) used the sentence picture verification task and found the same shape and orientation effects among children of different ages (7-13), both after listening to sentences and after reading them aloud. Importantly, the effect size did not increase as a function of age, suggesting that both novice and proficient readers (i.e., younger and older children, respectively) construct perceptual simulations of described objects during sentence comprehension, even when reading is effortful.

In contrast, Dekker, Mareschal, Johnson, and Sereno (2014) found that in highly proficient readers (i.e., adults), the same category-specific cortical regions for animals and tools were engaged during the processing of both pictures and written words, suggesting that sensorimotor representations for these categories were activated during both perceptual visual processing and lexical processing. However, in less-proficient readers (i.e., children 7-10 years old) category-specific cortical regions were activated during the processing of pictures, but not during the processing of written words, even though all children could read and comprehend all presented words. Hence, the possibility that older children or adults form richer and stronger perceptual simulation than younger children, due to more advanced language skills and greater life experience, cannot be ruled out.

Under the assumption that language experience and proficiency may modulate embodied language processing, because of weaker connectivity between perceptual and linguistic representations, the current study examined the nature of these connections in the L2, relative to the L1. It could be that less proficient language users, such as L2 readers, process words and sentences using mainly linguistic mechanisms that are not grounded in perception.

2. THE EMBODIMENT OF A SECOND LANGAUGE

2.1. Introduction

A critical question regarding the embodiment of an L2 concerns the way bilinguals represent the meaning of words in their L1 and their L2. Some models postulate that the bilingual mental lexicon consists of amodal conceptual representations, shared between the two languages (Kroll & Stewart, 1994). Accordingly, the conceptual representation of translation equivalent word-pairs in the L1 and the L2 is identical. Other models assume that the two languages have both shared and separate conceptual representations (De Groot, 1992; Dong, Gui, & MacWhinney, 2005), however, the nature of conceptual representations in these models remains unspecified.

Embodied models postulate that the bilingual mental lexicon consists of multimodal conceptual representations, which can be either shared between the two languages or exclusive to one language (Paivio & Desrochers, 1980; Pavlenko, 2009). For example, according to the bilingual dual coding theory (Paivio & Desrochers, 1980), concepts (e.g., dog) are represented in two separate systems, a non-verbal imagery system, comprised of modality-specific analogue representations (e.g., the visual image of a dog), and a verbal system, comprised of modality-specific linguistic representations (e.g., the visual form of the word "dog"). In the case of bilinguals, two separated but interconnected verbal systems, one for each language, are linked to a common imagery system. Crucially, in this view, the conceptual representation of translation equivalent word-pairs may differ, if the accumulated life experience during the use of the two languages is distinct. Thus, acquiring two languages in the same life-context would result in more shared conceptual representations in the non-verbal imagery system, whereas acquiring two languages in separate and distinct life-contexts (e.g., at different ages and/or in different countries and cultures) would result in some differences in the referential modal representation for L1 and L2 words.

Indeed, Jared, Poh, and Paivio (2013) have presented evidence supporting this claim. They employed a picture-naming task on late Chinese-English bilinguals that were born in China and had lived there for a minimum of 9 years before immigrating to Canada – their place of living at the time of testing. It was found that in these bilinguals, which have acquired and used their L1 and L2 in different cultural circumstances, culturally biased images (e.g., Chinese mailbox vs. Canadian mailbox) were named significantly faster in the culturally congruent language (i.e., Mandarin vs. English), than in the incongruent language.

These findings suggest that balanced bilinguals, immersed in the L2 culture, activate language-specific lexical representations as a function of the visual features of the perceived object. Thus, the lexical representations of translation equivalent word-pairs in the two languages were triggered by different perceptual images, due to different visual experiences associated with processing the word in each language.

Importantly, Jared et al. (2013) demonstrated that linguistic representations of both languages are linked to perceptual visual knowledge (which may be distinct for each language), by testing highly proficient late bilinguals living in their L2 country, who had the opportunity to establish embodied conceptual representations in both their L1 and their L2. However, it is possible that other types of bilinguals may exhibit less embodied conceptual processing in their L2, relative to their L1, or may not even process their L2 in an embodied manner. This possibility is assumed to occur especially among bilinguals who have not had the opportunity to experience their L2 in an immersive environment, such as those who have lived their entire lives in the L1 country. To test this assumption, the present study examined non-balanced late Hebrew-English bilinguals who have acquired their L2 in the L1 country (i.e., Israel) after the age 6.

Thus, experience-based differences in the acquisition and use of the L1 and the L2 in late bilinguals, may lead, in some cases, to qualitative differences in the specific embodied representations evoked by each language (Jared et al., 2013). Yet, in other cases, for example, when the L2 is learned and used mostly in formal settings (i.e., language courses; conferences, lectures, etc.) outside of the environment where it is commonly spoken (i.e., in the L1 country), these experience-based differences between the two languages of bilinguals, may cause quantitative differences in the degree to which each language is embodied (e.g., Vukovic & Shtyrov, 2014).

Naturally, babies, infants and children learn the meaning of linguistic structures, such as words, phrases, and sentences in their L1, while they use their body and interact with their environment. As a result, the conceptual representations evoked by their L1 are shaped by their physical experiences, which shift as a function of developmental motor changes (e.g., learning to sit and stand; for a review see Pexman, 2019). Growing up, they keep using their native language and experiencing the world simultaneously and constantly, establishing strong connections between language units and real-life experiences. Therefore, as reviewed above, L1 users routinely simulate physical features of the linguistic content during language comprehension, by activating the relevant perceptual, motor, and affective knowledge they have accumulated over their lifespan, about the objects and scenes described by language.

Conversely, late bilinguals, living in their native-tongue environment, usually acquire their L2 in a less natural and embodied setting, in which they often use translation to establish meaning, and then use their L2 in a relatively narrow and limited life-context. Thus, the learning and use of their L2 may be less associated with real-world experiences, in comparison to their L1. Therefore, it is possible that the L2 of these bilinguals may be less embodied, relative to their L1, or may not even evoke embodied simulations.

Such a presumable 'disembodiment' of an L2 may explain the foreign language effect found in a variety of decision-making tasks (e.g., Costa, Foucart, Arnon, Aparici & Apesteguia, 2014; Costa, Foucart, Hayakawa, Aparici, Apesteguia, Heafner & Keysar, 2014; Costa, Vives & Corey, 2017; Geipel, Hadjichristidis & Surian, 2015; Hayakawa & Keysar, 2018; Keysar, Hayakawa & An, 2012). Accordingly, people’s preferences, choices, and judgments are affected by whether information is presented in the L1 or the L2. For example, Keysar et al. (2012) demonstrated that the framing effect, according to which people’s decision-making is influenced by the positive or negative semantic framing of the described possible options, disappears when choices are presented in a foreign language. They found that while L1 users were risk averse for verbally described gains (e.g., preferring to save the lives of 200 out of 600 people for sure, than to take a chance of saving all of them or none; positive framing) and risk seeking for losses (e.g., preferring to take a chance of saving all 600 lives or none, than to lose the lives of 400 out of 600 people for sure; negative framing), L2 users were not influenced by this framing manipulation, suggesting that using a foreign language reduces decision-making biases due to its emotional disembodiment.

In the same vain, Hayakawa and Keysar (2018) have observed that L2 users reported less vivid imagery of sensory experiences (e.g., sight) while reading in their L2, relative to L1 users. They have further demonstrated that muted visual imagery in the L2 reduced accuracy when judging shape-similarity of imagined objects presented by L2 words (e.g., carrot-pen vs. carrot-mushroom). Finally, they showed that L2 users, as opposed to L1 users, are more likely to endorse the utilitarian action (e.g., to kill 1 person in order to save 5 lives) in a verbally described moral dilemma, assumingly because they are not able to visualize the situation clearly in their minds, as in a native language.

Taken together, these differences in decision-making patterns as a function of the nativeness of language may point to a reduced ability of language users to mentally simulate multimodal aspects of verbally described situations in an L2 (Keysar, et al., 2012; Pavlenko, 2012). Thus, there are good reasons to assume that the embodiment of the L2 in late bilinguals, living in the L1 environment, is limited, in comparison to their L1.

So far, a relatively limited number of studies have examined embodiment effects in the L2 (for reviews see Adams, 2016; Kühne & Gianelli, 2019; Monaco et al., 2019), and these have focused mainly on motor and emotion simulations. While some of these studies have suggested that modality-specific (i.e., motor and affective) embodied representations are similarly activated during both L1 and L2 processing (Buccino, Marino, Bulgarelli & Mezzadri, 2017; De Grauwe, Willems, Rueschemeyer, Lemhöfer, & Schriefers, 2014; Dudschig, De la Vega, & Kaup, 2014; Eilola, Havelka, & Sharma, 2007), others have proposed that the embodiment of an L2 is somewhat constrained in comparison to an L1 (Baumeister, Foroni, Conrad, Rumiati & Winkielman, 2017; Bergen, Lau, Narayan, Stojanovic & Wheeler, 2010; Conrad, Recio, & Jacobs , 2011; Eilola & Havelka, 2011; Ferré, Anglada-Tort & Guasch, 2018; Foroni, 2015; Harris, Ayçíçeğí, & Gleason, 2003; Hsu, Jacobs, & Conrad, 2015; Opitz & Degner, 2012; Segalowitz, Trofimovich, Gatbonton & Sokolovskaya, 2008; Sheikh & Titone, 2016; Vukovic & Shtyrov, 2014).

For example, De Grauwe et al. (2014) compared L1-Dutch users and late German-Dutch bilinguals, which were highly proficient L2 learners of Dutch, had lived in the L2 country for at least 1.5 years and used their L2 regularly, and showed similar embodied motor effects in both groups. Specifically, they found that during a visual lexical decision task on Dutch words, motor verbs referring to hand movement (e.g., throw), in comparison to non-motor verbs (e.g., hesitate), elicited greater levels of activation in motor-related brain regions, during both L1 and L2 processing. These results suggest that similar to L1 users, highly proficient L2 users immersed in the L2 environment evoke rich semantic representations that involve the activation of motor-related brain areas during word reading.

Dudschig et al. (2014) further demonstrated the same embodied motor effects in both the L1 and the L2 of un-immersed late bilinguals. They examined late German-English bilinguals that had started learning their L2-English in high school between the age of 11 and 13 and had never lived in an English-speaking country. Participants saw either L1 or L2 words referring to either entities with a typical spatial location (i.e., up or down; e.g., star or root) or to spatially associated emotions (i.e., positive-up or negative-down; e.g., happy or sad). On the reading of each target word, they had to respond to the words' ink color with an upward or downward arm movement. It was found that despite word meaning being fully task irrelevant, L2 words automatically activated motor responses similar to L1 words. In particular, they showed that spatially associated L2-English words (e.g., star, happy vs. root, sad) activated motor representations of a specific movement direction (e.g., up or down, respectively), leading to facilitation in the motor response required by the task, when it matched, rather than mismatched the spatial location implied by the L2 word, in the same way L1-German words did (Lachmair et al., 2011). These findings indicate that the reactivation of spatially associated motor knowledge during visual word processing, also occurs in the L2, even in un-immersed late L2 learners.

Eilola et al. (2007) tested unbalanced late Finnish-English bilinguals with proficient knowledge of English, in their L1-Finnish and L2-English. Participants saw both L1 and L2 words, in different lists, and had to report the ink color of each word as quickly and accurately as possible, while ignoring its meaning. Importantly, the critical words were either positive, neutral, negative, or taboo words. They found a significant main effect of word type and no significant interaction between word type and target language (i.e., L1, L2). Specifically, responses to negative and taboo words were significantly slower than responses to neutral words, irrespective of target language, indicating that the L1 and the L2 of unbalanced late bilinguals are equally capable of automatically activating emotion-related representations during lexical processing.

Conversaly, other studies have reported a limited (Bergen et al., 2010; Foroni, 2015; Hsu, Jacobs, & Conrad, 2015; Segalowitz et al., 2008), attenuated (Baumeister et al., 2017; Eilola & Havelka, 2011; Harris et al., 2003; Vukovic & Shtyrov, 2014), delyed (Conrad et al., 2011; Opitz & Degner, 2012), or different (Ferré et al., 2018; Sheikh & Titone, 2016) pattern of motor or emotional effects in the L2, relative to the L1. For instance, Hsu et al. (2015) examained proficient late German-English bilinguals in their two languages and found that reading short passages characterized by a positive emotional valence, led to stronger neural responses, relative to neutral passages. However, this emotional effect was restricted to L1 reading, suggesting that reading emotion-laden text in the L1 provides a stronger emotional experience than L2 reading and further supporting the calim that the L2 is emotionally dissembodied (e.g., Keysar, et al., 2012; Pavlenko, 2012).

Vukovic and Shtyrov (2014) also examined proficient late German-English bilinguals, who had started learning their L2-English as part of formal education in Germany, and reported weaker motor effects in the L2, relative to the L1, during passive reading of action words. Specifically, they compared the neural activity of participants in response to L1-German and L2-English verbs and demonstrated quantitative differences in motor-related brain activity between L1 and L2 processing, indicating that in proficient late bilinguals, the strength of motor activations is reduced in the L2, as compared to the L1.

Furthermore, findings presented by Bergen et al. (2010) suggest that motor simulations in the L2 are somewhat restricted, in comparison to the L1, since they may be modulated by language proficiency. They examined L1-English/L1-Cantonese users and relatively proficient L2-English users, which were enrolled in mainstream classes at an English-speaking university but varied in their L2 proficiency. Participants had to decide whether an image and a written verb depicted the same action or different actions. In critical trials, the actions were different, and the body part involved in the two actions (i.e., mouth, arm, leg) was either the same (e.g., a picture of a running man and the word “kick”) or different (e.g., a picture of a running man and the word “drink”). They found that both L1 and L2 users were slower to reject different-action trials, when the two actions involved the same effector, relative to the condition in which the effectors were different. Importantly, although motor representations of specific body-parts were activated while reading both L1 and L2 verbs, in the L2 users, L2 proficiency level correlated positively with the extent to which these modality-specific representations were activated.

Finally, Ferré et al. (2018) presented evidence, which suggests that the acquisition style of the L2 (i.e., early vs. late & immersive vs. formal, respectivaly) may also be a modulating factor of embodied L2 processing. They tested two groups of L2 users (1) highly proficient Catalan-Spanish bilinguals, who learned Spanish in early childhood within a bilingual immersion context and still lived in such a context at the time of testing; and (2) Catalan-Spanish-English trilinguals, who learned English after early childhood in an instructional setting and were proficient users of English. These researechers found that the emotional content of words (i.e. positive, negative, neutral) affected bilinguals’ performance in both groups. However, while a similar pattern of responses to positive, negative, and neutral words was found in both languages of early Catalan-Spanish bilinguals, distinct patterns were exhibited in the early learned language (i.e., Spanish) and in the late leraned language (i.e., English) of Catalan-Spanish-English trilinguals.

To the best of our knowledge, only four studies to date focused on visual simulations during L2 comprehension. Of these, two studies examined the activation of explicitly mentioned visual features of size, orientation, and distance (Koster, Cadierno, & Chiarandini, 2018; Vukovic & Williams, 2014), whereas the other two investigated the activation of implied visual shape (Ahn & Jiang, 2018; Chen, Wang, Zhang & Liu, 2020). These studies have presented conflicting results, either demonstrating activation of visual knowledge in both the L1 and the L2 (Ahn & Jiang, 2018; Koster et al., 2018; Vukovic & Williams, 2014), or showing visual effects only in the L1 (Chen et al., 2020). In addition, consistent with previous L1 studies (De Koning et al., 2017b; Zwaan & Pecher, 2012), the results of these studies suggest that different visual features may be simulated to different extents during language comprehension. It appears that while intrinsic visual properties such as size (Koster et al., 2018) and shape (Ahn & Jiang, 2018; Chen et al., 2020) are more strongly activated, the activation of extrinsic features such as spatial orientation is weaker (Koster et al., 2018).

For example, Koster et al. (2018) demonstrated a similar pattern of visual activations during sentence reading in L1 users and in L2 learners. They used the sentence picture verification task with sentences that explicitly indicated a visual property of the object, either size (e.g., "Anna puts the lipstick-big on the cutting board") or orientation (e.g., "Anna stands (vertically) the lipstick on the cutting board"). In the task, L1 users of Spanish and German and L2 learners of Spanish and German (i.e., beginner, intermediate, advanced) had to decide in each trial, whether or not a pictured object had been mentioned in the preceding sentence. On critical trials, the pictured object was indeed mentioned in the sentence, but its size/orientation could have either matched or mismatched the size/orientation stated in the sentence. They found that responses to target pictures were significantly faster on match trials, than on mismatch trials, but only for size sentences. Additionally, the interaction between trial type (i.e. match vs. mismatch) and language type (L1, L2 beginners, L2 intermediate, L2 advanced) was not significant. These results suggest that readers activate stated visual information during sentence comprehension, irrespective of language type and language proficiency, and that explicit visual information about the size of verbally described objects is more likely to be activated than explicit visual information regarding their spatial orientation.

More importantly, the two studies that examined the activation of the implied shape of mentioned objects during sentence reading presented conflicting findings (Ahn & Jiang, 2018; Chen et al., 2020). Both studies used the sentence picture verification task with sentences (e.g., "The ranger saw the eagle in the nest") that describe an object (e.g., eagle) in a specific location (e.g., nest), which implies its shape (e.g., an eagle with folded wings). On match trials, the shape of the pictured object matched the shape implied by the sentence (i.e., an eagle with folded wings), whereas on mismatch trials the shape of the pictured object was different (i.e., an eagle with its wings stretched out). Participants had to decide in each trial whether or not the pictured object had been mentioned in the preceding sentence.

On the one hand, Ahn and Jiang (2018) found that L2 comprehenders, like L1 comprehenders, simulate the specific shape of objects during sentence reading. In that study, the researchers presented Korean sentences and compared the performance of L1-Korean users and proficient late L2-Korean users. They found a significant main effect of trial type (match vs. mismatch) and no significant interaction between trial type and language group (i.e., L1-Korean users vs. L2-Korean users). Specifically, responses were faster on match, than on mismatch trials, in both language groups, suggesting that L1 and L2 comprehenders equally activate implied visual shape information about verbally described objects during sentence reading.

On the other hand, Chen et al. (2020) demonstrated that the L2 and the L3 of trilinguals (i.e., L1-Cantonese, L2-Mandarin, L3-English) are less associated with perceptual visual knowledge, in comparison to the L1. They used a delayed sentence picture verification task that consisted of two phases (Pecher et al., 2009). In the study phase, participants listened to L1, L2, and L3 sentences, presented in three separate and consecutive language blocks, and had to decide whether or not each sentence was meaningful. After a 10-min delay, in the test phase, participants saw pictures of objects and had to decide whether or not each object had been mentioned in one of the sentences from the previous study phase.

Their results demonstrated a significant interaction between shape condition (i.e., match vs. mismatch) and language type (i.e., L1 vs. L2 vs. L3). Thus, the shape effect (i.e., faster responses on match than on mismatch trials) was significant for L1 sentences but not for the L2 or L3 sentences, indicating that trilingual readers activated and maintained implied visual information about objects' shape only for L1 sentences. These results further suggest that while acquisition style (native learning in the L1-Cantonese vs. non-native formal learning in the L2-Mandarin and L3-English) had a significant impact on the exhibited shape effect, proficiency level in the non-native languages (high-proficiency in the L2-Mandarin vs. low-proficiency in the L3-English) had no influence on the effect.

In sum, a relatively small number of studies have investigated embodiment effects during L2 processing, and these have mainly focused on motor or emotion simulations. Thus, more research is needed, particularly with respect to perceptual visual simulations. Moreover, these previous studies have largely yielded inconsistent results. While some studies have shown that modality-specific simulations are similarly generated during L1 and L2 processing, other studies have demonstrated that the embodiment of the L2 is constrained in comparison to the L1.

These inconsistencies might be explained by variations across studies in (a) the L2 proficiency level of participants (Bergen et al., 2010); (b) the circumstances in which the L2 has been acquired and used across participants (i.e., early vs. late acquisition; natural/immersive vs. formal learning; Ferré et al., 2018); (c) the nature of the task (Lam et al., 2015; Lebois et al., 2015; Louwerse & Jeuniaux, 2010; Pecher et al., 1998; Yee, Ahmed & Thompson-Schill, 2012; Van Elk & Blanke, 2011); (d) the type of sensorimotor features that were examined (Koster et al., 2018); and (f) the way in which L1-L2 processing differences were examined (i.e., testing only L2 processing and comparing the findings to similar L1 studies; comparing L1 and L2 users of the same language; comparing L1 and L2 processing in the same bilinguals).

Thus, as detailed below, to further examine the extent to which L2 comprehension involves perceptual visual simulations, the current study evaluated embodied visual effects in the L2 while (a) controlling the possible influence of participants' L2 proficiency – testing a relatively homogeneous and highly proficient group of L2 users and considering subjective and objective proficiency measures in the statistical analyses; (b) focusing on late bilinguals with similar background of L2 acquisition and use – native Hebrew speakers who learned English in formal settings (i.e., school, university) in Israel and have lived there since birth; (c) utilizing two distinct tasks that involved different processing conditions – a sentence picture verification task (Zwaan et al. 2002) and a semantic judgment task (Zwaan & Yaxley, 2003a); (d) examining the activation of two distinct perceptual visual features – shape and spatial location; and (f) testing L1 and L2 processing in the same bilinguals, in order to compare the processing of the two languages in users with similar linguistic background.

2.2. Set A: Experiments 1 and 2

The first aim of the current study was to investigate whether under the circumstances of formal acquisition and use of an L2, proficient unbalanced late bilinguals construct perceptual simulations during word and sentence reading in their L2. Specifically, this study compared the ability of such bilinguals to activate implied visual properties (i.e., shape, spatial location) of verbally mentioned objects in both their L1 and their L2. It was predicted that, among these type of bilinguals, L2 processing will produce weaker visual simulations than L1 processing, assumingly because of the relatively formal fashion by which they have learned and used their L2.

To accomplish this aim, native Hebrew speakers (L1-Hebrew) that have lived their entire lives in the L1 environment (Israel), and learned their L2-English after the age 6 in a formal school setting, were asked to perform the same tasks in their L1-Hebrew and in their L2-English. The first task - the sentence picture verification task (Zwaan et al., 2002) – tested their ability to activate the implied visual shape of mentioned objects during sentence reading (Exp. 1). This task included both verbal and non-verbal perceptual stimuli (i.e., sentences and pictures); examined sentence-level processing; and provided readers adequate time to process and activate perceptual visual information during sentence reading[1]. The second task - the semantic judgment task (Zwaan & Yaxley, 2003a) – tested their ability to activate the typical spatial location of mentioned objects during word reading (Exp. 2). This task consisted of merely verbal stimuli (i.e., word-pairs); examined word-level processing; and constrained the processing time of written words.

Critically, in both tasks, the differences between L1 and L2 processing were evaluated by comparing the performance of Hebrew-English bilinguals in their L1-Hebrew (L1 block) and in their L2-English (L2 block). It was expected that words and sentences would produce stronger visual simulations of shape and spatial location in the L1 than in the L2.

2.2.1. *Experiment 1: Visual simulations of shape during sentences reading*

Exp. 1 examined whether visual shape features are simulated to the same extent during L1 and L2 sentence reading. To this end, the sentence picture verification task was used (Zwaan et al., 2002). In this task, participants were asked to read sentences (e.g., “The boy saw the balloon in the air”) and respond to target pictures. All sentences described an object (e.g., balloon) in a specific location (e.g., air) implying its shape (e.g., the shape of an inflated balloon). After each sentence, a picture of an object (e.g., balloon) was presented and participants had to decide whether or not the pictured object had been mentioned in the preceding sentence. On critical trials, the pictured object was indeed mentioned in the sentence. However, in the match condition its shape matched the shape implied by the sentence (e.g., a picture of an inflated balloon), whereas in the mismatch condition its shape was different (e.g., a picture of an inflated balloon).

Faster responses in the match, relative to the mismatch condition (i.e. the shape effect) are taken as evidence for the activation of visual shape properties during sentence reading (Zwaan & Madden, 2005). Therefore, if readers mentally simulate the described situation, and thus, strongly activate visual shape information during sentence comprehension, then they should exhibit a significant shape effect. Namely, their responses should be faster in the match relative to the mismatch condition. However, if readers rely mainly on linguistic mechanisms (i.e., do not simulate perceptual visual features during language comprehension), then their response latencies in the match and in the mismatch conditions should not differ.

[1] It was decided to lead off the investigation using the sentence picture verification task because it has consistently yielded robust visual shape effects in numerous previous L1 studies, including a recent study that has tested L1-Hebrew users (Peleg et al., 2018).

To test whether L2 sentence reading involves visual shape simulations, and if so, whether these simulations in the L2 are activated to the same extent as in the L1, proficient unbalanced late Hebrew-English bilinguals performed the task in their L1-Hebrew (L1 block) and in their L2-English (L2 block). Thus, differences between the two languages (L1 vs. L2) in the activation of implied shape information during sentence reading, were revealed by comparing the shape effect exhibited in the L1 block and in the L2 block.

The predictions were as follow: First, in line with previous L1 studies (e.g., Peleg et al., 2018, L1-Hebrew; Zwaan et al., 2002, L1-English), participants were expected to demonstrate a significant shape effect in the L1. Namely, L1 sentence reading was expected to substantially activate implied visual shape information. In addition, the L2 of this group of bilinguals was expected to produce weaker visual shape activations, relative to the L1, due to its formal manner of acquisition and use (e.g., Chen et al., 2020). Thus, the size of the shape effect was predicted to be smaller in the L2 block, relative to the L1 block.

2.2.1.1 Method

Participants

The participants were 80[2] students from Tel Aviv University (30 males; 50 females). Their age ranged between 18-30 (Mean=25; SD=2.51). All were unbalanced late Hebrew-English bilinguals – native Hebrew speakers living in Israel (their L1 environment)[3], who spoke only Hebrew until the age 6, learned English in a formal school setting in Israel for 8-12 years, and were highly proficient in their L2-English[4]. Participants were right-handed based on the Edinburgh Handedness Inventory (Oldfield, 1971), free of cognitive deficits, and with normal or corrected to normal vision. Most of them completed the experiments for payment, with some receiving course credits instead.

L2 Proficiency Measures

Participants completed a detailed language-history and self-rating questionnaire regarding their L2-English background, their English proficiency level (i.e., overall; reading; writing; comprehending spoken language; speaking) rated on a scale of 1 (very low

[2] The number of participants per experimental list (n=10) was determined based on previous L1 studies that used the same task (Zwaan et al., 2002; Lincoln et al., 2007).
[3] All participants had not lived in any English-speaking country over 6 months at the time of testing.
[4] All participnts had met the university entrance requirements in English, and scored at least 120/150 in the English section of the psychometric exam.

proficiency) to 7 (very high proficiency), and their average hours-per-week current use of English (i.e., overall; reading, writing; listening; speaking). The questionnaire was design based on Marian, Blumenfeld, and Kaushanskaya, (2007) and Lemhöfer and Broersma (2012).

To objectively evaluate lexical knowledge in the L2-English, participants performed an online lexical decision test for advanced learners of English called LexTALE (Lemhöfer & Broersma, 2012; www.lextale.com), in which the maximum score is 100. In addition, their English score on the psychometric exam, which could range between 120-150 according to our criterion for participants' selection, was collected. This exam tests the ability of L2-English users to complete sentences appropriately, to restate sentences, and to comprehend texts in English.

Importantly, to account for the possible effect of English proficiency in the statistical analyses, an English Proficiency Score was calculated for each participant, by averaging the Z-scores of the 12 proficiency measures that were collected. Hence, this measure of English proficiency represented various subjective and objective aspects of participants' L2 proficiency. See Table 1 for a summary of participants' proficiency measures in the L2-English.

<u>Materials</u>

The critical stimuli consisted of 56 pairs of pictures, 56 pairs of Hebrew sentences, and 56 pairs of English sentences, which were the exact translation of the Hebrew ones. Each pair of pictures presented the same object (e.g., balloon) in two different shapes (e.g., inflated vs. deflated). All sentences had the same structure: "The *person* saw the *object* in/on the *location*". Each sentence-pair described the same object in two different locations (e.g., air vs. package), implying two different object's shapes. For example, the sentence "The boy saw the balloon in the air" implies a shape of an inflated balloon, whereas the sentence "The boy saw the balloon in the package" implies a shape of a deflated balloon.

To create the two shape conditions (match/mismatch), each one of the sentences in each pair was matched with two pictures depicting the verbally described object in two different shapes. In the match condition, the shape of the pictured object matched the one implied by the sentence, whereas in the mismatch condition, the shape of the pictured object and the sentence-implied shape were different (see Table 2).

Table 1: Participants' proficiency measures in the L2-English in each experiment; Mean (SD)

Experiment Number Number of participants		**Exp. 1** n=80	**Exp. 2** n=40	**Exp. 3** n=160	**Exp. 4** n=80
English Proficiency Score mean Z-scores of the 12 proficiency measures		-0.00038 (.66)	0.00000 (.68)	-0.00019 (.62)	0.00038 (.69)
Lexical Test (LexTale) max score 100		73.00 (9.94)	70.33 (10.34)	69.36 (11.07)	70.70 (12.24)
Psychometric Exam max score 150		138.11 (8.35)	137.48 (8.69)	136.91 (8.57)	136.58 (8.33)
English Proficiency self-rating scale of 1-7	**Overall**	5.94 (0.74)	5.83 (0.83)	5.90 (0.93)	5.88 (0.81)
	Reading	6.03 (0.87)	5.98 (0.86)	6.05 (0.85)	6.05 (0.79)
	Writing	5.44 (1.07)	5.24 (1.13)	5.33 (1.12)	5.26 (1.13)
	Listening	6.13 (0.74)	6.15 (0.95)	6.35 (0.83)	6.20 (0.96)
	Speaking	5.63 (0.89)	5.60 (1.07)	5.78 (1.03)	5.65 (1.14)
Current Use of English self-estimate mean hours per-week	**Overall**	17.09 (21.49)	13.72 (13.82)	12.08 (10.54)	15.68 (21.36)
	Reading	9.96 (14.67)	6.28 (7.51)	4.78 (6.97)	8.01 (14.08)
	Writing	5.55 (12.39) *	2.17 (3.07)	1.84 (3.16)	2.53 (4.97)
	Listening	13.11 (18.17)	10.07 (10.54)	9.25 (7.50)	12.20 (15.75)
	Speaking	3.07 (9.18)	2.02 (5.67)	2.73 (8.19)	2.13 (8.22)

* Only the measure *current use of English in writing* in Exp. 1, significantly differ from all other experiments at the $p<.05$ level, based on a one-way ANOVA test with the Bonferroni corrections for multiple comparisons. All other measures did not significantly differ across experiments.

Thus, the critical stimuli were comprised of a list of 56 objects resulting in 112 pictures (56 picture-pairs of the same object in two different shapes), 112 Hebrew sentences (56 sentence-pairs describing the same object in two different locations and thus implying two different shapes), and 112 English sentences (the exact translation of the Hebrew ones).

To create the experimental lists, Target Language (L1-Hebrew/L2-English), Sentence Version (shape 1/shape 2) and Picture Version (shape 1/shape 2) were counterbalanced across 8 lists. To avoid repetition, each participant saw only one list of 56 critical objects. Each list was divided into two sub-lists, one for the L1-Hebrew block and one for the L2-English block. Each sub-list was comprised of 28 sentence-picture combinations, which included 14 combinations in the match condition and 14 combinations in the mismatch condition. Importantly, each participant saw each critical object only once.

To equate the number of “Yes” and “No” responses in each language block, additional filler items were created. These filler items consisted of 112 sentence-picture combinations, 56 in Hebrew and 56 in English. In each language, 14 combinations presented a picture of an object that was indeed mentioned in the sentence and thus required a "Yes" response and 42 combinations presented a picture of an object that was not mentioned in the sentence and thus required a “No” response. Notably, the 14 fillers, which required a “Yes” response, presented a picture of the described location, rather than the described object. For example, a picture of a table was presented after the sentence “The boy saw the laptop on the *table*”. This was done in order to prevent participants from merely paying attention to the main object in the sentence (e.g., laptop). These 56 filler items in each language were added to each critical sub-list (28), such that all final sub-lists (84) consisted of an equal number (42) of required “Yes” and “No” responses.

In sum, each sub-list (L1-Hebrew or L2-English) consisted of 84 items – 28 critical items presenting pictures of objects that were mentioned in the sentence, and 56 filler items, which included 14 items presenting pictures of objects that were mentioned in the sentence, and 42 items presenting pictures of objects that were not mentioned in the sentence. See Table 2 for examples of critical and filler items. See Appendix 2 for the full list of critical sentences and pictures.

Table 2: Examples of critical and filler items in the sentence picture verification task

Item Type; Condition	Sentence	Picture	Correct Response
Critical Item Shape Match Version 1	The boy saw the balloon in the air		Yes
Critical Item Shape Mismatch Version 1	The boy saw the balloon in the air		Yes
Critical Item Shape Match Version 2	The boy saw the balloon in the package		Yes
Critical Item Shape Mismatch Version 2	The boy saw the balloon in the package		Yes
Filler Item Related Location Picture	The boy saw the laptop on the table		Yes
Filler Item Unrelated Object Picture	The boy saw the butter in the fridge		No

Pre-tests: (1) To ensure that students would be likely to understand the meaning of the critical English sentences, 20 students that did not participated in the main experiments translated all English sentences to Hebrew. Only sentences that received correct translation scores of at least 80% were included in the main experiments. (2) To ensure that all critical pictures truly activate their target word, another 20 students named the designated pictures. Only objects that both of their pictures elicited the required naming by at least 80% of the students were included in the main experiments. (3) To ensure that the critical sentences actually imply the intended object's shape, all sentence-pairs describing the same object were divided to form two lists of sentences. Each list consisted of only one sentence for each object. Sentences in each list were presented along with both the shape-matching and the shape-mismatching picture. Another 40 students (20 per-list) were asked to choose the picture that best fit each sentence (following Connell, 2007). Only objects, which both of their sentences had the picture from the match condition chosen by at least 80% of the students, were used in the main experiments. Thus, out of an initial list of 82 objects, only 56 objects met the above requirements and were included in the main experiments.

Notably, the experimental stimuli were designed to nullify the influence of potential differences between the two pictures of each object other than their visual shape, by using two sentence versions for each object and presenting each one of the two pictures in both the match and the mismatch conditions (See Table 2). In this design, an exhibited difference between the match and the mismatch shape conditions, for a specific object, will be comprised of an equal number of responses to both pictures of the same objects. Nonetheless, in two additional pretests, all picture-pairs of the final 56 objects were further examined to trace existing differences between the two pictures in the ease of visual object recognition, in the degree of familiarity with the pictured object, and in the degree of canonicality/typicality of each picture.

For this purpose, the 56 critical picture-pairs were divided into two lists of 56 pictures. Each list consisted of only one picture of each object. First, another 40 students (20 per-list) were asked to rate (1) how easy it is to visually recognize the object in each picture, on a scale of 1 (very difficult to recognize) to 5 (very easy to recognize); and (2) the familiarity of each pictured object on a scale of 1 (very unfamiliar) to 5 (very familiar). Familiarity was defined as "the degree to which you come in contact with or think about the object in the picture" (Alario & Ferrand, 1999, p. 533).

For each object, the differences in visual identification ratings as well as in familiarity ratings between the two pictures were examined using a paired-sample t-test. In 13 out of the 56 objects there was a significant difference in visual identification ratings between the two pictures ($p<0.05$; toilet-paper, avocado, pineapple, corn, carrot, cigarette, mango, lemon, green-pepper, melon, chicken, onion, balloon), and in 5 out of the 56 objects there was a significant difference in familiarity ratings between the two pictures ($p<0.05$; wine-bottle, potato, onion, toilet-paper, lemon). Nevertheless, because of the limited number of possible stimuli, it was decided to use these objects in the main experiments, knowing that the experiment and stimuli were designed to control for these possible differences between the two pictures.

Second, to determine whether object recognition, in both pictures of the same object, was affected by the canonicality/typicality or view specificity of the two pictures, another 40 students (20 per-list) performed a word-picture matching task, in which they decided as quickly and accurately as possible in each trial, whether or not a picture, presented after a written word, matched the word meaning. All critical pictures were presented after their object's name and thus required a "Yes" response. To equate the number of "Yes" and "No" responses in both lists, an additional 56 filler pictures were presented after unrelated object names. Response latencies and errors were collected in all trials (following Connell, 2007). A paired-sample t-test revealed that overall, there was no significant difference in speed performance between the two lists of pictures ($p=0.221$). However, in 16 out of the 56 objects, a significant difference between the two pictures was found ($p<0.05$; balloon, cigarette, banana, toilet-paper, potato, carrot, jeans, sleeping-bag, tent, avocado, leaf, train, wine-bottle, cat, swimmer, ice-cream).

Yet, as mentioned above, the possible influence of these differences between the two pictures on the shape effect was controlled, since both the match and the mismatch conditions for each object included the two pictures (see Table 2). Furthermore, if the shape effect would be demonstrated despite the existing differences between the two pictures of the same object, it will strengthen the assumption that readers simulate the specific visual details of verbally described objects, irrespective of their ease of visual recognition, familiarity, or canonicality. Moreover, it will indicate that the visual simulation of a specific object during sentence comprehension is modulated primarily by the sentence context, and not by fixed or typical characteristics of the object.

Post-tests: To ensure that participants in the main experiments knew the exact meaning of the critical English sentences, at the end of the experimental session, they translated to Hebrew all the critical sentences that were presented in the L2-English experiment. English trials that consisted of sentences that were not correctly translated were removed from the statistical analyses.

Design

Since the current study aimed to examine L1 and L2 processing within the same bilinguals, a within-subject design was adopted. Thus, all participants performed the task in both their L1-Hebrew and their L2-English, in the same experimental session but in two separate blocks (i.e., L1 block; L2 block). To control for the possible effect of the order of the language blocks on task performance (i.e., L1 after L2 or L2 after L1), the language blocks' order was counterbalanced across participants, such that half performed the L1-Hebrew block first and the L2-English block second, and half performed the L2-English block first and the

L1-Hebrew block second. Thus, a 2x2 factorial design was used with Shape Condition (match/mismatch) and Target Language (L1-Hebrew/L2-English) as within-subject independent variables.

Procedure

The study was approved by the ethical committee of Tel-Aviv University (see Appendix 1), and all the participants (in all the experiments) signed an informed consent form before the research session.

Session: Testing was conducted in a single session. Participants were tested individually in a sound-attenuated room, seated in front of a computer screen with a screen-eye distance of 57 cm, so that 1 cm on the screen corresponded to 1° of visual angle. To ensure the above distance, participants' head position was controlled using a chin-rest.

Participants performed the task in their L1-Hebrew and in their L2-English in two consecutive blocks, separated by a 2-minutes brake, within the same experimental session. Each participant saw only one experimental list, in which two different sub-lists of objects were presented in the L1 block and in the L2 block. Within each language block, stimuli were presented in a random order. The block order (i.e., L1-Hebrew block then L2-English block/L2-English block then L1-Hebrew block) and the experimental lists were counterbalanced across participants.

Each experimental session took approximately 30 minutes and consisted of 6 parts, which were administered in a fixed order: (1) Performing the handedness assessment, using the computerized version (Zhang, 2014) of the Edinburgh Inventory (Oldfield, 1971); (2) Filling out the L2-history and self-rating questionnaire; (3) Performing the task in one language (L1-Hebrew block or L2-English block); (4) Performing the task in the other language (L2-English block or L1-Hebrew block); (5) Translating the experimental stimuli in the L2-English sub-list to Hebrew; (6) Performing the online English version of the lexical decision test (LexTALE; Lemhöfer & Broersma, 2012; http://lextale.com/takethetest.html).

Block: At the beginning of each language block, participants were instructed to decide as quickly and accurately as possible in each trial, whether or not the object depicted in the picture was mentioned in the preceding sentence. They were further instructed to respond with their right index finger by pressing the "Yes" or "No" buttons in the response box, which was placed on the table in front of them in a vertical manner, such that the "Yes" button was located closer to the screen and the "No" button was located closer to the participant. This was done in order to prevent participants from responding horizontally by pressing right and left buttons, since Exp. 3 examined hemispheric functioning and could have been affected by this manner of response.

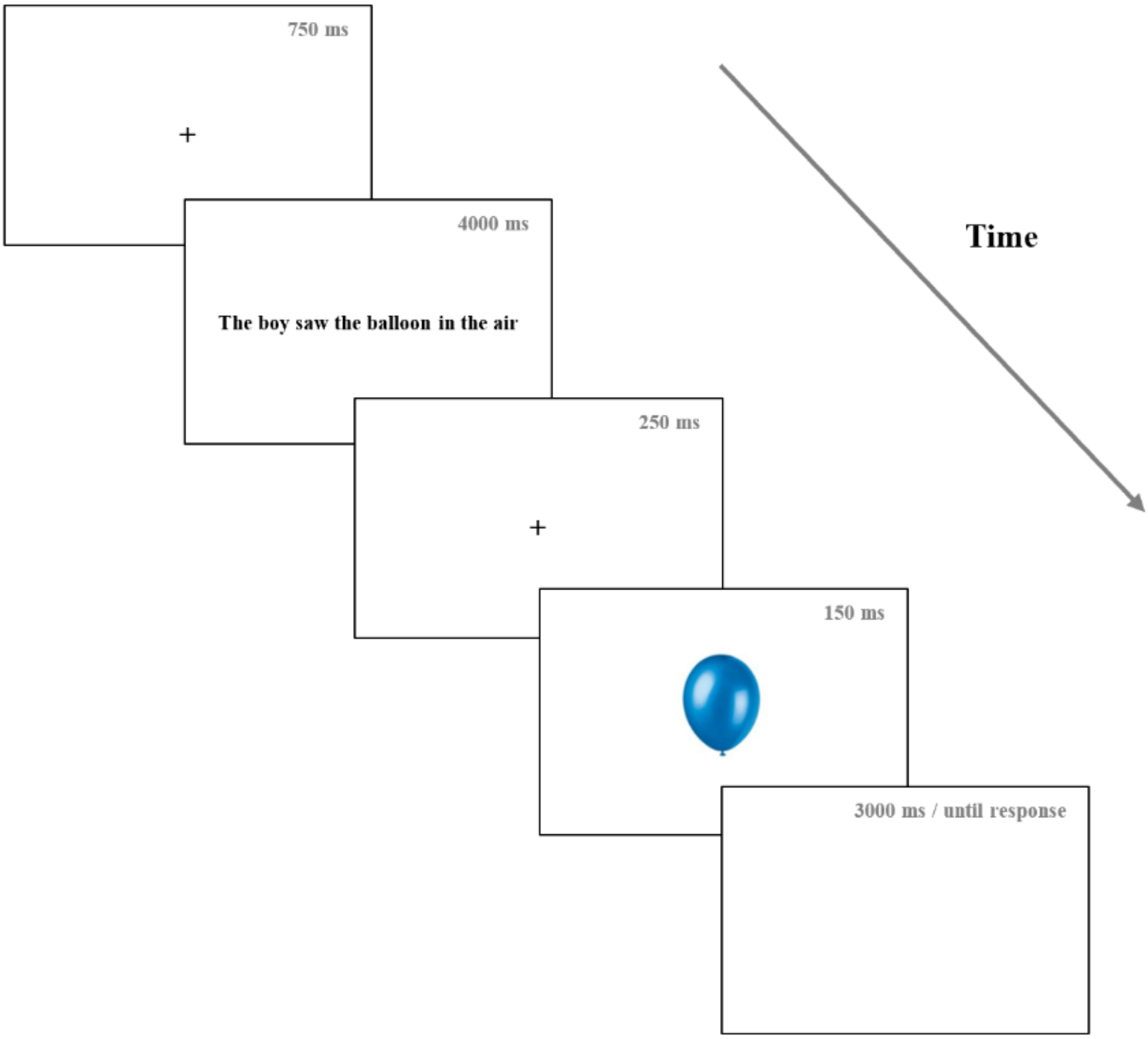
Initially, participants read the instructions and were introduced to 4 examples of sentence-picture matching decisions. Instructions were presented in Hebrew and the examples were presented, either in Hebrew prior to the L1 block or in English prior to the L2 block. Before each language block, participants performed a short practice, which consisted of 6 sentence-picture combinations, either in the L1-Hebrew or in the L2-English, half requiring a “Yes” response and half requiring a “No” response. During practice trials, participants received visual feedback for correct and incorrect responses.

Following Lincoln, Long, and Baynes (2007), all trials consisted of the same sequence of events. At the start of each trial, participants were presented with a central fixation cross for 750 ms. The offset of the marker was followed by a centrally presented sentence. The sentence was presented for 4000 ms, allowing adequate processing time in both languages. Then, a central fixation cross appeared for 250 ms, followed by a centrally presented picture that remained on the screen for 150 ms. Then, a white screen was presented until a response was made or until 3000 ms. In each trial, the response latency was measured from the onset of the picture presentation, and the response accuracy was recorded. See Figure 1 for an example of the sequences of events in each trial.

Stimuli presentation: Sentences were presented centrally on the screen in black letters on a white background, in either a Hebrew Times New Romans font size 28, or an English Time New Roman font size 30. The font’s height in both languages was 0.5 cm. Pictures were fitted to occupy a square in the size of 6x6 cm (217x217 pixels) surrounded by a 1 cm white frame and were displayed on a gray background. The total size of the framed pictures was 8x8 cm (289x289 pixels). Unframed pictures subtended a maximum of 6° of vertical and horizontal visual angle, at a viewing distance of 57 cm. Target pictures were presented at the center of the screen.

Apparatus: The experiments were programmed and run using the E-prime software (version 10.242, Psychology Software Tools, Pittsburgh, PA) on an HP Compaq Elite 8300 Micro-tower desktop computer. Stimuli were presented using a 24-inch BenQ ZOWIE XL2430 monitor sized 531.36X298.89 mm (1920X1080 pixels). Response time (RT) data and error data for each response were collected using a PST serial response box.

Figure 1: The sequence of events in each trial in Exp. 1



2.2.1.2. <u>Results</u>

<u>Data analysis protocol</u>

RT data and error data were analyzed using linear mixed effects (LME) models (Baayen, Davidson, & Bates, 2008), as implemented within the 'lme4' library in the R-Statistics software (version 3.5.2, R Core Team, 2018). The 'glmer' function for Binomial distribution was used for the error data and the 'lmer' function for Gaussian distribution was used for the RT data. These functions allow the testing of hypotheses while considering simultaneously the variance due to the random selection of participants and items.

The major hypothesis of Exp. 1 relates to the difference in the shape effect (i.e., faster responses in the match relative to the mismatch condition) between the 'L1-Hebrew' and the‘L2-English’. Therefore, the analyses focused on the main effects of the independent variables – Shape Condition (match/mismatch) and Target Language (L1-Hebrew/L2-English) and on the interaction between them. In addition, since each experimental session consisted of two blocks - one for each language (L1-Herbew & L2-English), the possibility that responses were influenced by the order of the blocks (L1 after L2 vs. L2 after L1) was also considered in the analyses. Furthermore, the likelihood that responses were affected by variations between participants in English proficiency was considered as well. Thus, the effects of the independent variables of primary interest (i.e., Shape Condition; Target Language) and the interaction between them, were examined while considering the possible effects of the independent variables Experimental Block (first-block/second-block) and English Proficiency Score.

To this end, three LME models were fitted to the RT data and to the error data. Model 1 included the fixed main effects of Shape Condition and Target Language, the interaction between them, and the random effects of Participants and Items. Model 2 included the fixed main effects of Shape Condition, Target Language, and Experimental Block, the interactions between them, and the random effects of Participants and Items. Model 3 included the fixed main effects of Shape Condition, Target Language, Experimental Block, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items.

To test whether one model provides a significantly improved fit for the data than the other two, these three models were compared using the ‘anova’ function in R, which computes an analysis of variance (ANOVA) for fitted linear models. The model, which best fitted the RT data or the error data, was selected for further analysis. Furthermore, to evaluate the significance of the main-effects and interactions within the selected model, a type-II ANOVA with Wald Chi-square test was computed, using the ‘Anova’ function in R. Finally, examinations of planned comparisons were performed using the Chi-Square test with the Bonferroni adjustment within the ‘testInteractions’ fuction in R.

Data Cleanup

The entire dataset, a total of 13440 trials (4480 critical trials and 8960 filler trials), was inspected in terms of accuracy rates per-participant as well as per-item, vocabulary knowledge of critical L2-items per-participant, and RT outliers.

First, accuracy rates were examined for each participant and item in each language. Participants or items that had a mean accuracy rate lower than 60%, in either the Hebrew or the English task, were excluded from analyses. None of the participants or items in Exp. 1 was rejected based on this criterion.

Next, 35 English trials that were incorrectly translated in the English-Hebrew translation post-test were removed, 31 trials with RT greater than 3000 ms or lower than 200 ms were removed, and 122 trials that fell outside the range of acceptable latencies (i.e., +/− 3.5 SD from participant's mean RT) were removed. This trimming procedure accounted for a total loss of 188 trials (1.4%). Finally, filler trials were excluded from the data.

RT Data

For the RT analyses, additional 104 critical trials (2.4%) were removed due to incorrect responses, and the final RT dataset consisted of correct critical trials only. Thus, 4281 data points (2169 in L1-Hebrew and 2112 in L2-English) that 80 participants produced by responding to 56 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 2 fitted the RT data significantly better than Model 1 ($\chi^2(4)=105.43$, $p<.001$) and that Model 3 did not fit the data significantly better than Model 2 ($\chi^2(8)=4.68$, $p=.79$). Therefore, Model 2, which included the fixed main effects of Shape Condition, Target Language, and Experimental Block, the interactions between them, and the random effects of Participants and Items, was selected for further analysis. Mean correct RTs (in ms) by Shape Condition, Target Language, and Experimental Block, are presented in Table 3.

Within Model 2, the main effect of Shape Condition was significant ($\chi^2(1)=13.80$, $p<.001$), indicating that overall responses to 'match' trials (Mean=596.29, SD=189.51) were faster than responses to 'mismatch' trials (Mean=612.18, SD=195.95). In addition, the main effect of Experimental Block was significant ($\chi^2(1)=99.04$, $p<.001$), indicating that overall responses to 'first-block' trials (Mean=626.72, SD=202.47) were slower than responses to 'second-block' trials (Mean=581.64, SD=180.01).

Table 3: Mean correct RTs (in ms) by Shape Condition, Target Language, and Experimental Block in Exp. 1

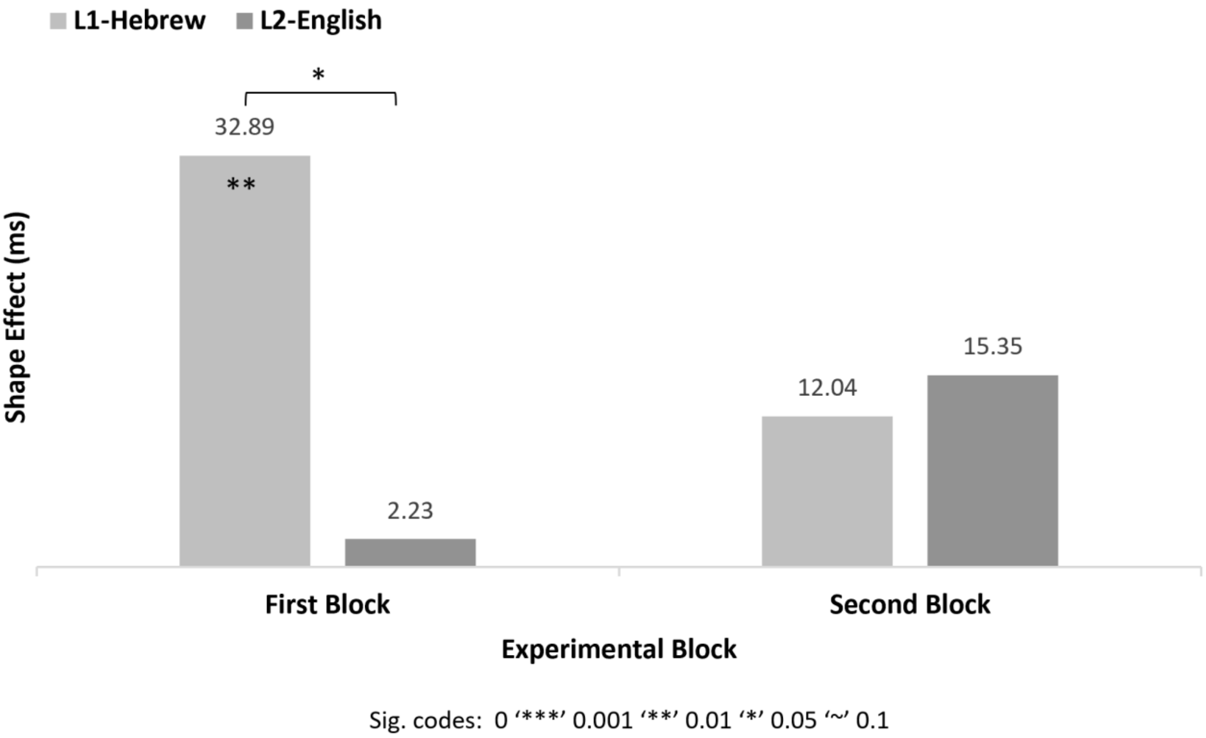
ExpBlock	Language	ShapeCond	RT.mean	RT.sd	Effect
First	He	match	589.9945	186.0328	
First	He	mismatch	622.8843	205.5411	32.89
First	En	match	646.2143	208.2675	
First	En	mismatch	648.4401	204.5469	2.23
Second	He	match	602.1618	181.2158	
Second	He	mismatch	614.2048	189.6082	12.04
Second	En	match	546.3226	167.3313	
Second	En	mismatch	561.6744	172.1550	15.35

Furthermore, the two-way interaction between Experimental Block and Target Language was marginally significant ($\chi^2(1)=3.04$, $p=.08$). Examination of the effect of Experimental Block separately for each Target Language revealed that while in the 'L1-Hebrew' the RT-difference between 'first-block' trials (Mean=606.35, SD=196.57) and 'second-block' trials (Mean=608.20, SD=185.48) was not significant ($\chi^2(1)=.01$, $p=1.00$), in the 'L2-English', the effect of Experimental Block was significant ($\chi^2(1)=11.25$, $p<.01$), such that 'first-block' trials (Mean=647.33, SD=206.32) were significantly slower than 'second-block' trials (Mean=553.94, SD=169.83). Thus, the influence of Experimental Block on speed performance was significantly evident only on 'L2-English' trials.

More importantly, the three-way interaction between Shape Condition, Target Language, and Experimental Block was significant ($\chi^2(1)=4.45$, $p<.05$), indicating that Experimental Block modulated the interaction between Shape Condition and Target Language. Thus, the two-way interaction between Shape Condition and Target Language was analyzed separately in each Experimental Block. This analysis revealed that this interaction was significant only in the 'first-block' ($\chi^2(1)=6.12$, $p<.05$), but not in the 'second-block' ($\chi^2(1)=.27$, $p=1.00$).

Further examination of the effect of Shape Condition in each Target Language within 'first-block' trials revealed that, while in the 'L1-Hebrew', the shape effect was reliable ($\chi^2(1)=13.11$, $p<.01$), such that 'match' trials (Mean=589.99, SD=186.03) were significantly faster than 'mismatch' trials (Mean=622.88, SD=205.54), in the 'L2-English', the RT-difference between 'match' trials (Mean=646.21, SD=208.27) and 'mismatch' trials (Mean=648.44, SD=204.55) was not significant ($\chi^2(1)=.02$, $p=1.00$), indicating that the influence of Shape Condition on speed performance was significantly evident only on 'L1-Hebrew' trials. The shape effect (in ms) by Target Language and Experimental Block, is illustrated in Figure 2.

Figure 2: The shape effect (in ms) by Target Language and Experimental Block in Exp. 1



<u>Error Data</u>

The final error dataset consisted of critical trials only. Thus, 4385 data points (2225 in L1-Hebrew and 2160 in L2-English) that 80 participants produced by responding to 56 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 3 fitted the error data significantly better than Models 1 and 2 ($\chi^2(8)=17.26$, $p<.05$). Therefore, Model 3, which included the fixed main effects of Shape Condition, Target Language, Experimental Block, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items, was selected for further analysis.

Within Model 3, only the interaction between English Proficiency Score and Experimental Block was significant ($\chi^2(1)=9.13$, $p<.01$). To further examine this interaction the effect of Experimental Block was examined separately for participants with ‘high-score’ (i.e., half of the participants that had the highest scores) and ‘low-score’ (i.e., the other half of the participants that had the lowest scores) of English proficiency[5]. This examination revealed that while participants with ‘high-score’ had lower error rate on ‘first-block’ trials (Mean=.01, SD=.11) than on ‘second-block’ trials (Mean=.02, SD=.15), participants with ‘low-score’ had higher error rate on ‘first-block’ trials (Mean=.04, SD=.18) than on ‘second-block’ trials (Mean=.03, SD=.16). Yet, the error-difference between ‘first-block’ and ‘second-block’ trials was not significant, neither for participants with ‘high-score’ ($\chi^2(1)=.05$, $p=1.00$) nor for participants with ‘low-score’ ($\chi^2(1)=1.73$, $p=.38$), indicating that the influence of Experimental Block on accuracy performance was relatively weak, irrespective of participants’ English Proficiency Score. As can be seen, the accuracy measure in Exp. 1 was not sensitive to the shape effect, possibly due to a ceiling effect, in both the L1 experiment (mean accuracy=.97, SD=.16) and the L2 experiment (mean accuracy=.96, SD=.21).

2.2.1.3 <u>Discussion</u>

The results of Exp. 1 revealed a significant shape effect, in the RT data, only in the ‘L1-Hebrew’, and only when participants performed the L1 block before the L2 block (i.e., only on L1-Hebrew first-block trials).

These results demonstrate a substantial L1-L2 difference in the extent to which implied visual shape information is activated during sentence reading, such that perceptual visual activations are weaker in the L2 relative to the L1. Interestingly, the results further show cross-language influences on the degree to which sentence comprehension in the L1 and in the L2 involves perceptual visual simulations. In what follows I discuss these two findings in more details.

First, the significant shape effect that was obtained in the L1 is in line with previous L1 studies (e.g., Peleg et al., 2018, L1-Hebrew; Zwaan et al., 2002, L1-English), which have consistently demonstrated a significant RT-facilitation in the sentence picture verification task when the shape of the pictured object matched, rather than mismatched, the sentence-implied shape (i.e., the shape effect). More importantly, the fact that a significant shape effect

[5] The continuous, quantitative variable English Proficiency Score was transformed into the categorical variable English Proficiency Group, which consisted of two levels – ‘high-score’ (half of the participants that had the highest proficiency scores) and ‘low-score’ (the other half of the participants that had the lowest proficiency scores).

was found only in the L1 (on first-block trials), and not in the L2, of proficient unbalanced late bilinguals that have acquired and used their L2 primarily in formal settings, supports our initial prediction that, among these type of bilinguals, the mental representation resulting from sentence comprehension in the L2 is less grounded in sensorimotor knowledge, relative to the L1.

These findings can be interpreted within the framework of the language and situated simulation theory (Barsalou et al., 2008). This theory postulates a distinction between linguistic-based comprehension processes ,which are assumed to result in a relatively shallow conceptual encoding, and simulation-based processes, which are assumed to result in deeper conceptual encoding that forms the bases for the generation of predictions and inferences during comprehension. In principle, the sentence picture verification task can be performed by both systems – the linguistic system and the simulation system. However, the shape effect is expected only when (visual) simulation processes are involved. The results of Exp. 1 suggest that simulation processes characterize L1 but not L2 comprehension. That is, while L1 comprehension involves substantial simulation-based processes, L2 comprehension relies mainly on linguistic representations. Accordingly, L1-L2 differences in comprehension abilities may be expected in this type of bilinguals because they seem to engage different comprehension processes in their L1 and in their L2.

As mentioned above, two previous studies that utilized a similar paradigm have yielded different results. On the one hand, Chen et al. (2020) found a significant interaction between Shape Condition and Target Language, in which the shape effect was significant only in the L1, but not in the L2 nor in the L3, of late trilinguals. On the other hand, Ahn and Jiang (2018), observed a significant shape effect during both L1 and L2 sentence reading. Notably, the significant modulation of the shape effect by the target language, which was observed in the present study, is consistent with Chen et al.'s (2020) findings, but not with the findings of Ahn and Jiang (2018). This inconsistency between the current study (as well as Chen et al., 2020) and Ahn and Jiang (2018), regarding L1-L2 differences in the exhibited shape effect, may be explained by differences between these studies in (1) the experimental design, and specifically in the manipulation of the language variable; and in (2) the linguistic background of participants.

First, in Ahn and Jiang (2018) study, the language variable (L1 vs. L2) was manipulated by testing two different groups of language users (L1 vs. L2 users of Korean). Thus, the difference between L1 and L2 processing was examined in participants with different cultural and linguistic backgrounds. Additionally, in the L2-Korean group, participants varied in their L1s. However, in the current study (as well as in Chen et al., 2020) the language variable (L1 vs. L2) was manipulated by examining the same bilinguals in their two languages (L1-Hebrew vs. L2-English). Thus, the difference between L1 and L2 processing was examined in participants with the exact same cultural and linguistic background. Critically, these differences may cause the distinct pattern of results that was observed in Ahn and Jiang (2018).

Moreover, participants in the L2 group in Ahn and Jiang (2018) had lived in Korea (i.e., L2 environment) for a period of up to six years. However, in the present study, most of the participants (n=77) had not lived in any English-speaking country (i.e., L2 environment), and the few that did (n=3), had stayed there only for a period of up to six months. Likewise, the trilingual participants in Chen et al., (2020) had lived in their L1 environment (i.e., Cantonese) and had learned and used their L2 (i.e., Mandarin) and L3 (i.e., English) primarily in formal school settings. Therefore, it is possible that the late bilinguals in Ahn and Jiang (2018) had more immersive L2 experience that resulted in simulation-driven sentence comprehension, whereas the lack of an immersive L2 background among late bilinguals in the current study (as well as in Chen et al., 2020) resulted in sentence comprehension processes that relied mainly on linguistic mechanisms and did not involve visual simulations. Clearly, more studies comparing different types of bilinguals are needed in order to reach stronger conclusions in this regard.

The second finding of this experiment is that the order of block presentation (i.e., the Experimental Block variable: L1 block presented before L2 block vs. L2 block presented before L1 block) modulated the shape effect in both languages, but in opposite directions. Thus, in the L1-Hebrew, the shape effect was smaller on ‘second-block’ trials relative to ‘first-block’ trials, whereas in the L2-English, the shape effect was larger on ‘second-block’ trials relative to ‘first-block’ trials (See Figure 2). This pattern of results indicates that L1/L2 sentence processing in the ‘first-block’ affected L2/L1 sentence processing in the ‘second-block’. That is, in the L1, visual shape simulations in the ‘second-block’ were reduced, relative to the ‘first-block’, due to the immediate recent experience with L2 sentence reading, in which comprehension relies heavily on linguistic mechanisms. However, in the L2, visual shape simulations in the ‘second-block’ were magnified, relative to the ‘first-block’, due to the immediate recent experience with L1 sentence reading, in which comprehension involves simulating the described situation.

Crucially, when only ‘first-block’ trials were analyzed, in which task performance could not have been affected by cross-language influences, a significant interaction between

Shape Condition and Target Language was observed, such that, in the L1, the shape effect was highly significant, whereas in the L2, the match and mismatch conditions hardly differed. However, when only ‘second-block’ trials were analyzed, the interaction between Shape Condition and Target Language was not evident and the shape effect was not reliable in both languages, probably because the recent exposure to the task in the other language eliminated L1-L2 differences in the shape effect.

These finding are in line with previous studies, which have also observed an effect of recent experience in the L1/L2 on task performance in the other language (Ben-Dror, Bentin, & Frost, 1995; Degani, Kreiner, Ataria, & Khateeb, 2020; Kreiner & Degani, 2015). For example, Ben-Dror et al. (1995) demonstrated that, among Hebrew-English bilinguals, the pattern of phonological awareness during auditory word processing in the L1-Hebrew, was significantly affected by whether they recently experienced word processing in their L2-English. In this study, participants were tested in both their L1 and L2, in two separate and consecutive lists. After each word, they were asked to delete the first "sound" of the word and say as fast as possible what is left of the word after this omission. The two language lists presented monosyllabic words, which consisted of a consonant, then a vowel, and then a final consonant (i.e., CVC structure).

Importantly, it was found that the order of list presentation significantly affected participants’ performance. Specifically, on first-list trials, participants responded differently to Hebrew and English words. In Hebrew, participants tended to omit the first two phonemes of words (e.g., בת /bat/ = /t/), assumingly because in Hebrew writing, vowels are usually not marked by letters, and thus, omitting the first letter of a word results in the omission of both the first consonant and the vowel that follows it. Alternatively, in English, participants tended to omit only the first phoneme of words (e.g., but /bat/ => /at/), assumingly because in English writing, vowels are always marked by letters, and thus, omitting the first letter of a word results in the omission only of its first consonant.

Interestingly, on second-list trials, the recent exposure to the task in English changed the pattern of performance in Hebrew. Namely, performing the L1-Hebrew list, after the L2-English list, resulted in omitting only the first consonant of Hebrew words. These results suggest that when the same task is performed in both the L1 and the L2 successively, the specific processing patterns usually employed in each language, may become more similar to the processing pattern of the other language, as was also demonstrated in the current study.

Along the same lines, Degani et al. (2020) found that Arabic-Hebrew bilinguals were less accurate and produced more L2-L1 cross-language errors during a picture naming task in their L1-Arabic, following an immediate brief exposure to their L2-Hebrew (i.e., reading a list of Hebrew words aloud). Likewise, Kreiner and Degani (2015) found that the TOT (tip-of-the-tongue) rates of Russian-Hebrew bilinguals during a picture naming task in their L2-Hebrew, increased following an immediate brief exposure to their L1-Russian (i.e., watching a Russian movie).

To conclude, the results of Exp. 1 clearly indicate that visual shape simulations are reduced in an L2, at least in the case of proficient unbalanced late bilinguals that have acquired and used their L2 primarily in formal settings. These results are consistent with previous studies, showing reduced and limited activations of modality-specific knowledge during L2 reading, in comparison to L1 reading (e.g., Chen et al., 2019; Hsu et al., 2015; Vukovic & Shtyrov, 2014); and may be explained by the formal and un-immersive nature of L2 acquisition and use, which is usually less related to real-life experiences.

2.2.2. *Experiment 2: Visual simulations of spatial location during word reading*

Exp. 2 examined whether visual features of spatial location are simulated to the same extent during word reading in the L1 and in the L2. To this end, the semantic judgment task was used (Zwaan & Yaxley, 2003a). In this task, participants were asked to decide whether or not two words, presented one above the other on a computer screen, are semantically related. All critical word-pairs denoted concrete nouns with strong semantic relation, and thus required a “Yes” response. Importantly, their referents consisted of a typical spatial-vertical relation (e.g., car-road). These word-pairs were presented in either a match or a mismatch spatial condition. In the match condition, the spatial arrangement of the two words on the screen matched the typical spatial relation of their referents (e.g., “car” was displayed above “road”). In the mismatch condition, the spatial arrangement of the two words did not match the typical spatial relation of their referents (e.g., “road” was displayed above “car”).

Faster responses in the match, relative to the mismatch condition (i.e. the spatial effect), are taken as evidence for the activation of visual spatial properties during word reading (Zwaan & Madden, 2005). Therefore, if readers mentally simulate the described situation and thus strongly activate visual spatial information during lexical processing, then they should exhibit a significant spatial effect. Namely, their responses should be faster in the match relative to the mismatch condition. However, if readers rely mainly on linguistic mechanisms (i.e., do not simulate visual features during language comprehension), then their response latencies in the match and in the mismatch conditions should not differ.

To test whether L2 word reading involves visual spatial simulations, and if so, whether these simulations in the L2 are activated to the same extent as in the L1, proficient unbalanced late Hebrew-English bilinguals performed the task in their L1-Hebrew (L1 block) and in their L2-English (L2 block). Thus, differences between the two languages (L1 vs. L2) in the activation of implied spatial information during word reading, were revealed by comparing the spatial effect exhibited in the L1 and in the L2.

The predictions were as follow. In line with previous L1 studies (e.g., Zwaan & Yaxley, 2003a, L1-English), participants were expected to demonstrate a significant spatial effect in the L1. Namely, L1 word reading was expected to substantially activate visual spatial information regarding objects' typical location. In addition, the L2 of this group of bilinguals was expected to produce weaker visual spatial activations, relative to the L1, due to its formal manner of acquisition and use (e.g., Chen et al., 2020). Thus, the size of the spatial effect was predicted to be smaller in the L2 relative to the L1.

2.2.2.1. Method

Participants

The participants were 40[6] students from Tel Aviv University (17 males; 23 females). Their age ranged between 19-32 (Mean=25; SD=2.4). Participants' characteristics were the same as in Exp. 1.

L2 Proficiency Measures

The L2 proficiency measures that were collected were the same as in Exp. 1. See Table 1 for a summary of participants' proficiency measures in the L2-English.

Materials

The critical stimuli consisted of 56 concrete word-pairs in Hebrew, and 56 word-pairs in English, which were the exact translation of the Hebrew ones. These word-pairs were all semantically related and thus required a "Yes" response in the semantic judgment task. Importantly, all word-pairs denoted common objects or parts of objects that are typically viewed in a fixed vertical orientation (e.g., car-road). To create the two spatial conditions

[6] The number of participants per experimental list (n=10) was determined based on previous L1 studies that used the same task (Zwaan & Yaxley, 2003a; 2003b) and on the number of critical items that were used in the current study.

(match/mismatch), each word-pair was displayed on the screen in two visual spatial arrangements. In the match condition, the spatial presentation of the two words matched the typical spatial relation of their referent, whereas in the mismatch condition, the spatial presentation of the two words was inverse to the typical spatial position of their referents.

To create the experimental lists, Target Language (L1-Hebrew/L2-English) and Spatial Condition (match/mismatch) were counterbalanced across 4 lists. To avoid repetition, each participant saw only one experimental list of 56 critical word-pairs. Each list was divided into two sub-lists, one for the L1-Hebrew block and one for the L2-English block. Each sub-list consisted of 28 critical word-pairs, 14 pairs in the match condition and 14 pairs in the mismatch condition. Importantly, each participant saw each critical word-pair only once.

To equate the number of "Yes" and "No" responses in each language block, additional filler items were created. These filler items consisted of 112 word-pairs, 56 in Hebrew and 56 in English. Like the critical items, all word-pairs in the filler items denoted concreate nouns. Importantly, in contrast to the critical items, the referents of the word-pairs in the filler items had no typical spatial relation. In each language, 14 fillers were semantically related pairs (e.g., pizza-pasta) and thus required a "Yes" responses, and 42 fillers were semantically unrelated pairs (e.g., coat-avocado) and thus required a "No" response. Notably, the semantically related fillers were added to further dim the distinction between critical and filler word-pairs and thus, to prevent participants from linking "Yes" responses to critical word-pairs and "No" response to filler word-pairs. The 56 filler items in each language were added to each sub-list of 28 critical word-pairs, such that all final sub-lists consisted of an equal number (42) of required "Yes" and "No" responses.

In sum, each sub-list (L1-Hebrew or L2-English) consisted of 84 word-pairs – 28 critical items, which consisted of vertically and semantically related word-pairs and required a "Yes" response, and 56 filler items, which consisted of 14 semantically related word-pairs with no vertical relation that required a "Yes" response and 42 semantically unrelated word-pairs with no vertical relation that required a "No" response. See Table 4 for examples of the critical and filler items. See Appendix 3 for the full list of critical word-pairs.

Table 4: Examples of critical and filler items in the semantic judgment task

Item Type	Condition	Word-Pairs	Correct Response
Critical	Spatial Match	car road	Yes
Critical	Spatial Mismatch	road car	Yes
Filler	Semantically Related	pizza pasta	Yes
Filler	Semantically Unrelated	coat avocado	No

Pre-tests: (1) To ensure that the two words in each pair, in both the critical and filler items, are semantically related or unrelated, 20 students that did not participated in the main experiments rated the strength of semantic relatedness of the two words in each pair on a scale of 1 (very week relation) to 5 (very strong relation). Importantly, all word-pairs that were used in the main experiments as semantically related pairs, were rated on average above 3.5, and all word-pairs that were used in the main experiments as semantically unrelated pairs, were rated on average under 2.5. Word-pairs that were rated on average between 2.5 to 3.5 were not included in the main experiments. (2) To ensure that the referents of each word-pair consist or does not consist of a typical vertical-spatial relation, the same 20 students rated the degree to which the vertical-spatial relation between the two referents of each word-pair is consistent (i.e. whether one object constantly located above the other) on a scale of 1 (very low consistency) to 5 (very high consistency; following Louwerse, 2008 and Louwerse, & Jeuniaux, 2010). All word-pairs that were used in the main experiments as vertically related pairs, were rated on average above 3.5, and all word-pairs that were used in the main experiments as vertically unrelated pairs, were rated on average under 2.5. Word-pairs that were rated on average between 2.5 to 3.5 were not included in the main experiments.

Post-tests: To ensure that participants in the main experiments knew the exact meaning of the critical English word-pairs, at the end of the experimental session, they translated to Hebrew all the critical word-pairs presented in the L2-English experiment. English trials that consisted of word-pairs, which were not correctly translated, were removed from the statistical analyses.

Design

The experimental design was identical to that of Exp. 1, except that a different task was employed (i.e., semantic judgment of word-pairs), and therefore, a different type of visual effect was examined (i.e., spatial effect). Thus, a 2x2 factorial design was used with Spatial Condition (match/mismatch) and Target Language (L1-Hebrew/L2-English) as within-subject independent variables.

Procedure

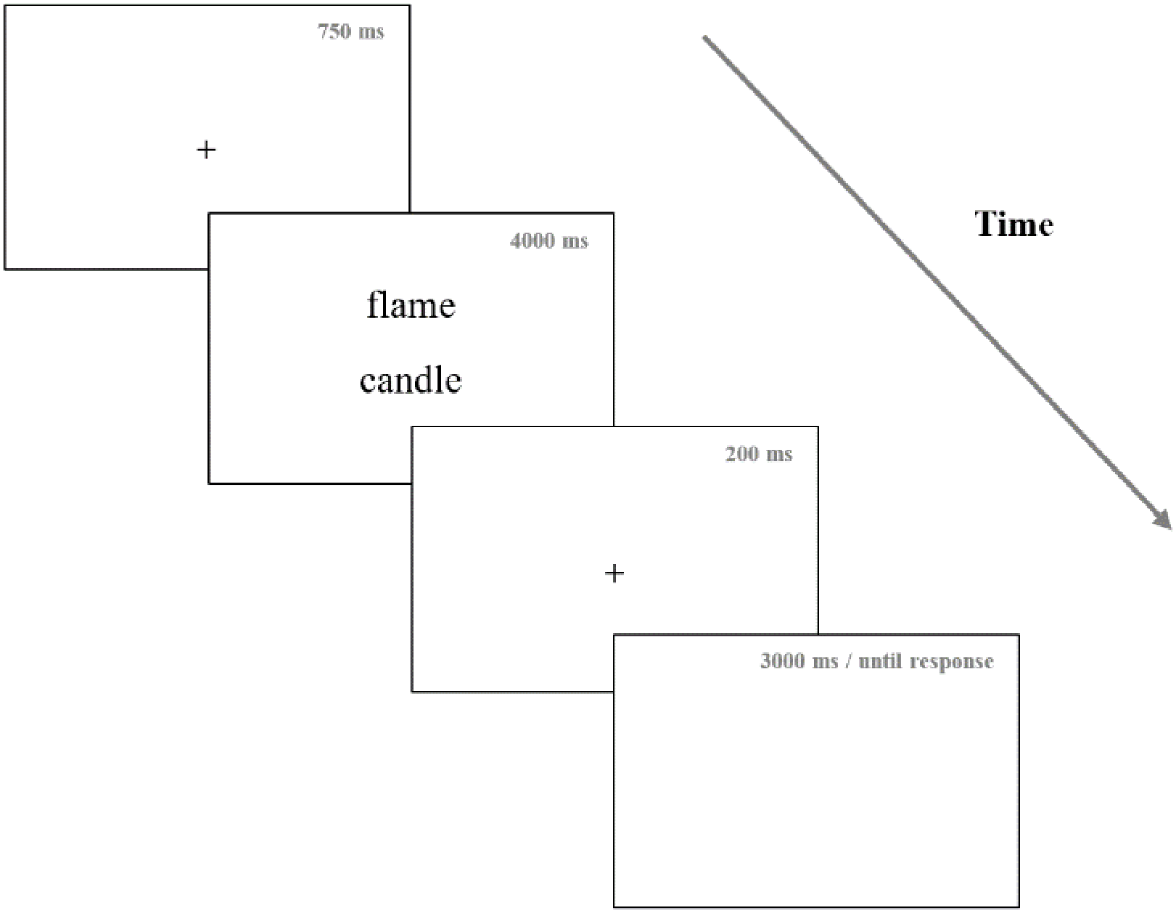
Session: The session procedure was identical to that of Exp. 1.

Block: At the beginning of each language block, participants were instructed to decide as quickly and accurately as possible in each trial, whether or not the two presented words are semantically related. They were further instructed to respond with their right index finger by pressing the “Yes” or “No” buttons in the response box, which was placed on the table in front of them in a vertical manner, such that the “Yes” button was located closer to the screen and the “No” button was located closer to the participant. This was done in order to prevent participants from responding horizontally by pressing right and left buttons, since Exp. 4 examined hemispheric functioning and could have been affected by this manner of response.

Initially, participants read the instructions and were introduced to 4 examples of semantic-relatedness judgments regarding word-pairs. Instructions were presented in Hebrew and the examples were presented, either in Hebrew prior to the L1-Hebrew block or in English prior to the L1-English block. Before each language block, participants performed a short practice, either in the L1-Hebrew or in the L2-English, which consisted of 6 word-pairs, half requiring a “Yes” response and half requiring a “No” response. During practice trials, participants received visual feedback for correct and incorrect responses.

All trials consisted of the same sequence of events. At the start of each trial, participants were presented with a central fixation cross for 750 ms. The offset of the marker was followed by a centrally presented word-pair for 200 ms (following Zwaan & Yaxley, 2003b). Then, a blank screen was presented until a response was made or until 3000 ms. In each trial, the response latency was measured from the onset of the word-pair presentation, and response accuracy was recorded. See Figure 3 for an example of the sequence of events in each trial.

Figure 3: The sequence of events in each trial in Exp. 2



Stimuli Presentation: Words were presented in black letters on a white background, in Arial font size 18. The font's height in both languages was 0.57 cm. The length of the shortest critical word (the Hebrew word "גג") was 0.5 cm, and the length of the longest critical word (the English word "lighthouse") was 3 cm. Thus, words subtended 0.57° of vertical visual angle and between 0.5° to 3° of horizontal visual angle, at a viewing distance of 57 cm. Word-pairs were presented one above the other at the center of the screen, such that the distance between the two words from the lowest point in the upper word to the highest point in the lower word was 0.2 cm. The overall distance from the highest point in the upper word to the lowest point in the lower word was 1.34 cm. Thus, each word-pair subtended 1.34° of vertical visual angle, at a viewing distance of 57 cm.

Apparatus: The apparatus was identical to the one used in Exp. 1.

2.2.2.2. <u>Results</u>

<u>Data analysis protocol</u>

The procedure of data analysis was identical to that of Exp. 1, except that the three LME models that were fitted to the RT data and the error data included the independent variable Spatial Condition instead of Shape Condition. Thus, Model 1 included the fixed main effects of Spatial Condition and Target Language, the interaction between them, and the random effects of Participants and Items. Model 2 included the fixed main effects of Spatial Condition, Target Language, and Experimental Block, the interactions between them, and the random effects of Participants and Items. Model 3 included the fixed main effects of Spatial Condition, Target Language, Experimental Block, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items.

<u>Data Cleanup</u>

The entire dataset, a total of 6720 trials (2240 critical trials and 4480 filler trials), was inspected in terms of accuracy rates per-participant as well as per-item, vocabulary knowledge of critical L2-items per-participant, and RT outliers.

First, accuracy rates were examined for each participant and item in each language. Participants and items that had a mean accuracy rate lower than 60%, in either the L1-Hebrew task or the L2-English task, were excluded from analyses. Based on this criterion, 1 participant and 9 items were excluded from the data, resulting in a total loss of 519 trials (7.7%).

Next, 133 English trials that were incorrectly translated in the English-Hebrew translation post-test were removed, 32 trials with RT greater than 3000 ms or lower than 200 ms were removed, and 38 trials that fell outside the range of acceptable latencies (i.e., +/− 3.5 SD from participant's mean RT) were removed. This trimming procedure accounted for a total loss of 203 trials (3.3%). Finally, filler trials were excluded from the data.

<u>RT Data</u>

For the RT analyses, additional 194 critical trials (11.5%) were removed due to incorrect responses, and the final RT dataset consisted of correct critical trials only. Thus, 1488 data points (845 in L1-Hebrew and 643 in L2-English) that 39 participants produced by responding to 47 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 3 fitted the RT data significantly better than Model 1 and 2 ($\chi^2(8)=49.10$, $p<.001$). Therefore, Model 3, which included the fixed main effects of Spatial Condition, Target Language, Experimental Block, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items, was selected for further analysis. Mean correct RTs (in ms) by Spatial Condition, Target Language, Experimental Block, and English Proficiency Group (see footnote 4), are illustrated in Table 5.

Table 5: Mean correct RTs (in ms) by Spatial Condition, Target Language, Experimental Block, and English Proficiency Group in Exp. 2

ExpBlock	Language	EnProfGroup	SpatialCond	RT.mean	RT.sd	Effect
First	He	High	match	956.9806	249.3535	
First	He	High	mismatch	954.3448	244.2880	-2.63
First	He	Low	match	1000.5096	378.3819	
First	He	Low	mismatch	929.3793	238.3590	-71.13
First	En	High	match	1163.5204	304.2628	
First	En	High	mismatch	1159.6778	325.5334	-3.84
First	En	Low	match	1334.0746	431.7387	
First	En	Low	mismatch	1240.0161	367.2358	-94.06
Second	He	High	match	920.2500	291.2038	
Second	He	High	mismatch	934.0000	304.4360	13.75
Second	He	Low	match	930.8137	279.9576	
Second	He	Low	mismatch	910.4500	243.7276	-20.36
Second	En	High	match	1150.6629	332.0578	
Second	En	High	mismatch	1085.8750	285.9917	-64.78
Second	En	Low	match	1296.9342	381.2991	
Second	En	Low	mismatch	1312.5062	430.0873	15.58

Within Model 3, the main effect of Target Language was significant ($\chi^2(1)=364.66$, $p<.001$), indicating that overall responses to 'L1-Hebrew' trials (Mean=941.39, SD=283.10) were faster than responses to 'L2-English' trials (Mean=1211.23, SD=364.52). In addition, the main effect of Experimental Block was significant ($\chi^2(1)=9.50$, $p<.01$), indicating that overall, responses to 'second-block' trials (Mean=1046.22, SD=352.25) were faster than responses to 'first-block' trials (Mean=1070.31, SD=342.20).

Furthermore, the two-way interaction between English Proficiency Score and Target Language was significant ($\chi^2(1)=46.33$, $p<.001$). Further examination of the effect of English

Proficiency Score separately for each Target Language revealed that while in the 'L1-Hebrew', the RT-difference between participants with 'high-score' (i.e., half of the participants with the highest proficiency scores) and 'low-score' (i.e., the other half of the participants with the lowest proficiency scores) was not significant ($\chi^2(1)=.01$, $p=1.00$), in the 'L2-English', the RT-difference between participants with 'high-score' (Mean=1141.95, SD=313.14) and 'low-score' (Mean=1297.71, SD=404.12) was significant ($\chi^2(1)=10.27$, $p<.01$). This indicates that speed performance was significantly influenced by English Proficiency Score, such that higher scores resulted in faster responses, only in the 'L2-English'.

Error Data

The final Error dataset consisted of critical trials only. Thus, 1682 data points (913 in L1-Hebrew and 769 in L2-English) that 39 participants produced by responding to 47 critical items were analyzed.

The comparison of Models 1, 2 and 3 revealed that Model 2 did not fit the Error data better than Model 1 ($\chi^2(4)=3.21$, $p=.52$) and Model 3 did not fit the data better than Model 2 ($\chi^2(8)=7.26$, $p=.51$). Therefore, Model 1, which included the fixed main effects of Spatial Condition and Target Language, the interactions between them, and the random effects of Participants and Items, was selected for further analysis.

Within Model 1, only the main effect of Target Language was significant ($\chi^2(1)=35.60$, $p<.001$), indicating that overall 'L1-Hebrew' trials (Mean=.08, SD=.26) resulted in a significantly lower error rate than 'L2-English' trials (Mean=.16, SD=.37).

2.1.2.3 Discussion

The results of Exp. 2 did not demonstrate the spatial effect, neither in the L1 nor in the L2. That is, no significant evidence for the activation of implied visual spatial information during word reading was found. Thus, in contrast to previous L1 studies, which demonstrated a significant spatial effect using the same semantic judgment task (Louwerse, 2008; Zwaan & Yaxley, 2003a), here we did not observe significant facilitation when the vertical-spatial position of the two words on the screen matched the relative spatial location of their referents. However, it is important to note that the spatial effect in the semantic judgment task has not been consistently evident in all previous studies (Louwerse & Jeuniaux, 2010; Van Elk &

Blanke, 2011), indicating that this effect may be relatively weak or may be modulated by other factors.

For example, consistent with the current results, Van Elk and Blanke (2011) failed to demonstrate the spatial effect when participants judged the semantic relatedness of concrete word-pairs denoting body-parts with typical vertical-spatial relation (e.g., eye-mouth). Interestingly, a significant spatial effect was found when the task focused on the visual-spatial properties of referred body-parts. That is, responses were significantly faster in the match than in the mismatch condition, when participants were explicitly asked to judge whether or not the vertical configuration of presented word-pairs matched the typical spatial position of their referents (i.e., iconicity judgment task). Similarly, Louwerse and Jeuniaux (2010) demonstrated that the iconicity rating of word-pairs (i.e., a subjective estimation of the likelihood that the words' referents appear one above the other in the real world) did not significantly predict the RTs in the semantic judgment task, however, it significantly predicted the RTs in the iconicity judgment task. These results indicate that visual spatial information may be more strongly activated when using an explicit task, which directly instructs participants to retrieve visual spatial information about the verbally referred objects, than when using an implicit task, in which visual spatial information is supposed to be retrieved spontaneously, without participants' intention.

In addition, Louwerse and Jeuniaux (2010) further showed that when the semantic judgment task consisted of non-verbal visual stimuli (i.e., picture-pairs), rather than verbal stimuli (i.e., word-pairs), the spatial effect was evident and the size of the effect significantly correlated with the extent to which the referent's spatial relation in the real world is constant (i.e., iconicity ratings), suggesting that non-verbal visual stimuli, as opposed to verbal stimuli, spontaneously activated the typical visual spatial properties of the presented objects.

Moreover, previous studies have suggested that different visual properties may be activated to different extent during language comprehension. It appears that while more intrinsic visual properties, such as size and shape, are more strongly activated, the activation of extrinsic features, such as spatial orientation, is weaker (De Koning, Wassenburg, Bos, & van der Schoot, 2017b; Koster et al., 2018; Zwaan & Pecher, 2012).

Finally, the failure to demonstrate a significant spatial effect in the current study may be the result of the high difficulty level of the semantic judgment task, in which participants had to judge the semantic relatedness of very briefly presented (i.e., 200 ms) word-pairs. Indeed, this task has yielded significantly lower accuracy rates (Mean=.88, SD=.32), in comparison to the sentences picture verification task used in Exp. 1 (Mean=0.97, SD=.18;

t(46)=2.01, p<.001). Additionally, the low accuracy rates in Exp. 2 led to the exclusion of 1 participant and 9 critical items that their mean accuracy rate was below 60%. Critically, this trimming procedure resulted in a considerable reduction in the analyzed data, in comparison to Exp.1, in which none of the participants nor items were excluded.

Thus, the possibility that performing the same task under less demanding processing conditions would result in a significant spatial effect, was further examined in Exp. 5 (see Appendix 4). This experiment was identical to Exp. 2, except that it included longer presentations of word-pairs (3500 ms) to allow sufficient processing time in both languages. In addition, to further facilitate the task in the L2-English, the list of critical items in Exp. 5 included only 48 items (out of 56) that received the highest translation score in the English-Hebrew translation post-test. Indeed, accuracy rates in Exp. 5 (Mean=.96, SD=.19) were significantly higher than in Exp. 2 (t(53)=2.01, p<.001) and did not significantly differ from those exhibited in Exp. 1 (t(105)=1.98, p=.75). Still, even under less difficult conditions, the spatial effect was not significantly evident. Notably, a marginally significant interaction was found between Spatial Condition and Target Language, in which only in the 'L1-Hebrew', responses were faster in the match than in the mismatch spatial condition. However, this difference between match and mismatch trials was not significant, indicating that the effect of Spatial Condition on speed performance in the 'L1-Hebrew' was relatively weak[7].

To conclude, at least two possible explanations could underlie the absence of the spatial effect in Exp. 2 (as well as in Exp. 5). First, it could be that the construction of visual spatial simulations during word reading is not automatic, but rather task-dependent (e.g., Lebois et al., 2015). Namely, visual spatial activations are more likely to occur when readers are explicitly asked by the task to access the visual spatial features of concepts (Elk & Blanke, 2011; Louwerse & Jeuniaux, 2010) or when the task is perceptually oriented, for example, because it presents non-verbal visual stimuli, which may direct participants' attention to other visual aspects of the stimuli (Louwerse & Jeuniaux, 2010). Second, it could be that visual spatial properties (i.e., location, orientation) are activated to a lesser degree because they are less intrinsic (De Koning, Wassenburg, Bos, & van der Schoot, 2017b; Koster et al., 2018; Zwaan & Pecher, 2012).

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[7] Nevertheless, given that the data in this study were based on a relatively smaller set of items, it is possible that a larger set would be able to detect a significant difference between the two languages (L1 vs. L2) in terms of their ability to activate spatial information during lexical processing.

2.2.3 *Conclusions*

Set A demonstrated that among proficient unbalanced late bilinguals, which have acquired and used their L2 primarily in formal settings, L1 sentence reading produced substantial visual simulations, whereas L2 sentence reading did not result in significant activations of perceptual visual information. Consistent with our initial predictions, these results suggest that while L1 comprehension involves simulation-based processes, L2 comprehension relies mainly on linguistic representations, and thus, the activation of perceptual visual knowledge by L2 input is significantly reduced, in comparison to the L1.

Interestingly, we found that the embodied/disembodied processing nature of each language (i.e., L1/L2, respectively) was affected by the recent exposure to the other language. Thus, simulation processes appeared to be weaker in the L1 after performing the task in the L2, suggesting that the embodied processing nature of the L1 was affected by the disembodied processing nature of the L2. In contrary, simulation processes in the L2 seemed to be stronger after preforming the task in the L1, suggesting that the disembodied processing nature of the L2 was influenced by the embodied processing nature of the L1.

Moreover, the current findings also demonstrated that visual simulations were modulated by the nature of the task, such that when the task was more perceptually oriented (i.e., involved pictures) and tested a more intrinsic visual property (i.e., shape), as in Exp. 1, visual effects were significantly exhibited. However, when the task was less related to perceptual information (i.e., involved only verbal stimuli) and tested a less intrinsic visual feature (i.e., spatial location), as in Exp. 2, visual effects were less pronounced.

Nevertheless, despite these differences, visual effects (when found) were only observed during L1 comprehension. Thus, the results of Set A are consistent with the notion that in this type of bilinguals the L2 is less embodied than the L1. The next set of experiments (Set B) investigated the neural mechanisms that support the construction of these visual simulations, specifically focusing on the separate and combined abilities of the two cerebral hemispheres to activate perceptual visual properties of mentioned objects during L1 and L2 comprehension.

3. EMBODIED LANGUAGE COMPREHENSION IN THE TWO HEMISPHERES

3.1. Introduction

The view that some cognitive abilities tend to reside in one side of the brain was initially supported by studies on patients with unilateral brain injury (Broca, 1863; Wernicke, 1874) and later on by split-brain studies, in which patients had undergone corpus callosum section causing hemispheric disconnection that allowed researchers to test the capacities of each hemisphere independently of the other (Gazzaniga, Bogen & Sperry, 1962). These studies have revealed a right hemisphere (RH) dominance for several non-verbal visuospatial functions and a left hemisphere (LH) dominance for linguistic functions, including exclusive control for speech (Corballis, Funnell & Gazzaniga, 2002; Gazzaniga, 2005; Sperry, 1982). Thus, it is generally assumed that the RH is more visually tuned, whereas the LH is more verbally oriented (Corballis, 2003; Hugdahl, 2000).

A RH specialization for a variety of visuospatial abilities and a LH specialization for verbal abilities have also been documented in studies on healthy participants. For example, Kelley, Miezin, McDermott, Buckner, Raichle, Cohen, Ollinger, Akbudak, Conturo, Snyder and Petersen (1998) demonstrated that the encoding of written words (i.e., verbal information) produced a left-lateralized neural activation, the encoding of unfamiliar faces (i.e., visual information) evoked brain activity in the RH, whereas the encoding of nameable objects, (i.e., verbal and nonverbal information) elicited bilateral activation.

Several studies have shown that during visual object recognition, the RH is more efficient at classifying objects as specific exemplars (e.g., robin), whereas the LH is better at classifying objects at the categorical level (e.g., bird), suggesting that the RH plays a greater role in processing the specific form features of visually perceived objects, whereas the LH is specialized in abstract semantic processing (e.g., Laeng, Zarrinpar, & Kosslyn, 2003; Simons, Koutstaal, Prince, Wagner, & Schacter, 2003; Marsolek, 1999).

One task that has consistently produced a reliable processing difference between the two hemispheres is the lexical decision task (i.e., whether or not a letter string is a real word), in which a LH dominance for visual word processing is usually found (e.g., Brederoo, Nieuwenstein, Cornelissen & Lorist, 2019; Hausmann, Brysbaert, van der Haegen, Lewald, Specht, Hirnstein, Willemin, Barton, Buchilly, Chmetz, & Roch, 2019; Willemin, Hausmann, Brysbaert, Dael, Chmetz, Fioravera, Gieruc & Mohr, 2016). Indeed, recently, Hausmann et al. (2019) have observed the same LH advantage in a lexical decision task, across six different languages and different types of language users (i.e., monolinguals, early and late bilinguals), further emphasizing the crucial role of the LH in the processing of written words.

Nevertheless, although most verbal processes are typically lateralized to the LH, it is now commonly accepted that both hemispheres are involved in language comprehension, albeit in distinct and complementary ways (e.g., Federmeier, 2007; Harpaz, Levkovitz, & Lavidor, (2009); Jung-Beeman, 2005; Peleg & Eviatar, 2008; 2009; 2012; 2017; Peleg, Markus, & Eviatar, 2012). In particular, it is generally agreed that while the LH is crucial for basic linguistic comprehension processes at the word- and sentence-level, such as word recognition (e.g., Hausmann et al., 2019) and propositional representation (e.g., Long & Baynes, 2002), the RH mostly contributes to higher-level complex comprehension functions (Johns, Tooley & Traxler, 2008), such as inferences generation (e.g., Beeman, 1993; Brownell, Potter, Bihrle, & Gardner, 1986; Schneiderman, Murasugi & Saddy, 1992) and the appreciation of various forms of non-literal and context-dependent meanings (e.g., Coulson & Wu, 2005; Mashal, Faust, Hendler, & Jung-Beeman, 2007; Weylman, Brownell, Roman, & Gardner, 1989). Yet, the exact nature of these RH contributions is still under investigation.

One simple explanation for the involvement of the RH in language comprehension relates to the need of additional neural resources when processing is more demanding. Namely, as language input become more complex it may require more cognitive capacities that can be recruited in the RH. Indeed, it appears that the involvement of the RH in language comprehension increases as the contextual complexity of the linguistic stimuli increases (i.e., words vs. sentences vs. narrative; Xu, Kemeny, Park, Frattali & Braun, 2005). Similarly, several studies have reported greater RH involvement in L2 processing, relative to L1 processing, assumingly because the neural computation of the L2 is more effortful, especially when proficiency level in the L2 is lower, or when the L2 is learned later in life (e.g., Cieślicka & Heredia, 2011; Leonard, Brown, Travis, Gharapetian, Hagler Jr, Dale, Elman & Halgren, 2010; Xiang, Van Leeuwen, Dediu, Roberts, Norris & Hagoort, 2015). For example, Cieślicka and Heredia (2011) showed that during figurative sentence reading, while the LH remained active throughout all time windows during both L1 and L2 processing, the RH showed activation for L1 processing only at 0ms inter stimulus interval (ISI), but for L2 processing at 0ms, 300ms and 800ms ISI, suggesting that the effortfulness of figurative sentence processing in the L2 may draw on additional bilateral hemispheric resources.

Another explanation relates to the unique involvement of the RH in higher-level pragmatic processes. In this view, general pragmatic aspects of meaning, driven from the physical, social, or cultural context of the linguistic input, are processed mainly by the RH (e.g., Cutica, 2005; Cutica, Bucciarelli, & Bara, 2006). Thus, during language comprehension, the RH is responsible for relating language input to world knowledge, whereas the LH is responsible for low-level linguistic processes. For example, it has been demonstrated that language comprehension in RH-damaged patients is guided mainly by their largely intact linguistic abilities within the LH, and less by other non-verbal essential aspects of natural communication, such as the plausibility of the situation, the speaker's mood and affective tone, or the nature of inter-personal relations, often leading to failure in comprehending non-literal meanings of utterance during conversation (e.g., Brownell, Carroll, Rehak, & Wingfield., 1992; Kaplan, Brownell, Jacobs, & Gardner, 1990).

Other accounts reason that the contribution of the RH resides in low-level lexical processes, which determine the range of semantic meanings that are evoked and maintained during language processing (e.g., Beeman, 1998; Beeman, Friedman, Grafman, & Perez, 1994; Burgess & Simpson, 1988; Faust & Chiarello, 1998; Faust & Gernsbacher, 1996). Accordingly, the RH weakly and diffusely activates and maintains a wide range of meanings over time, including distantly related, subordinate, and contextually irrelevant ones, whereas the LH strongly activate a focused range of closely related and dominant meanings and quickly select a single meaning that is contextually relevant, while discarding all others. Thus, lexical semantic processes in the RH are relatively less controlled, whereas the LH employs controlled semantic processes that are sensitive to the sentence context and involve the selection of the most dominant, strongly related, or contextually relevant meanings, and the suppression of the irrelevant ones (e.g., Burgess & Simpson, 1988; Faust & Chiarello, 1998). Crucially, the co-activation of wide semantic fields by single words in the RH, results in semantic overlaps of relatively unrelated meanings, which are necessary for comprehending complex, unpredicted, and context-dependent interpretations (i.e., non-literal, implied) of the linguistic input (Beeman, 1998).

Indeed, it has been demonstrated that, during language comprehension, the RH uniquely activates a wide range of implied elaborative meanings (Beeman, Bowden & Gernsbacher, 2000; Metusalem, Kutas, Urbach & Elman, 2016). For example, Metusalem et al. (2016) showed that inferences about event-related knowledge are available and affect linguistic expectations only in the RH. In this ERP study, participants read short passages, in which a target word in the final sentence was either (1) contextually-appropriate, (2) contextually-inappropriate but event-related, or (3) contextually-inappropriate and event-unrelated (e.g., "A huge blizzard swept through town last night; My kids ended up getting the day off from school; They spent the whole day outside building a big *snowman/jacket/couch* in the front yard”). They found that, only in the RH, the processing of contextually inappropriate targets (i.e., jacket/couch) was modulated by their relatedness to the described event, such that the processing of contextually inappropriate but event-related words (e.g., jacket) elicited a reduced N400, relative to event-unrelated words (e.g., couch), indicating that event-related implied information was activated in the RH during reading.

Finally, rather than focusing on hemispheric asymmetries in either semantic or pragmatic processes, several researchers have proposed that the two hemispheres differ in the manner in which orthographic, phonological, and semantic representations interact in the two hemispheres (e.g., Federmeier, 2007; Peleg & Eviatar, 2012). For example, the production affects reception in left only model (Federmeier, 2007) assumes that because in the LH comprehension and production processes share resources, the connections between lexical forms and semantic representations in the LH are bi-directional. However, in the RH, information flows from form to meaning in a serial fashion, because the RH is only involved in comprehension. Importantly, the feedback connections in the LH allow for effective top-down processing, which involves early use of contextual information in order to generate predictions regarding the meaning of upcoming words, whereas feed-forward connections in the RH allow for effective bottom-up processing and integration of meanings in later processing stages. Thus, the availability of predictions in the LH prepares the system to rapidly process upcoming stimuli, yet, results in the loss of the original information, which is needed if upcoming stimuli is less predicted. In such cases, the retainage of the veridical stimulus in the RH enables to reanalyze the linguistic input and to better associate between distant pieces of information.

The present study aimed to expand this type of hemispheric models by examining how linguistic and perceptual representations interact in the two hemispheres. In particular, Set B explored the possibility that while intra-system connections among linguistic representations are stronger in the LH (e.g., Peleg & Eviatar, 2012; 2017), inter-system connections between verbal and non-verbal representations are more extensive in the RH. Under this assumption, the two hemispheres may differ in their ability to spontaneously activate non-verbal perceptual information during language comprehension and to construct rich mental simulations of verbally described situations. Specifically, it is assumed that while the RH comprehends language using mainly simulation processes, which support the comprehension of complex language, the LH establishes comprehension using mainly linguistic processes, which support more basic and shallow comprehension functions (Barsalou et al., 2008).

This possibility is consistent with the dual coding theory (Paivio, 1990; 2010; 2014), which postulates that language comprehension processes may involve both verbal representations within the left-lateralized language system (e.g., the visual and auditory form of the word "dog"), and non-verbal perceptual representations in bilateral sensory mechanisms (e.g., the image and sound of a dog). Accordingly, bilateral brain activation is expected when processing strongly embodied linguistic input, which can explain the processing advantage of concrete over abstract words (Paivio, 1991; Paivio and Te Linde, 1982). That is, the operation of two systems in the case of strongly embodied verbal stimuli such as concrete words (i.e., a left-lateralized language system and a bilateral sensory system) results in a more efficient and rapid processing as compared to a single system operation, in the case of less embodied stimuli such as abstract words. Indeed, several studies demonstrated that concrete words, which denote concepts that can easily be experienced by the senses and thus encoded both verbally and non-verbally, are processed bilaterally. However, the processing of abstract words, which denote concepts that are less linked to sensory representations, and thus are encoded mainly in the language system, is left-lateralized (Binder, Westbury, McKiernan, Possing & Medler, 2005; Dhond, Witzel, Dale & Halgren, 2007; Kounios & Holcomb, 1994; Hines, 1976; Sabsevitz, Medler, Seidenberg & Binder, 2005).

Similarly, the dual coding assumption can explain the enhanced memory for namable pictures of objects relative to unnamable abstract pictures (e.g., Whitehouse, 1981). Thus, while the former can be stored in memory using both an imagery-based code (i.e., a visual representation) and a verbal code (i.e., the name of the object), the later can only be encoded perceptually. Indeed, Whitehouse (1981) found that dually encodable stimuli (i.e., picturable nouns and nameable pictures) were easier to memorize than single-coded stimuli (i.e., abstract pictures and abstract nouns) for both RH- and LH-damaged patients, suggesting that dual coding may enhance the processing of both verbal and perceptual stimuli. More importantly, he found that while LH-damaged patients exhibited intact perceptual encoding for pictures and impaired verbal encoding for words, RH-damaged patients demonstrated the opposite pattern, suggesting that while the LH is mainly responsible for the encoding of verbal codes, the RH mainly encodes perceptual visual information.

Even though Paivio's theory predicts that during language comprehension perceptual simulations of verbally described situations should be activated in both hemispheres, it is possible that, in the case of perceptual visual simulations, the contribution of the RH is more extensive (e.g., Whitehouse, 1981), since the RH has an advantage over the LH in visuospatial processing (Corballis, 2003; Hugdahl, 2000). Furthermore, according to this account, the involvement of the two hemispheres in language comprehension depends on the nature of language processing (i.e., embodied vs. disembodied processing). Thus, both hemispheres are expected to be involved in language comprehension when comprehenders rely on simulation mechanisms, as may be the case of L1 users. However, when comprehenders rely more heavily on linguistic mechanism, as may be the case of L2 users, the RH may be less involved (see Exp. 1).

In sum, although it is generally agreed that the RH contributes to language comprehension mainly at higher processing levels (Johns, Tooley & Traxler, 2008), the exact nature of this contribution is still under investigation. A relatively unexplored account suggests that the contribution of the RH to language comprehension lies in its ability to link language input to perceptual (visual) knowledge in order to simulate verbally described objects, places, and events. This possibility was further examined in Set B.

3.1.1. *Visual simulations in the two hemispheres*

One way to investigate hemispheric contribution to language comprehension in general, and to the construction of visual simulations in particular, is the divided visual field (DVF) paradigm (e.g., Hausmann et al., 2019). This technique takes advantage of the fact that stimuli presented in the left side of the visual field (LVF) are initially perceived and processed exclusively by the RH, whereas stimuli presented in the right side of the visual field (RVF) are initially perceived and processed exclusively by the LH (Bourne, 2006). Namely, only the hemisphere contra lateral to the visual field of stimuli presentation receives direct sensory input, and thus the initial visual processing of the stimuli starts unilaterally. In addition, the subsequent transmission of visual information to the ipsilateral hemisphere may be delayed or may result in loss of information (Banich, 2003). Therefore, the interpretation of DVF paradigms rests on the assumption that responses to stimulus presented briefly to one visual field, reflect mainly the processing of that stimulus by the contralateral hemisphere. Namely, responses to stimuli displayed in the RVF reflect LH processes, and responses to stimuli presented in the LVF reflect RH processes (for theoretical, electrophysiological and neuroimaging support for this assumption, see Banich, 2003; Coulson, Federmeier, Van Petten, & Kutas, 2005; Hunter & Brysbaert, 2008).

Several studies, employing the DVF technique, have yielded inconsistent evidence regarding the ability of each hemisphere to activate perceptual visual knowledge during language comprehension. While some findings suggest that, during language comprehension, perceptual visual knowledge is mainly activated in the RH (Huang, Lee & Federmeier, 2010; Male & Gouldthorp, 2020; Zwaan & Yaxley, 2003b), others suggest either no hemispheric difference in this respect (Berndt, Dudschig, Miller & Kaup, 2019), or the opposite (Francken, Kok, Hagoort, & De Lange, 2015; Lincoln et al., 2007; Zwaan & Yaxley, 2004).

For example, in an ERP study, Huang et al. (2010) examined neural differences in the processing of concrete and abstract words. They found that only when presented in the LVF to the RH, concrete embodied concepts, as opposed to abstract ones, elicited sustained frontal negativity in the 500-900 ms time window (i.e., N700), assumed to be linked to sensory imagery (e.g., Gullick, Mitra, & Coch, 2013; West & Holcomb, 2000). These findings suggest that the RH plays a critical role in linking language input to visual knowledge (Huang & Federmeier, 2015).

In another ERP study, Male and Gouldthorp (2020) demonstrated a RH-advantage in constructing an integrated visual spatial simulation of the linguistic content. In this study, participants heard sentences describing the individual visual elements of an image, and then saw a laterally presented picture in one of three conditions. In the integrated condition, they saw a picture of the described image that consisted of the correct spatial relations between the visual elements. In the unintegrated condition, they saw a meaningless picture of the described visual elements that omitted meaningful spatial relations. In the unrelated condition, they saw a picture of an unrelated image that did not contain any of the verbally described visual elements. They found that only under LVF/RH presentations of pictures, the amplitude of the N300 component, considered to reflect visual processes of object identification, was reduced in the integrated condition relative to the unintegrated condition, indicating that only the RH constructed a mental representation that integrated perceptual information about the correct spatial relations of the verbally described visual elements.

Along similar lines, using the semantic judgment task (Zwaan & Yaxley, 2003a) in conjunction with lateral presentations of stimuli, Zwaan and Yaxley (2003b) showed a RH-advantage in activating visual spatial properties of objects described by words. In the task, participants had to judge whether or not visually presented word-pairs are semantically related. Critically, the two words in each pair were displayed one above the other in a vertical manner. They found that responses were faster when the visual spatial arrangement of the two words on the screen matched, rather than mismatched, the typical spatial relation of their referents (e.g., flame-candle), but only in the RH. Namely, this spatial effect was significantly evident only when word-pairs were presented in the LVF to the RH, suggesting that visual information about the typical spatial location of objects mentioned by written words was substantially activated only in the RH (but see Berndt et al., 2019).

Supporting evidence for the advantage of the RH in linking language input to visual knowledge, also comes from studies using other methods. For instance, using the sentence picture verification task (Zwaan et al., 2002) on RH- and LH-damaged patients, Lincoln, Long, Swick, and Baynes (2008) showed a RH-advantage in activating the implied shape of objects mentioned in sentences. In that study, participants had to respond to target pictures of objects, which their shape could have either matched or mismatched the object's shape implied by a preceding sentence. The performance of brain-damaged patients, with either a RH- or a LH-impairment, was compared to healthy participants, and a significant interaction between Group (RH-patients/LH-patients/healthy controls) and Shape Condition (match/mismatch) was demonstrated, in which only healthy controls exhibited a significant shape effect (i.e., faster responses in the match than the mismatch condition). However, further examination of the shape effect only within the group of patients, revealed that when the effects of lesion size and comprehension ability were controlled, hemisphere was a reliable predictor of the shape effect, such that patients with LH-damage were more likely to show the effect, than were patients with RH-damage. These findings suggest that although both hemispheres are required to construct a significant visual shape simulation, the RH may be more crucial than the LH in activating implied visual shape information during sentence reading.

Similarly, using the sentence picture verification task (Zwaan et al., 2002) in conjunction with a manipulation of the spatial frequencies of pictures (i.e., low vs. high), Hirschfeld and Zwitserlood (2011) found that the shape effect was only apparent when target pictures contained low-spatial frequencies (i.e., the vague global shape of an image), as opposed to a visual condition in which target pictures contained high-spatial frequencies (i.e., the sharp contour of an image). These findings suggest that object's shape information evoked by the sentence, enhanced the visual processing of the subsequent picture, assumingly by shaping top-down visual predictions. These predictions are assumed to be rapidly generated at the initial stage of visual object recognition based on the low-spatial frequencies that are extracted from an image (Bar, 2004). Importantly, previous findings suggest that these low-spatial frequencies are processed more efficiently in the RH (e.g., Kitterle, Hellige & Christman, 1992; Peyrin, Chauvin, Chokron & Marendaz, 2003; Piazza & Silver, 2014).

Yet, other studies either failed to demonstrate hemispheric differences in linking verbal input to visual knowledge or demonstrated a LH-advantage in this regard. For example, Berndt et al. (2019) showed that both hemispheres can activate visual information regarding the typical spatial location of verbally mentioned objects. They used the semantic judgment task in conjunction with lateral presentations of stimuli (Zwaan & Yaxley, 2003b), but did not find a significant interaction between Spatial Condition (match/mismatch) and Visual Field (RVF/LVF), suggesting that the activation of visual spatial properties of objects during lexical processing is not necessarily restricted to the RH, and may be equally supported by both hemispheres.

Further, Zwaan and Yaxley (2004) have suggested that during lexical processing only the LH activates the typical visual shape properties of referred objects. In this study, participants judged whether or not a laterally presented target word is semantically related to a previously, centrally presented prime word. They found that participants were significantly slower to reject semantically unrelated target words, when the prime and the target referred to entities with a similar shape (e.g., railroad-ladder), but only when targets were presented in the RVF to the LH. These findings suggest that visual shape information was activated only in the LH, hindering the semantic judgment of unrelated target words presented to this specific hemisphere.

Similarly, Francken et al. (2015) observed that responses in a visual motion-detection task were faster when the visual motion target (i.e., upwards or downwards movement) matched the direction implied by the preceded word (e.g., rise or dive). Crucially, this visual-motion effect was exhibited only when target stimuli were presented in the RVF to the LH, suggesting that during lexical processing visual information about motion direction was activated only in the LH.

Finally, using the sentence picture verification task (Zwaan et al., 2002) in conjunction with lateral presentation of target pictures, Lincoln et al. (2007) demonstrated a LH-advantage in activating the implied shape of objects mentioned in sentences. They found that although the interaction between Shape Condition (match/mismatch) and Visual Field (RVF/LVF) was not significant, when the shape effect was examined separately in each visual field, responses were significantly faster in the match than in the mismatch condition only when target pictures were presented in the RVF to the LH.

In sum, RH-LH differences in language comprehension have been hypothesized to result from the distinct processing nature of each hemisphere (e.g., Beeman, 1998; Federmeier, 2007). Critically, the possibility that the two hemispheres differ in perceptual visual simulation processes has hardly been considered. Moreover, the few studies that examined this issue tested only L1 processing and yielded contradicting findings (e.g., Berndt et al., 2019; Lincoln et al., 2007; 2008; Zwaan & Yaxley, 2003b). Thus, Set B of the current study further examined whether the two hemispheres differ in their contribution to the construction of perceptual visual simulations during L1 comprehension, and extended the investigation to L2 comprehension.

3.2. Set B: Experiments 3 and 4

The second aim of the current study was to investigate the relative contribution of each hemisphere to the construction of visual simulations during word and sentence reading, in the L1 and in the L2. It was assumed that although non-verbal perceptual representations exist in both hemispheres (Paivio, 1990; 2010; 2014), perceptual visual information may be activated to a greater extent in the RH (Whitehouse, 1981), since it has an advantage over the LH in processing perceptual visual information (Corballis, 2003; Hugdahl, 2000).

To accomplish this aim, another set of experiments was conducted (Set B). Set B was identical to Set A, except that the target stimuli were presented laterally (to the LH or to the RH), rather than centrally (to both hemispheres). Thus, in Set B, like in Set A, proficient unbalanced late bilinguals that have acquired and used their L2 in formal and relatively limited settings, were tested in their L1-Hebrew (L1 block) and in their L2-English (L2 block). Exp. 3 employed the same sentence picture verification task used in Exp. 1, whereas Exp. 4 employed the same semantic judgment task used in Exp. 2. Importantly, in order to test hemispheric asymmetries in the activation of perceptual visual features during L1 and L2 reading, these two tasks were used in conjunction with the DVF technique. Thus, in both tasks, target stimuli were presented, either in the LVF to the RH or in the RVF to the LH, and the visual effects obtained under LVF/RH and RVF/LH presentations were compared.

3.2.1. *Experiment 3: Visual simulations of shape during sentence reading*

Exp. 3 examined hemispheric asymmetries in the ability to simulate visual shape features of mentioned objects during L1 and L2 sentence reading. To this end, the sentence picture verification task was used in conjunction with the DVF technique (Linclon et al., 2007). Thus, in both the L1-Hebrew block and the L2-English block, target pictures were presented laterally, either in the RVF to the LH or in the LVF to the RH. In each trial, participants had to decide whether or not the object in the lateralized picture (e.g., inflated/deflated balloon) had been mentioned in the preceding sentence (e.g., “The boy saw the balloon in the air/package”). On critical trials, the pictured object was indeed mentioned in the sentence, however, its shape could have either matched (i.e., match condition) or mismatched (i.e., mismatch condition) the shape implied by the sentence.

To reveal differences between the two hemispheres in the ability to activate implied shape information during sentence reading, in both languages, the shape effect (i.e., faster responses in the match relative to the mismatch condition) that was exhibited on RVF/LH trials, was compared with the effect obtained on LVF/RH trials. Note that the assumption of DVF studies is that the processing of target stimuli (i.e., the pictured objects in the current experiment) in each visual field presentation (RVF/LVF) reflects the processing influence of the centrally presented primes (i.e., the sentences in the current experiment) processed by the corresponding hemisphere (LH/RH respectively; e.g., Coulson et al., 2005).

The predictions of Exp. 3 were as follow. Given evidence suggesting that the RH specializes in processing non-verbal visual information (Corballis, 2003; Hugdahl, 2000), and specifically in processing the form features of visually perceived objects (Laeng et al., 2003), it was predicted that the shape effect would be stronger on LVF/RH trials, than on RVF/LH trials. In addition, the effect was expected to be stronger in the L1, than in the L2, because under CVF presentation, when target pictures were presented to both hemispheres (Exp. 1), only L1 sentences have yielded significant shape effect.

3.2.1.1. Method

Participants

The participants were 160[8] students from Tel Aviv University (53 males; 107 females). Their age ranged between 18-34 (Mean=24.2; SD=2.4). Participants' characteristics were the same as in the previous experiments.

L2 Proficiency Measures

The L2 proficiency measures that were collected were the same as in the previous experiments. See Table 1 for a summary of participants' proficiency measures in the L2-English.

[8] The number of participants per experimental list (n=10) was determined based on previous L1 studies that used the same task (Zwaan et al., 2002; Lincoln et al., 2007).

Materials

The stimuli (i.e., sentences and pictures) were identical to those used in Exp. 1, except that, in order to create the experimental lists, Target Language (L1-Hebrew/L2-English), Sentence Version (shape 1/shape 2), Picture Version (shape 1/shape 2), and Visual Field (RVF/LVF) were counterbalanced across 16 lists. Thus, each sub-list (L1-Hebrew/L2-English) consisted of 84 items – 28 critical items, which presented pictures of objects that were mentioned in the sentence ("Yes" response) and 56 filler items, which included 14 items presenting pictures of objects that were mentioned in the sentence ("Yes" response) and 42 items presenting pictures of objects that were not mentioned in the sentence ("No" response). In the critical sentence-picture combinations, there were 14 combinations in the match condition and 14 combinations in the mismatch condition. Importantly, in each shape condition, 7 pictures were presented in the RVF and 7 pictures were presented in the LVF. Similarly, in 28 filler items, pictures were presented in the RVF, and in the other 28 fillers, pictures were presented in the LVF. See Table 2 for examples of critical and filler items. See Appendix 2 for the full list of critical sentences and pictures.

Design

The experimental design was identical to that of Exp. 1, except that the Visual Field variable was also included. Thus, a 2x2x2 factorial design was used with Shape Condition (match/mismatch), Target Language (L1-Hebrew/L2-English) and Visual Field (RVF/LVF) as within-subject independent variables. However, the data analysis of this experiment eventually focused on first-block trials only (see the Results section for more details), resulting in a different design in which Target Language was a between-subject variable. Thus, looking only at first-block trials, each participant performed the task only in one language and saw only 28 out of the 56 critical items.

Procedure

Sessions: The session procedure was identical to that of the previous experiments.

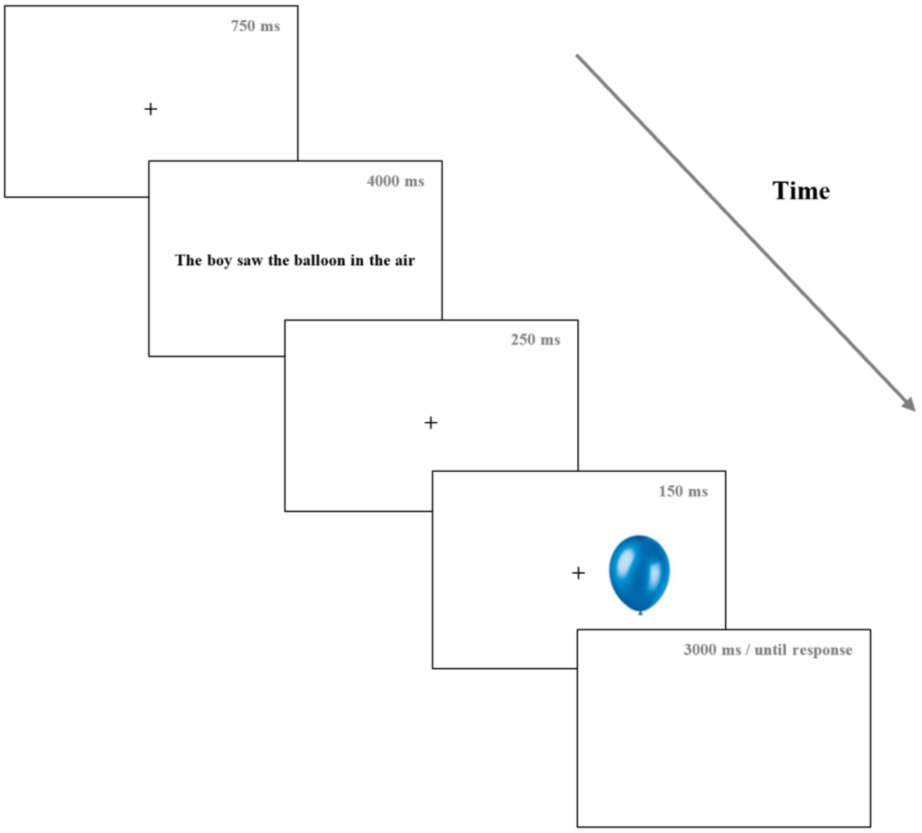
Block: The block procedure was identical to that of Exp. 1, except that target pictures were presented laterally, either in the RVF to the LH or in the LVF to the RH. In addition, to make sure that participants will not focus their gaze on either the RVF or the LVF prior to the presentation of target pictures, they were instructed to look at a fixation cross located at the center of the screen whenever it was displayed throughout the experiment. Like in Exp. 1, participants were instructed to respond with their right index finger by pressing the "Yes" or

"No" buttons in the response box. See Figure 4 for an example of the sequence of events in each trial.

Stimuli presentation: The stimuli presentation was identical to the one employed in Exp. 1, except that target pictures were displayed laterally, either in the RVF or in the LVF. Specifically, lateralized pictures were presented such that the distance from the center of the screen to the center of each picture was always 5.2 cm and subtended a horizontal visual angle of 5.2° at a viewing distance of 57 cm. In this manner, the distance from the center of the screen to the inner edge of the unframed pictures (i.e. the left edge of pictures presented in the RVF and the right edge of pictures presented in the LVF) was never closer than 2.2 cm and subtended at least 2.2° of horizontal visual angle (following Lincoln et al., 2007), and the distance from the center of the screen to the outer edge of unframed pictures (i.e. the right edge of pictures presented in the RVF and the left edge of pictures presented in the LVF) was never larger than 8.2 cm and subtended at most 8.2° of horizontal visual angle at a viewing distance of 57 cm.

Apparatus: The apparatus was identical to the one used in the previous experiments.

Figure 4: The sequence of events in each trial in Exp. 3



3.2.1.2. Results

Data analysis protocol

The procedure of data analysis was identical to the one employed in Exp. 1, except that the independent variable Visual Field (RVF/LVF) was added to the LME models that were fitted to the RT data and error data. In addition, in Exp. 3 only data from 'first-block' trials were analyzed. This was done since in Exp. 1, the interaction between Shape Condition, Target Language, and Experimental Block was significant, indicating that the shape effect, in both languages, was influenced by whether the task was done in the first or in the second block, assumingly due to cross-language influences on 'second-block' trials. Thus, in order to eliminate these possible cross-language influences on the exhibited shape effect in Exp. 3, it was decided to examine only data from 'first-block' trials, which as opposed to 'second-block' trials, could not have been affected by performing the task in the other language. Nevertheless, the entire dataset of Exp. 3 (first- and second- block trials) was also analyzed, revealing a similar pattern of results (see Appendix 5).

Thus, two LME models were fitted to the RT data and error data of 'first-block' trials in Exp. 3. Model 1 included the fixed main effects of Shape Condition, Target Language, and Visual Field, the interaction between them, and the random effects of Participants and Items. Model 2 included the fixed main effects of Shape Condition, Target Language, Visual Field, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items.

Data Cleanup

The entire dataset of 'first-block' trials, a total of 13440 trials (4480 critical trials and 8960 filler trials), was inspected in terms of accuracy rates per-participant as well as per-item, vocabulary knowledge of critical L2-items per-participant, and RT outliers.

First, accuracy rates were examined for each participant and item in each language. Participants and items that had a mean accuracy rate lower than 60%, in either the Hebrew or the English task, were excluded from analyses. None of the participants or items in Exp. 3 was rejected based on this criterion.

Next, 48 English trials that were incorrectly translated in the English-Hebrew translation post-test were removed, 24 trials with RT greater than 3000 ms or lower than 200 ms were removed, and 178 trials that fell outside the range of acceptable latencies (i.e., +/−

3.5 SD from participant's mean RT) were removed. This trimming procedure accounted for a total loss of 250 trials (1.9%). Finally, filler trials were excluded from the data.

RT Data

For the RT analyses, additional 125 critical trials (2.9%) were removed due to incorrect responses, and the final RT dataset consisted of correct critical trials only. Thus, 4242 data points (2135 in L1-Hebrew and 2107 in L2-English) that 160 participants produced by responding to 56 critical items were analyzed.

The comparison of Models 1 and 2 revealed that Model 2 did not fit the RT data better than Model 1 ($\chi^2(8)=3.53$, $p=.90$). Therefore, Model 1, which included the fixed main effects of Shape Condition, Target Language, and Visual Field, the interactions between them, and the random effects of Participants and Items, was selected for further analysis. Mean correct RTs (in ms) by Shape Condition, Visual Field, and Target Language, are presented in Table 6.

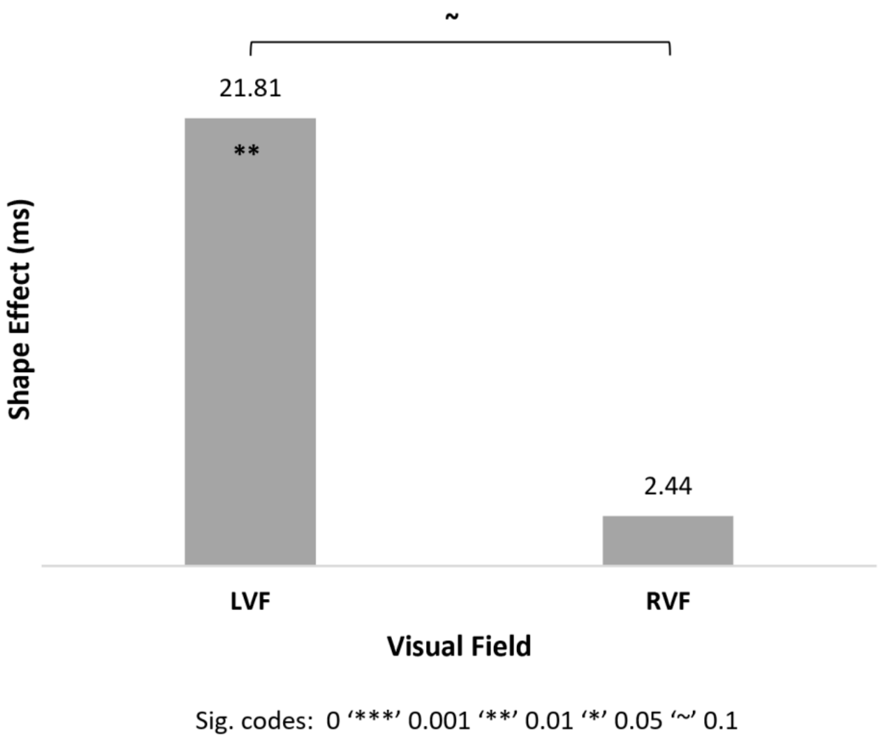
Table 6: Mean correct RTs (in ms) by Shape Condition, Visual Field, and Target Language in Exp. 3 (first-block trials)

Language	VF	ShapeCond	RT.mean	RT.sd	Effect
He	LVF	match	677.2131	217.0040	
He	LVF	mismatch	693.8144	214.0434	16.60
He	RVF	match	668.2019	207.7903	
He	RVF	mismatch	674.5338	214.8743	6.33
En	LVF	match	677.2958	200.8229	
En	LVF	mismatch	704.3276	237.0808	27.03
En	RVF	match	673.1922	233.8184	
En	RVF	mismatch	671.7011	212.1218	-1.49

Within Model 1, the main effect of Shape Condition was significant ($\chi^2(1)=6.46$, $p<.05$), indicating that overall responses to 'match' trials (Mean=673.95, SD=215.16) were faster than responses to 'mismatch' trials (Mean=686.09, SD=220.01). In addition, the main effect of Visual Field was significant ($\chi^2(1)=11.06$, $p<.001$), indicating that overall responses to ‘RVF’ trials (Mean=671.90, SD=217.26) were faster than responses to ‘LVF’ trials (Mean=688.12, SD=217.78).

More importantly, the interaction between Shape Condition and Visual Field was marginally significant ($\chi^2(1)=3.67$, $p=.055$). Examination of the shape effect separately in each Visual Field, revealed that on ‘LVF’ trials the effect was significant ($\chi^2(1)=9.96$, $p<.01$), such that responses to ‘match’ trials (Mean=677.25, SD=209.06) were significantly faster than responses to ‘mismatch’ trials (Mean=699.06, SD=225.78). However, on ‘RVF’ trials the effect was not reliable ($\chi^2(1)=.20$, $p=1.00$), such that responses to ‘match’ trials (Mean=670.69, SD=221.05) hardly differed from responses to ‘mismatch trials (Mean=673.13, SD=213.42). These results indicate that the shape effect was stronger in the RH, irrespective of Target Language. The shape effect (in ms) by Visual Field is illustrated in Figure 5.

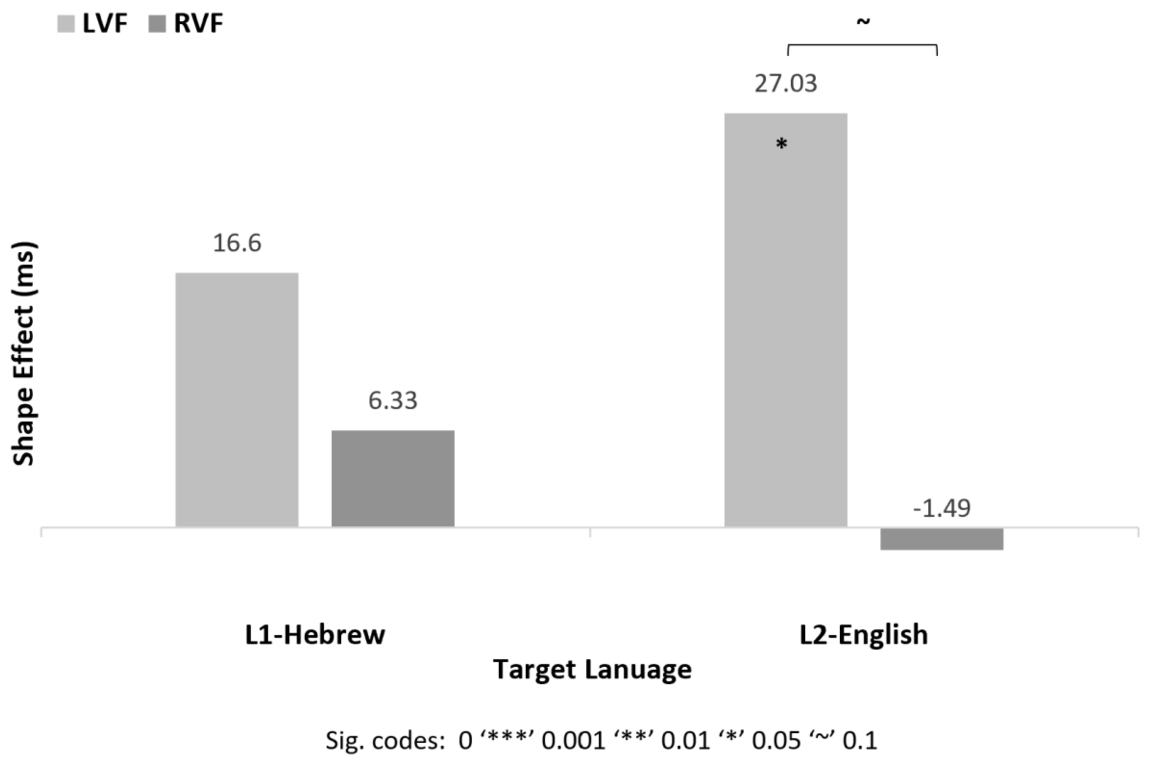
Figure 5: The shape effect (in ms) by Visual Field in Exp. 3 (first-block trials)



Planned chi-square tests: Even though the main effect of Target Language was not significant, and Target Language did not significantly interact with any of the variables of interest (i.e., Shape Condition, Visual Field), separate analyses were performed for each Target Language. This was done since it was initially hypothesized and was also supported by the results of Exp. 1, that the shape effect would be modulated by Target Language, such that the effect would be stronger in the L1-Hebrew, relative to the L2-English. Thus, to examine this hypothesis planned chi-square tests were performed testing the interaction between Visual Field and Shape Condition as well as the main effect of Shape Condition separately for each Target Language.

Examination of the two-way interaction between Shape Condition and Visual Field, separately for each Target Language, revealed that this interaction was marginally significant on ‘L2-English’ trials ($\chi^2(1)=3.91$, $p=.096$), but was not reliable on ‘L1-Hebrew’ trials ($\chi^2(1)=.55$, $p=.92$). Indeed, further examination of the shape effect in each Visual Field, separately for each Target Language, revealed that, while in the ‘L1-Hebrew’ the effect was not reliable, neither on ‘LVF’ ($\chi^2(1)=2.89$, $p=.36$) nor on ‘RVF’ trials ($\chi^2(1)=.44$, $p=1.00$), in the ‘L2-English’, the effect was significant on ‘LVF’ trials ($\chi^2(1)=7.62$, $p<.05$), but not on ‘RVF’ trials ($\chi^2(1)=.00$, $p=1.00$), indicating that the RH-LH difference in the shape effect was more pronounced in the ‘L2-English’ than in the ‘L1-Hebrew’. The shape effect (in ms) by Visual Field and Target Language is illustrated in Figure 6

Figure 6: The shape effect (in ms) by Visual Field and Target Language in Exp. 3 (first-block trials)



Error Data

The final error dataset consisted of critical trials only. Thus, 4367 data points (2207 in L1-Hebrew and 2160 in L2-English) that 160 participants produced by responding to 56 critical items were analyzed.

The comparison of Models 1 and 2 revealed that Model 2 did not fit the error data significantly better than Model 1 ($\chi^2(8)=7.18$, $p=.52$). Therefore, Model 1, which included the fixed main effects of Shape Condition, Target Language, and Visual Field, the interactions between them, and the random effects of Participants and Items, was selected for further analysis.

Within Model 1, the main effect of Shape Condition was marginally significant ($\chi^2(1)=3.63$, $p=.057$), indicating that overall 'match' trials (Mean=.024, SD=.154) resulted in a lower error rate than 'mismatch' trials (Mean=.033, SD=.179).

3.2.1.3. Discussion

The RT data of Exp. 3 revealed a significant shape effect, irrespective of the language involved. Importantly this shape effect was modulated by visual field presentation, such that LVF/RH presentation resulted in a significant effect, while RVF/LH presentation resulted in a non-significant effect. Such results indicate that perceptual visual simulations during sentence reading are more extensively activated in the RH, than in the LH; and are consistent with the notion that the RH is more efficient in processing perceptual visual input (Corballis, 2003; Hugdahl, 2000), and more specifically, in processing the form features of visually perceived objects (Laeng et al., 2003).

Although the three-way interaction between Shape Condition, Visual Field, and Target Language was not significant, examination of the interaction between Shape Condition and Visual Field separately for each language, revealed that this hemispheric asymmetry in the ability to activate perceptual visual information during sentence processing, was more pronounced in the L2 than in the L1. Specifically, in the L2-English, the RH produced a significant shape effect, whereas in the LH the effect was not evident at all. Alternatively, in the L1-Hebrew, a similar pattern was observed in both hemispheres - responses were faster in the match than in the mismatch condition, but the effect did not reach significance. This, together with the results of Exp. 1 (CVF presentation), suggests that the two hemispheres may be differently engaged during L1 and L2 sentence processing. To explore this possibility, additional analyses were conducted, in which performance patterns (i.e., the shape effect) that were observed under CVF presentation (Exp. 1) were compared with those observed under LVF or RVF presentations (Exp. 3).

3.2.1.4. <u>Central vs. unilateral presentations</u>

The comparison of task performance when stimuli are presented unilaterally to one hemisphere (i.e., in the LVF to the RH or in the RVF to the LH) to the performance when stimuli are presented centrally to both hemispheres (i.e., in the CVF) can reveal the patterns of interhemispheric interactions – what is the hemispheric division of labor during natural (central) reading. If both hemispheres contribute to meaning comprehension during natural reading (i.e., interhemispheric integration or summation), then central presentation should elicit different response patterns than unilateral presentation. However, if natural reading is controlled by one hemisphere (i.e., interhemispheric control or metacontrol), 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 (e.g., Eviatar, Hellige, & Zaidel, 1997; Luh & Levy, 1995; Peleg & Eviatar, 2017).

Thus, to further examine the extent to which each hemisphere contributes to the activation of implied shape information under natural reading conditions (i.e., CVF presentation), the results from the central (Exp. 1) and unilateral (Exp. 3) experiments were compared. Given the results of Exp. 1 and Exp. 3, we speculated that in the case of L1 processing, task performance under central viewing reflects interhemispheric interaction, in which both hemispheres contribute to the shape effect, whereas in the case of L2 processing, task performance under central viewing is controlled by the LH, and thus, mainly reflects LH processing, under which the shape effect was not evident.

<u>Data analysis protocol</u>

To this end, two analyses were conducted. The first analysis compared LVF and CVF trials, whereas the second analysis compared RVF and CVF trials. In addition, like in Exp. 3, in both analyses, only data from ‘first-block’ trials were included. Thus, for each analysis, two LME models were initially fitted to the RT data and error data of ‘first-block’ trials from Exp. 1 and Exp. 3. Model 1 included the fixed main effects of Shape Condition, Target Language, and Visual Field, the interaction between them, and the random effects of Participants and Items. Model 2 included the fixed main effects of Shape Condition, Target

Language, Visual Field and English Proficiency Score, the interactions between them, and the random effects of Participants and Items.

Data Cleanup

As was done in previous analyses, the entire dataset of 'first-block' trials from Exp. 1 and Exp. 3, a total of 20160 trials (6720 critical trials and 13440 filler trials), was inspected in terms of accuracy rates per-participant as well as per-item, vocabulary knowledge of critical L2-items per-participant, and RT outliers.

First, accuracy rates were examined for each participant and item in each language. Participants and items that had a mean accuracy rate lower than 60%, in either the Hebrew or the English task, were excluded from analyses. None of the participants or items in Exp. 1 and Exp. 3 was rejected based on this criterion.

Next, 63 English trials that were incorrectly translated in the English-Hebrew translation post-test were removed, 28 trials with RT greater than 3000 ms or lower than 200 ms were removed, and 225 trials that fell outside the range of acceptable latencies (i.e., +/− 3.5 SD from participant's mean RT) were removed. This trimming procedure accounted for a total loss of 316 trials (1.6%). Finally, filler trials were excluded from the data, and for the RT analyses, additional 177 critical trials (2.7%) were removed due to incorrect responses.

The final RT dataset consisted of correct critical trials only. Thus, 6391 data points (3214 in L1-Hebrew and 3177 in L2-English) that 240 participants produced by responding to 56 critical items were analyzed. The final error dataset consisted of critical trials only. Thus, 6568 data points (3319 in L1-Hebrew and 3249 in L2-English) that 160 participants produced by responding to 56 critical items were analyzed.

LVF-CVF analysis

RT data: To compare the speed performance under LVF and CVF presentations, while considering the possible influence of English Proficiency Score, two LME models were fitted to the RT data of LVF and CVF trials, as detailed above. The comparison of Models 1 and 2 revealed that Model 2 did not fit the RT data significantly better than Model 1 ($\chi^2(8)=2.41$, $p=.97$). Therefore, Model 1, which included the fixed main effects of Shape Condition, Target Language, and Visual Field (LVF/CVF), the interactions between them, and the random effects of Participants and Items, was selected for further analyses. Mean correct RTs (in ms) by Shape Condition, Visual Field, and Target language, are presented in Table 7.

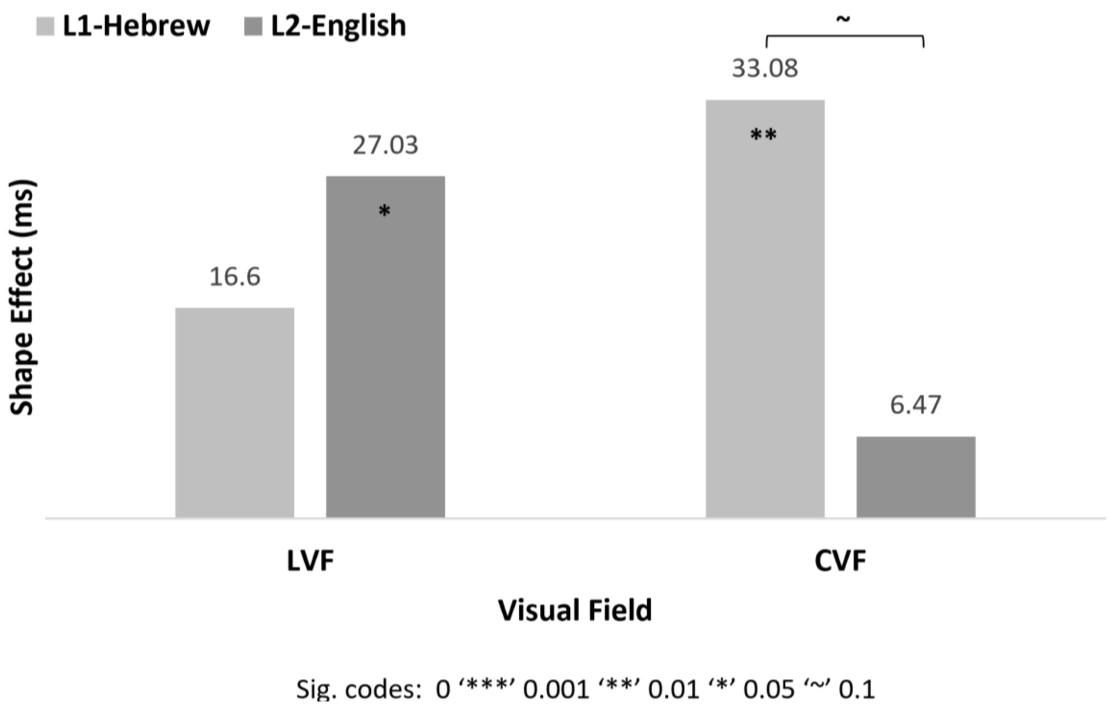
Table 7: Mean correct RTs (in ms) by Shape Condition, Visual Field, and Target Language in the LVF-CVF analysis

Language	VF	ShapeCond	RT.mean	RT.sd	Effect
He	CVF	match	590.5387	188.2277	
He	CVF	mismatch	623.6220	206.0927	33.08
He	LVF	match	677.2131	217.0040	
He	LVF	mismatch	693.8144	214.0434	16.6
En	CVF	match	648.4259	214.2448	
En	CVF	mismatch	654.8994	222.8815	6.47
En	LVF	match	677.2958	200.8229	
En	LVF	mismatch	704.3276	237.0808	27.03

Within Model 1, the main effect of Shape Condition was significant ($\chi^2(1)=17.42$, $p<.001$), such that 'match' trials (Mean=648.03, SD=208.27) were faster than 'mismatch' trials (Mean=668.86, SD=222.43). In addition, the main effect of Visual Field was significant ($\chi^2(1)=11.81$, $p<.001$), such that 'CVF' trials (Mean=629.25, SD=209.59) were faster than 'LVF' trials (Mean=688.12, SD=217.78).

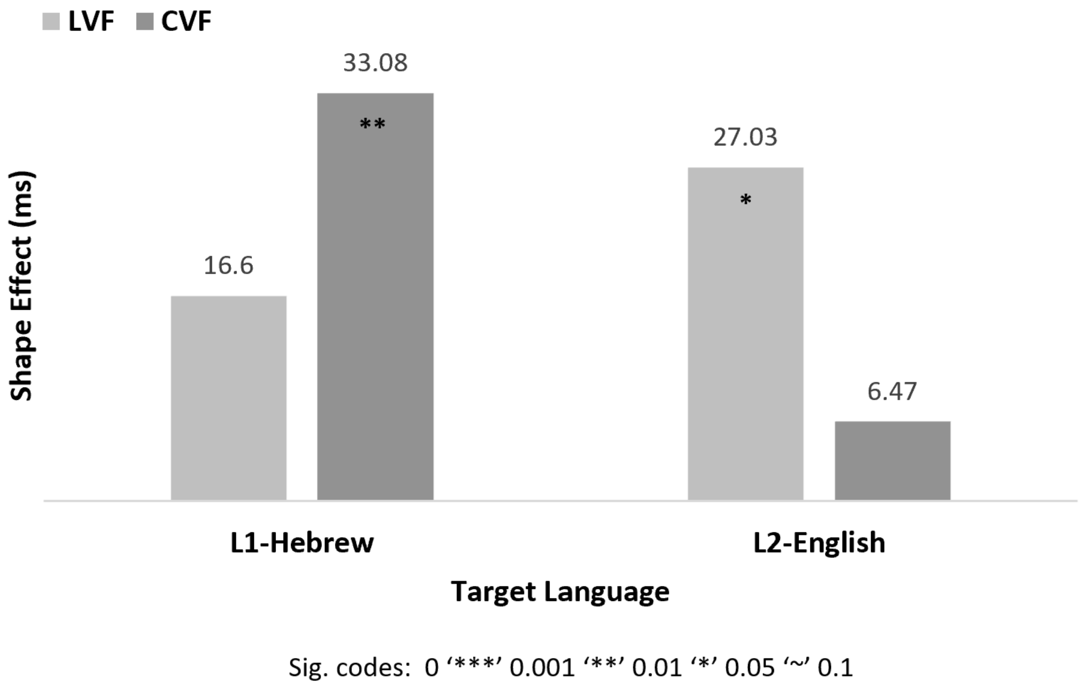
More importantly, the three-way interaction between Shape Condition, Target Language, and Visual Field was marginally significant ($\chi^2(1)=3.72$, $p=.054$). Examination of the two-way interaction between Shape Condition and Target Language, separately for each Visual Field, revealed that, while on 'CVF' trials this interaction was marginally significant ($\chi^2(1)=3.92$, $p=.095$), on 'LVF' trials it was not reliable ($\chi^2(1)=.57$, $p=.90$). Further examination of the shape effect in each Target Language, separately for each Visual Field, revealed that in the 'CVF', the effect was significant on 'L1-Hebrew' trials ($\chi^2(1)= 10.84$, $p<.01$), but not on 'L2-English' trials ($\chi^2(1)= .24$, $p=1.00$). However, in the 'LVF', the effect was significant on 'L2-English' trials ($\chi^2(1)= 7.90$, $p<.05$), but not on 'L1-Hebrew' trials ($\chi^2(1)= 3.10$, $p=.31$). These results suggest that L1 and L2 processing differed, in terms of the exhibited shape effect, under both central (CVF) and unilateral (LVF/RH) viewing, yet i\ opposite directions and to different extent. Namely, while in the CVF the shape effect was significant only in the L1, in the LVF the effect was significant only in the L2. In addition, the processing difference between the two languages was more pronounced in the CVF. The shape effect (in ms) by Target Language and Visual Field is illustrated in Figure 7.

Figure 7: The Shape effect (in ms) by Target Language and Visual Field in the LVF-CVF analysis



Furthermore, examination of the two-way interaction between Shape Condition and Visual Field, separately for each Target Language, revealed that this interaction was not significant, neither on 'L1-Hebrew' trials ($\chi^2(1)$= 1.14, p=.57) nor on 'L2-English' trials ($\chi^2(1)$=2.76, p=.14), indicating that within each language, CVF presentation did not significantly differ from LVF/RH presentation. Nevertheless, while in the 'L1-Hebrew' the shape effect was significant only on 'CVF' trials ($\chi^2(1)$= 10.84, p<.01), in the 'L2-English' the effect was significant only on 'LVF' trials ($\chi^2(1)$= 7.90, p<.05), suggesting that in both languages, CVF presentation differed to some extent from LVF/RH presentation, though in opposite directions. The shape effect (in ms) by Visual Field and Target Language is illustrated in Figure 8.

Figure 8: The shape effect (in ms) by Visual Field and Target Language in the LVF-CVF analysis



Error data: To compare the accuracy performance under LVF and CVF presentations, while considering the possible influence of English Proficiency Score, two LME models were fitted to the error data of LVF and CVF trials, as detailed above. The comparison of Models 1 and 2 revealed that Model 2 fitted the error data significantly better than Model 1 ($\chi^2(8)=19.42$, $p<.05$). Therefore, Model 2, which included the fixed main effects of Shape Condition, Target Language, Visual Field, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items, was selected for further analysis.

Within Model 2, the main effect of Target Language was marginally significant ($\chi^2(1)=3.21$, $p=.073$), indicating that 'L2-English' trials (Mean=.022, SD=.147) resulted in a lower error rate than 'L1-Hebrew' trials (Mean=.032, SD=.175). In addition, the main effect of English Proficiency Score was significant, indicating that participants with 'high-score' (Mean=.019, SD=.138) exhibited a lower error rate than participants with 'low-score' (Mean=.033, SD=.177). Moreover, the interaction between Visual Field and English Proficiency Score was significant ($\chi^2(1)=6.74$, $p<.01$). Examination of the effect of Visual Field in each English Proficiency Group (see footnote 5) revealed that the error difference between 'LVF' and 'CVF' trials was not significant, neither for participants with 'high-score'

($\chi^2(1)$=.27, p=1.00) nor for participants with ‘low-score’ ($\chi^2(1)$=.17, p=1.00), suggesting that the effect of Visual Field on accuracy performance was relatively weak in both groups of participants.

RVF-CVF analysis

RT data: To compare the speed performance under RVF and CVF presentations, while considering the possible influence of English Proficiency Score, two LME models were fitted to the RT data of RVF and CVF trials, as detailed above. The comparison of Models 1 and 2 revealed that Model 2 did not fit the RT data significantly better than Model 1 ($\chi^2(8)$=4.06, p=.85). Therefore, Model 1, which included the fixed main effects of Shape Condition, Target Language, and Visual Field (RVF/CVF), the interactions between them, and the random effects of Participants and Items, was selected for further analysis. Mean correct RTs (in ms) by Shape Condition, Visual Field (RVF/CVF), and Target language, are presented in Table 8.

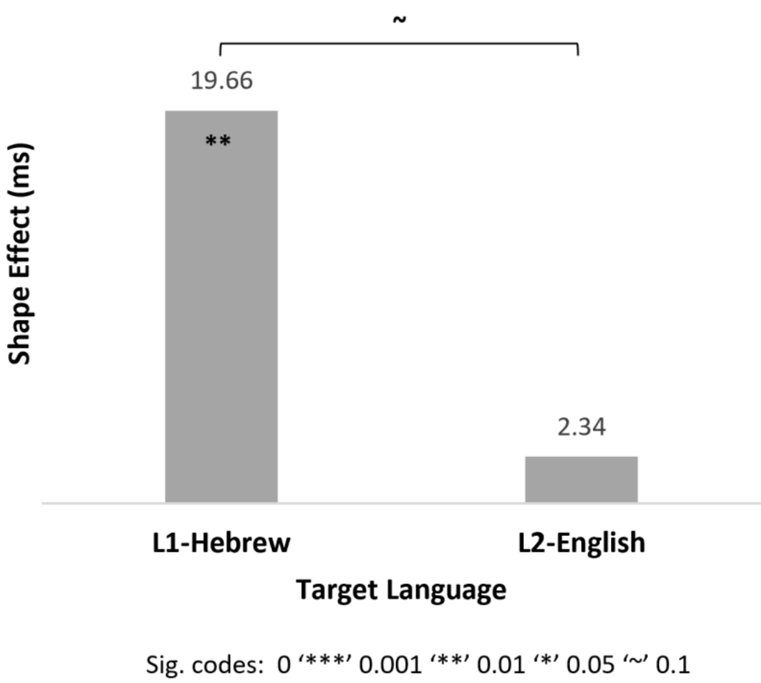
Table 8: Mean correct RTs (in ms) by Shape Condition, Visual Field, and Target Language in the RVF-CVF analysis

Language	VF	ShapeCond	RT.mean	RT.sd	Effect
He	CVF	match	590.5387	188.2277	
He	CVF	mismatch	623.6220	206.0927	33.08
He	RVF	match	668.2019	207.7903	
He	RVF	mismatch	674.5338	214.8743	6.33
En	CVF	match	648.4259	214.2448	
En	CVF	mismatch	654.8994	222.8815	6.47
En	RVF	match	673.1922	233.8184	
En	RVF	mismatch	671.7011	212.1218	-1.49

Within Model 1, the main effect of Shape Condition was significant ($\chi^2(1)$=4.97, p<.05), indicating that ‘match’ trials (Mean=644.98, SD=213.98) were faster than ‘mismatch’ trials (Mean=656.04, SD=214.90). In addition, the main effect of Visual Field was significant ($\chi^2(1)$=6.00, p<.05), such that ‘CVF’ trials (Mean=629.25, SD=209.59) were faster than ‘RVF’ trials (Mean=671.90, SD=217.26).

More importantly, the two-way interaction between Shape Condition and Target Language was marginally significant ($\chi^2(1)=3.31$, $p=.069$). Further examination of the shape effect in each Target Language revealed that in the 'L1-Hebrew', the effect was significant ($\chi^2(1)=8.14$, $p<.01$), such that responses to 'match' trials (Mean=629.30, SD=201.91) were significantly faster than responses to 'mismatch' trials (Mean=648.96, SD=211.95). However, in the 'L2-English', the effect was not reliable ($\chi^2(1)=.08$, $p=1.00$), such that responses to 'match' trials (Mean=660.84, SD=224.51) and to 'mismatch' trials (Mean=663.18, SD=217.70) hardly differed. The shape effect (in ms) by Target Language is illustrated in Figure 9.

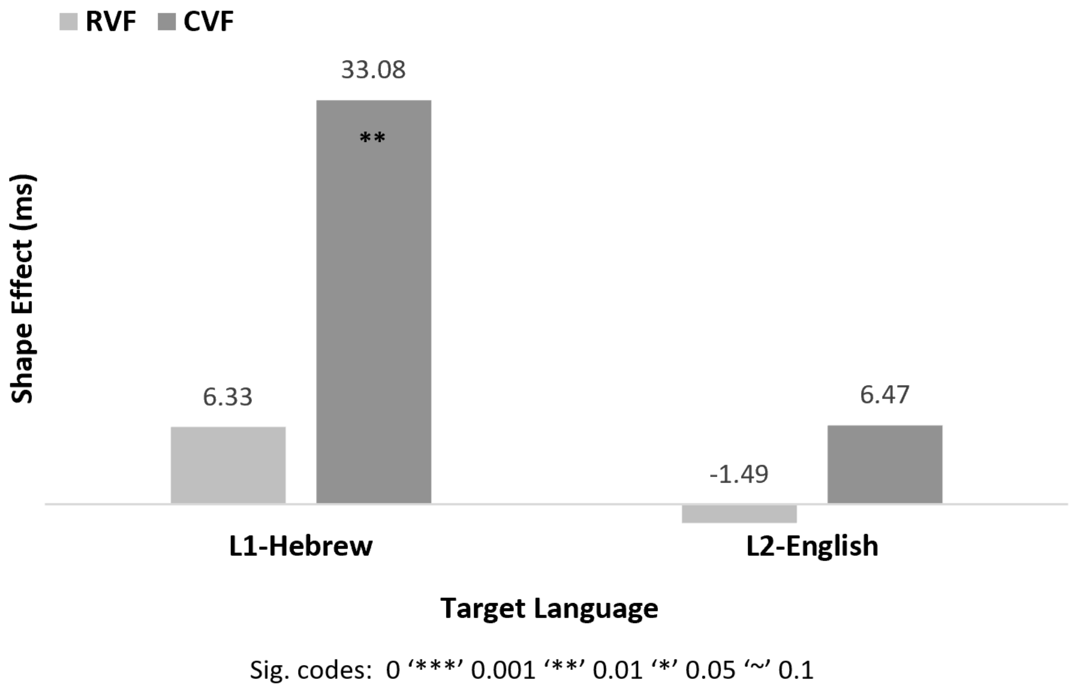
Figure 9: The shape effect (in ms) by Target Language in the RVF-CVF analysis



Planned chi-square tests: Examination of the two-way interaction between Shape Condition and Visual Field, separately for each Target Language, revealed that this interaction was not reliable, neither on 'L1-Herbrew' trials ($\chi^2(1)=3.22$, $p=.15$) nor on 'L2-English' trials ($\chi^2(1)=.15$, $p=1.00$), suggesting that CVF presentation did not significantly differ from RVF/LH presentation, in terms of the exhibited shape effect, in both languages.

However, examination of the shape effect in each Visual Field, separately for each Target Language, revealed that in the 'L1-Herbew', the effect was significant on 'CVF' trials ($\chi^2(1)=10.85$, $p<.01$) but not on 'RVF' trials ($\chi^2(1)=.56$, $p=1.00$), whereas in the 'L2-English', the effect was not reliable neither on ‘CVF’ trials ($\chi^2(1)$=.23, p=1.00) nor on ‘RVF’ trials ($\chi^2(1)$=.01, p=1.00). These results suggest that while in the ‘L1-Hebrew’, the pattern of the shape effect obtained under CVF presentation (i.e., a significant effect) differed to some extent from the pattern obtained under RVF/LH processing (i.e., a non-significant effect), in the ‘L2-English’, the patterns of the shape effect obtained under CVF and RVF/LH presentations were similar (i.e., a non-significant effect). The shape effect (in ms) by Visual Field and Target Language is illustrated in Figure 10.

Figure 10: The shape effect (in ms) by Visual Field and Target Language in the RVF-CVF analysis



Error data: To compare the accuracy performance under RVF and CVF presentations, while considering the possible influence of English Proficiency Score, two LME models were fitted to the error data of RVF and CVF trials, as detailed above. The comparison of Models 1 and 2 revealed that Model 2 fitted the error data better than Model 1 ($\chi^2(8)$=14.34, p=.07). Therefore, Model 2, which included the fixed main effects of Shape Condition, Target Language, Visual Field, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items, was selected for further analysis.

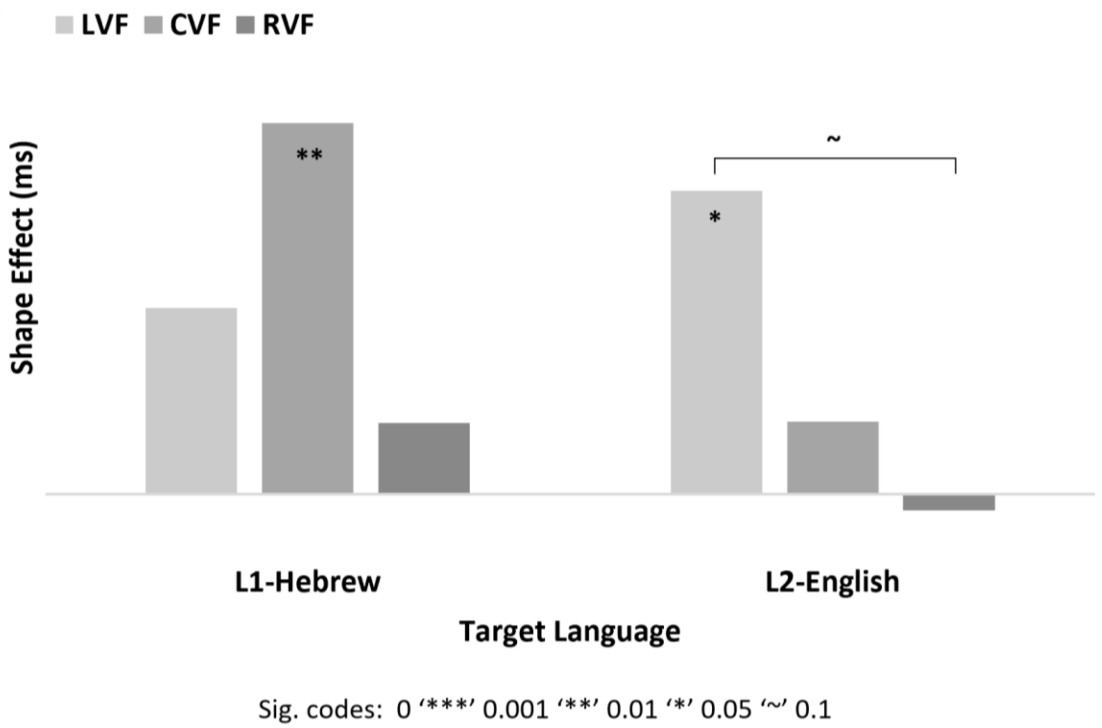
Within Model 2, the main effect of Shape Condition was marginally significant ($\chi^2(1)=3.51$, $p=.061$), indicating that 'match' trials (Mean=.022, SD=.146) resulted in a lower error rate than 'mismatch' trials (Mean=.030, SD=.171). Moreover, the interaction between Visual Field and English Proficiency Score was significant ($\chi^2(1)=8.18$, $p<.01$). Examination of the effect of Visual Field in each English Proficiency Group (see footnote 5) revealed that the error difference between 'RVF' and 'CVF' trials was not significant, neither for participants with 'high-score' ($\chi^2(1)=.00$, $p=1.00$) nor for participants with 'low-score' ($\chi^2(1)=.05$, $p=1.00$), suggesting that the effect of Visual Field on accuracy performance was relatively weak in both groups of participants.

Discussion

The results of the RT analyses, comparing LVF-CVF and RVF-CVF trials, demonstrate that, in both languages, the CVF patterns did not significantly differ from either of the peripheral visual fields, suggesting that both hemispheres may be involved in natural L1 and L2 reading. Nevertheless, the examination of the shape effect in the three visual fields (see Figure 11 below) suggests that different patterns of hemispheric involvement may be employed during natural reading in each language. As illustrated in Figure 11, in the L1, the construction of visual simulations during natural (central) reading seems to require both hemispheres, as the shape effect was significantly evident only when target pictures were presented in the CVF to both hemispheres, but was not reliable when target pictures were presented only to one hemisphere, in the LVF/RH or in the RVF/LH. Namely, natural (central) L1 reading reflects interhemispheric interaction, in which both hemispheres contribute to reading performance. However, in the L2, the shape effect was significantly evident only in the LVF/RH but was not reliable in the RVF/LH nor in the CVF. Thus, in the L2, the performance pattern in the CVF is more similar to the performance pattern in the RVF/LH (in both cases the shape effect was not significant) than to the performance observed in the LVF/RH (in this case the shape effect was significant). Namely, natural (central) L2 reading mainly reflects LH processing.

Taken together, these results suggest that under typical (central) reading conditions, the involvement of the RH is greater in the L1 than in the L2, at least in the case of unbalanced late bilinguals who learned their L2 in a formal manner, outside of the environment where it is commonly and naturally spoken. Given that the shape effect was more pronounced in the RH than in the LH, irrespective of language (Exp. 3), this L1-L2 difference in the degree to which the RH is involved in natural reading, may explain why visual shape simulations are evident in natural L1 reading but not in natural L2 reading (Exp. 1).

Figure 11: The shape effect (in ms) in the three visual fields in each Target Language



3.2.2. *Experiment 4: Visual simulations of spatial location during word reading*

Although under central presentation of word-pairs, the spatial effect was not significantly evident in both languages (Exp. 2), the results of Exp. 3 justify further examination of the spatial effect under unilateral presentation of word-pairs. That is, in Exp. 3, a significant shape effect in the L2 was demonstrated under LVF/RH presentation, even though such an effect was not exhibited in Exp. 1 under CVF presentation. Therefore, it is possible that if the processing of target word-pairs will occur independently in each hemisphere, the spatial effect will be exhibited, assumingly because some processes may occur automatically in either the RH or the LH but may not influence natural reading due to the pattern of hemispheric involvement.

Thus, Exp. 4 examined the separate ability of the RH and the LH to simulate visual information about the typical spatial location of mentioned objects during L1 and L2 word reading. To this end, the semantic judgment task was used (Exp. 2) in conjunction with the DVF technique (Zwaan & Yaxley, 2003b). Thus, in both the L1-Hebrew block and the L2-

English block, word-pairs were presented laterally, either in the RVF to the LH or in the LVF to the RH. In each trial, participants had to decide whether or not the two words (e.g., car-road), which were displayed one above the other on the screen, are semantically related. On critical trials, the two words were semantically and spatially related, however, their spatial arrangement on the screen could have either matched (i.e., match condition) or mismatched (i.e., mismatch condition) the typical spatial relation of their referents in the world.

To reveal differences between the two hemispheres in the ability to activate visual spatial information during word reading, in both languages, the spatial effect (i.e., faster responses in the match relative to the mismatch condition) that was exhibited on RVF/LH trials was compared to the effect obtained on LVF/RH trials. Since it was assumed that the RH plays an important role in the construction of visual simulations, it was predicted that the spatial effect would be stronger on LVF/RH trials than on RVF/LH trials.

3.2.2.1. Method

Participants

The participants were 80[9] students from Tel Aviv University (27 males; 53 females). Their age ranged between 19-34 (Mean=24.5; SD=2.57). Participants' characteristics were the same as in the previous experiments.

L2 Proficiency Measures

The L2 proficiency measures that were collected were the same as in the previous experiments. See Table 1 for a summary of participants' proficiency measures in the L2-English.

Materials

The stimuli (i.e., word-pairs) were identical to those used in Exp. 2, except that, in order to create the experimental lists, Target Language (L1-Hebrew/L2-English), Spatial Condition (match/mismatch), and Visual Field (RVF/LVF) were counterbalanced across 8 lists. Thus, each sub-list (L1-Hebrew/L2-English) consisted of 84 items – 28 critical items, which consisted of vertically and semantically related word-pairs ("Yes" response), and 56

[9] The number of participants per experimental list (n=10) was determined based on previous L1 studies that used the same task (Zwaan & Yaxley, 2003a; 2003b) and the number of critical items that were used in the current study.

filler items, which consist of 14 semantically related word-pairs (“Yes” response) and 42 semantically unrelated word-pairs with no vertical relation (“No” response). Importantly, in the critical items, 14 word-pairs were presented in the match condition and 14 word-pairs were presented in the mismatch condition. In addition, in each spatial condition, 7 word-pairs were displayed in the RVF and 7 word-pairs were displayed in the LVF. Similarly, in the filler items, 28 word-pairs were presented in the RVF, and 28 word-pairs were presented in the LVF. See Table 4 for examples of critical and filler items. See Appendix 3 for the full list of critical word-pairs.

Design

The experimental design was identical to that of Exp. 2, except that the Visual Field variable was also included. Thus, a 2x2x2 factorial design was used with Spatial Condition (match/mismatch), Target Language (L1-Hebrew/L2-English), and Visual Field (RVF/LVF) as within-subject independent variables.

Procedure

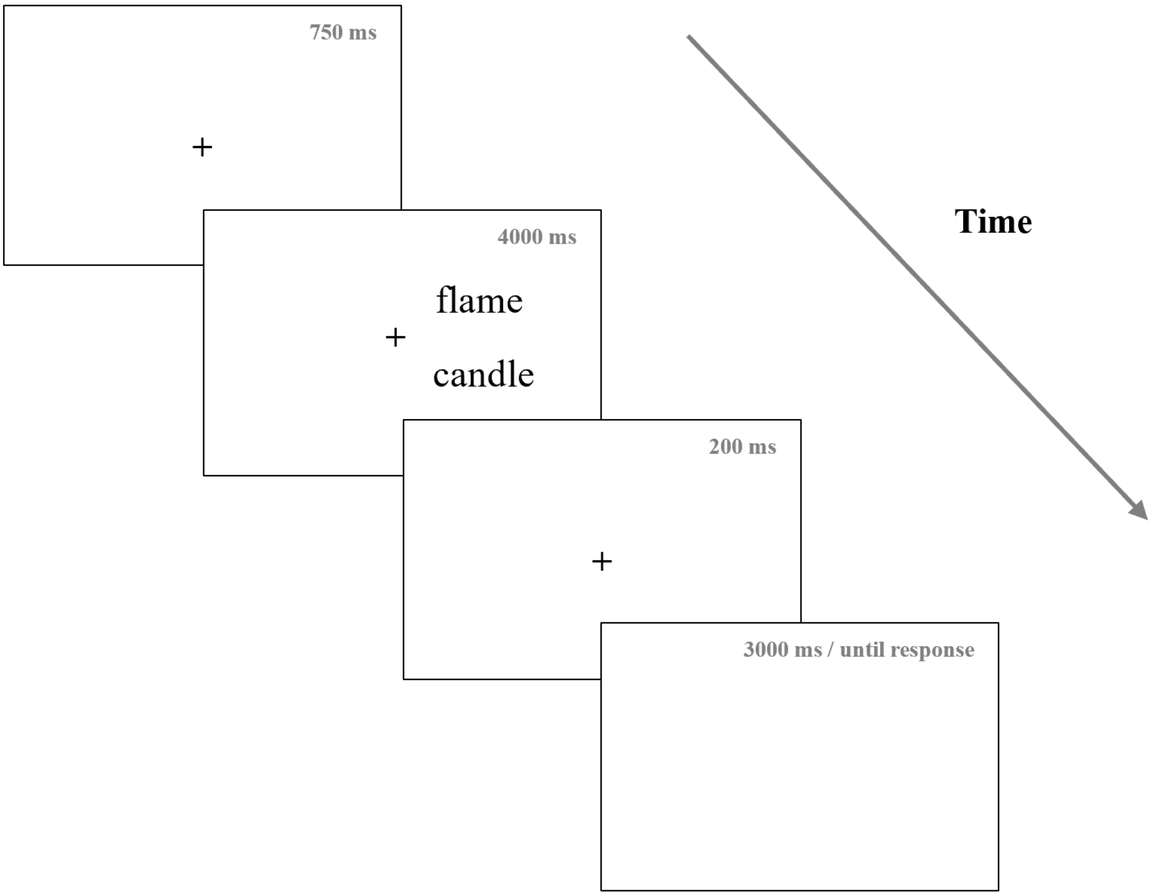
Sessions: The session procedure was identical to that of the previous experiments.

Block: The block procedure was identical to that of Exp. 2, except that target word-pairs were presented laterally, either in the RVF to the LH or in the LVF to the RH. In addition, to ensure that participants did not focus their gaze on either the RVF or the LVF prior to the presentation of word-pairs, they were instructed to look at a fixation cross located at the center of the screen whenever it was displayed throughout the experiment. See Figure 12 for an example of the sequence of events in each trial.

Stimuli presentation: The stimuli presentation was identical to the one employed in Exp. 2, except that target word-pairs were presented laterally, either in the RVF or in the LVF. Specifically, lateralized word-pairs were presented such that the distance from the center of the screen to the center of each lateralized word-pair was always 3 cm and subtended a horizontal visual angle of 3°. In this manner, the distance from the center of the screen to the inner edge of words (i.e. the left edge of words presented in the RVF and the right edge of words presented in the LVF) was at least 1.5 cm and subtended at least 1.5° of horizontal visual angle. In addition, the distance from the center of the screen to the outer edge of words (i.e. the right edge of words presented in the RVF and the left edge of words presented in the LVF) was at most 4.5 cm and subtended at most 4.5° of horizontal visual angle, at a viewing distance of 57 cm.

Apparatus: The apparatus was identical to the one used in the previous experiments.

Figure 12: The sequence of events in each trial in Exp. 4



3.2.2.2. <u>Results</u>

<u>Data analysis protocol</u>

The procedure of data analysis was identical to the one employed in Exp. 2, except that the variable Visual Field (RVF/LVF) was added to the three LME models that were fitted to the RT data and error data. Like in Exp. 2, the data analysis included the entire dataset (i.e., first- and second-block trials). Thus, Model 1 included the fixed main effects of Spatial Condition, Target Language, and Visual Field, the interaction between them, and the random effects of Participants and Items. Model 2 included the fixed main effects of Spatial Condition, Target Language, Visual Field and Experimental Block, the interactions between them, and the random effects of Participants and Items. Model 3 included the fixed main effects of Spatial Condition, Target Language, Visual Field, Experimental Block, and English

Proficiency Score, the interactions between them, and the random effects of Participants and Items.

Data Cleanup

The entire dataset, a total of 13440 trials (4480 critical trials and 8960 filler trials), was inspected in terms of accuracy rates per-participant as well as per-item, vocabulary knowledge of critical L2-items per-participant, and RT outliers.

First, accuracy rates were examined for each participant and item in each language. Participants and items that had a mean accuracy rate lower than 60%, in either the L1-Hebrew experiment or the L2-English experiment, were excluded from analyses. Based on this criterion, 4 participants and 15 items were excluded from the data, resulting in a total loss of 1812 trials (13.5%).

Next, 194 English trials that were incorrectly translated in the English-Hebrew translation post-test were removed, 123 trials with RT greater than 3000 ms or lower than 200 ms were removed, and 54 trials that fell outside the range of acceptable latencies (i.e., +/− 3.5 SD from participant's mean RT) were removed. This trimming procedure accounted for a total loss of 371 trials (3.2%). Finally, filler trials were excluded from the data.

RT Data

For the RT analysis, additional 410 critical trials (14.3%) were removed due to incorrect responses. The final RT dataset consisted of correct critical trials only. Thus, 2467 data points (1393 in L1-Hebrew and 1074 in L2-English) that 76 participants produced by responding to 41 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 3, fitted the RT data significantly better than Model 1 and Model 2 ($\chi^2(16)=41.73$, $p<.001$). Therefore, Model 3, which included the fixed main effects of Spatial Condition, Target Language, Visual Field, Experimental Block, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items, was selected for further analysis. Mean correct RTs (in ms) by Spatial Condition, Visual Field, Target language, Experimental Block, and English Proficiency Group (see footnote 5) are presented in Table 9.

Table 9: Mean correct RTs (in ms) by Spatial Condition, Visual Field, Target Language, Experimental Block, and English Proficiency Group in Exp. 4

ExpBlock	EnProfGroup	Language	VF	SpatialCond	RT.mean	RT.sd	Effect
First	High	He	LVF	match	989.24	285.51	
First	High	He	LVF	mismatch	952.88	242.64	-36.57
First	High	He	RVF	match	995.73	292.87	
First	High	He	RVF	mismatch	1024.62	345.69	28.89
First	High	En	LVF	match	1213.75	249.64	
First	High	En	LVF	mismatch	1299.25	303.35	85.5
First	High	En	RVF	match	1308.54	387.36	
First	High	En	RVF	mismatch	1274.85	319.38	-33.69
First	Low	He	LVF	match	979.35	272.69	
First	Low	He	LVF	mismatch	971.12	250.51	-8.23
First	Low	He	RVF	match	952.79	247.63	
First	Low	He	RVF	mismatch	961.33	276.24	8.54
First	Low	En	LVF	match	1288.79	287.27	
First	Low	En	LVF	mismatch	1323.68	325.73	34.89
First	Low	En	RVF	match	1240.52	304.82	
First	Low	En	RVF	mismatch	1266.49	303.68	25.97
Second	High	He	LVF	match	1000.25	241.18	
Second	High	He	LVF	mismatch	1000.83	256.98	0.58
Second	High	He	RVF	match	1017.29	335.56	
Second	High	He	RVF	mismatch	1033.79	265.17	16.5
Second	High	En	LVF	match	1209.96	308.55	
Second	High	En	LVF	mismatch	1270.85	418.91	60.89
Second	High	En	RVF	match	1166.99	371.69	
Second	High	En	RVF	mismatch	1142.45	271.56	-24.54
Second	Low	He	LVF	match	945.30	218.10	
Second	Low	He	LVF	mismatch	913.16	220.01	-32.14
Second	Low	He	RVF	match	957.11	300.67	
Second	Low	He	RVF	mismatch	924.72	245.50	-32.39
Second	Low	En	LVF	match	1369.76	467.72	
Second	Low	En	LVF	mismatch	1312.85	375.41	-56.91
Second	Low	En	RVF	match	1401.40	424.97	
Second	Low	En	RVF	mismatch	1275.45	320.94	-125.95

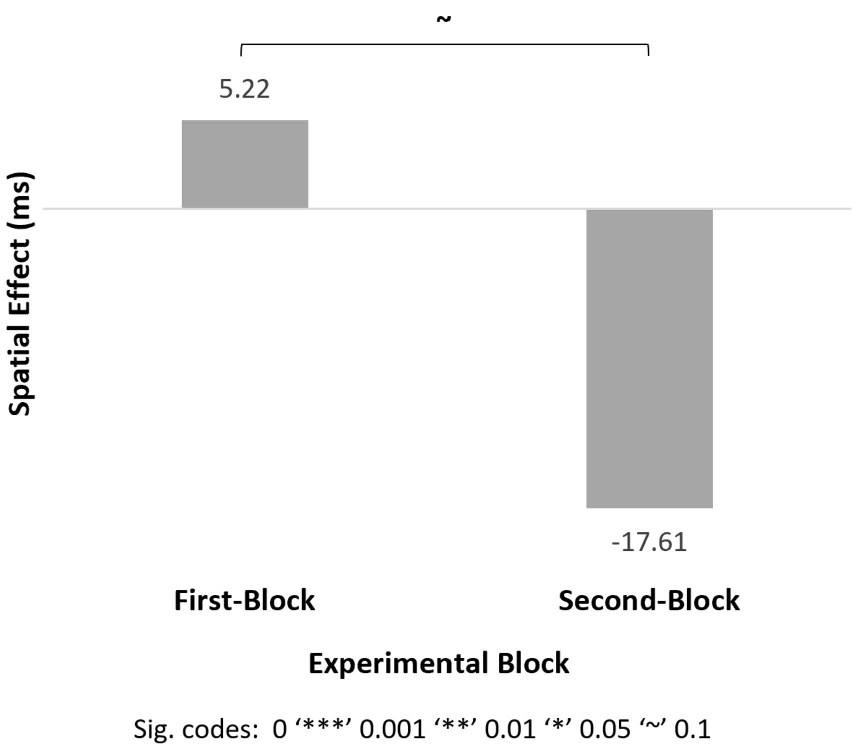
Within Model 3, the main effect of Target Language was significant ($\chi^2(1)=664.62$, $p<.001$), such that responses to ‘L1-Hebrew’ trials (Mean=977.90, SD=272.30) were faster than responses to ‘L2-English’ trials (Mean=1267.44, SD=348.10).

Furthermore, the two-way interaction between Visual Field and Target Language was significant ($\chi^2(1)=4.23$, $p<.05$). Examination of the effect of Visual Field separately in each Target Language, revealed that while in the ‘L1-Hebrew’, responses to ‘LVF’ trials (Mean=970.46, SD=250.32) were faster than responses to ‘RVF’ trials (Mean=985.11, SD=292.02), in the ‘L2-English’, responses to ‘RVF’ trials (Mean=1253.07, SD=346.32) were faster than responses to ‘LVF’ trials (Mean=1282.41, SD=349.56). Yet, the RT-difference between ‘RVF’ and ‘LVF’ trials was not significant, neither in the ‘L1-Hebrew’ ($\chi^2(1)=.26$, $p=1.00$), nor in the ‘L2- English’ ($\chi^2(1)=3.79$, $p=.10$), indicating that the effect of Visual Field on speed performance was relatively weak, in both languages.

Moreover, the two-way interaction between English Proficiency Score and Target Language was significant ($\chi^2(1)=36.15$, $p<.001$). Examination of the effect of English Proficiency Score, separately in each Target Language, revealed that only in the ‘L2-English’, participants with ‘high-score’ (i.e., half of the participants with the highest proficiency scores; Mean=1270.98, SD=365.65) responded faster than participants with ‘low-score’ (i.e., the other half of the participants with the lowest proficiency scores; Mean=1325.84, SD=372.52). Still, the RT-difference between participants with ‘high-score’ and ‘low-score’ was not significant, neither in the ‘L1-Hebrew’ ($\chi^2(1)=1.80$, $p=.36$) nor in the ‘L2-English’ ($\chi^2(1)=2.81$, $p=.19$), indicating that the influence of English Proficiency Score on speed performance was relatively weak, in both languages.

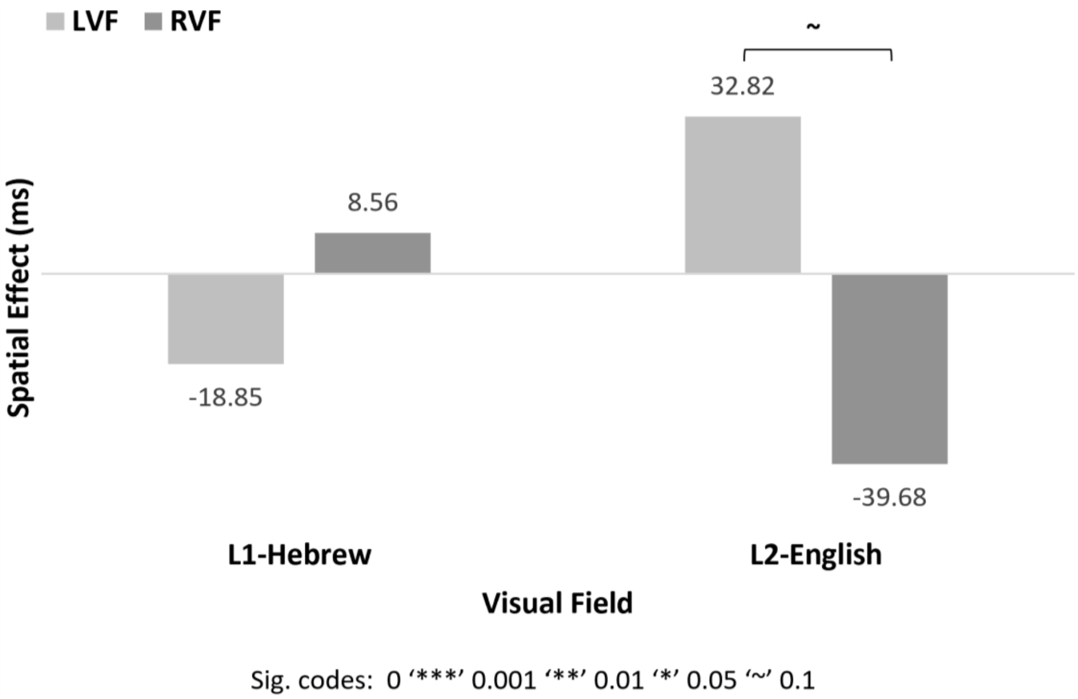
In addition, the two-way interaction between Spatial Condition and Experimental Block was marginally significant ($\chi^2(1)=3.10$, $p=.07$). Examination of the effect of Spatial Condition, separately for each Experimental Block, revealed that only ‘first-block’ trials were influenced by the effect of Spatial Condition, such that ‘match’ trials (Mean=1103.53, SD=323.83) led to faster responses than ‘mismatch’ trials (Mean=1108.75, SD=332.53). In contrast, ‘second-block’ trials resulted in faster responses to ‘mismatch’ trials (Mean=1093.15, SD=331.22) than to ‘match trials (Mean=1110.76, SD=369.52). Yet, the difference between ‘match’ and ‘mismatch’ trials was not significant, neither in the ‘first-block’ ($\chi^2(1)=1.90$, $p=.34$) nor in the ‘second-block’ ($\chi^2(1)=2.29$, $p=.26$), indicating that the effect of Spatial Condition on speed performance was relatively weak. The spatial effect (in ms) by Experimental Block, is illustrated in Figure 13.

Figure 13: The spatial effect (in ms) by Experimental Block in Exp. 4



More importantly, the three-way interaction between Spatial Condition, Visual Field, and Target Language was significant ($\chi^2(1)=4.24$, $p<.05$). Examination of the two-way interaction between Spatial Condition and Visual Field, separately for each Target Language, revealed that this interaction was marginally significant in the 'L2-English' ($\chi^2(1)=4.05$, $p=.09$), but was not reliable in the 'L1-Hebrew' ($\chi^2(1)=.83$, $p=.73$). However, further examination of the spatial effect in each Visual Field, separately for each Target Language, revealed that the effect was not significant neither in the 'L2-English', on 'RVF' trials ($\chi^2(1)=1.96$, $p=.65$) and on 'LVF' trials ($\chi^2(1)=2.09$, $p=.59$), nor in the 'L1-Hebrew', on 'RVF' trials ($\chi^2(1)=.28$, $p=.1.00$) and on 'LVF' trials ($\chi^2(1)=.58$, $p=1.00$), indicating that the effect of Spatial Condition on speed performance was relatively weak, in both languages and in both hemispheres. The spatial effect (in ms) by Target Language and Visual Field is illustrated in Figure 14.

Figure 14: The spatial effect (in ms) by Visual Field and Target Language in Exp. 4



Finally, the three-way interaction between Target Language, Experimental Block, and English Proficiency Score was significant ($\chi^2(1)=7.06$, $p<.01$), as was the four-way interaction between Target Language, Visual Field, Experimental Block, and English Proficiency Score ($\chi^2(1)=6.38$, $p<.05$). However, the implications of these interactions are not within the scope of the current study.

<u>Error Data</u>

The final Error dataset consisted of critical trials only. Thus, 2877 data points (1531 in L1-Hebrew and 1346 in L2-English) that 76 participants produced by responding to 41 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 2 did not fit the Error data better than Model 1 ($\chi^2(8)=12.23$, $p=.14$), and Model 3 did not fit the data better than Model 2 ($\chi^2(16)=15.50$, $p=.49$). Therefore, Model 1, which included the fixed main effects of Spatial Condition, Target Language, and Visual Field, the interactions between them, and the random effects of Participants and Items, was selected for further analysis.

Within Model 1, the main effect of Target Language was significant ($\chi^2(1)=71.14$, $p<.001$), indicating that 'L1-Hebrew' trials (Mean=.09, SD=.29) resulted in a lower error rate than 'L2-English' trials (Mean=.20, SD=.40). In addition, the main effect of Visual Field was also significant ($\chi^2(1)=6.00$, $p<.05$), indicating that 'RVF' trials (Mean=.13, SD=.33) resulted in a lower error rate than 'LVF' trials (Mean=0.16, SD=.37).

3.2.2.3. Discussion

The results of Exp. 4 did not significantly demonstrate the spatial effect, neither in the LH nor in the RH, in both languages. Thus, like in Exp. 2, no significant evidence for the activation of visual spatial information during word reading was found. Furthermore, even though the interaction between Spatial Condition, Visual Field, and Target Language was significant, in the RT data, further examination of the spatial effect in each Visual Field, separately for each Target Language, did not reveal significant effects. These results cannot support our initial predictions regarding the advantage of the RH in activating perceptual visual information during reading.

In contrast to previous L1 studies (Berndt et al., 2019; Zwaan & Yaxley, 2003b), which have demonstrated a significant spatial effect, using the same lateralized semantic judgment task, here we did not observed a significant facilitation in the semantic judgment of word-pairs, when the vertical spatial position of the two words on the screen matched the spatial relation of their referents, neither under RVF/LH presentation nor under LVF/RH presentation, in both the L1 and the L2.

Yet, the current results are somewhat consistent with the findings of Zwaan and Yaxley (2003b), which have demonstrated a significant spatial effect in the L1-English only when word-pairs were presented in the LVF to the RH. In the current study, a similar trend was observed in the L2-English, as far as to the direction of the spatial effect. That is, only in the L2-English, the shape effect was modulated by hemisphere, such that responses were faster in the match than in the mismatch condition only in the RH. Still, the RT-difference between match and mismatch trials in the RH was not significant.

Finally, since the results of Exp. 2 and Exp. 4 did not yield significant spatial effects, regardless of whether stimuli were presented centrally (i.e., in the CVF) or unilaterally (i.e., in the LVF/RVF), the possibility that this effect was not evident under central viewing in Exp. 2 because of the pattern of hemispheric involvement during natural reading, seems implausible. Therefore, it was decided that further examination of interhemispheric interactions was not required.

3.2.3. *Conclusions*

Set B demonstrated that RH processing of written sentences produced more extensive perceptual visual activations, in comparison to LH processing, irrespective of target language (Exp. 3). Consistent with our initial predictions, these results suggest that the RH is more crucial than the LH for the construction of visual simulations during language comprehension.

Interestingly, it was found that the embodied/disembodied processing nature of each language (i.e., L1/L2, respectively) that was exhibited in Exp. 1 may derive from L1-L2 difference in the pattern of hemispheric involvement when stimuli is presented to both hemispheres (i.e., natural reading). Namely, it seems that visual simulations are stronger in the L1 because both hemispheres are involved in natural L1 reading, and thus additively contribute to the construction of visual simulations during comprehension. However, visual simulations are reduced in the L2, because the RH is less involved in natural L2 reading, at least in the case of an L2 that is learned later in life in formal and un-immersive settings, and thus, its significant contribution to the construction of visual simulations is not evident.

4. GENERAL DISCUSSION

Numerous studies have shown that L1 comprehenders spontaneously simulate perceptual visual properties of verbally described situations (e.g., Zwaan et al., 2002, Zwaan & Yaxley, 2003a). The present study has attempted to expand these findings in two directions by (1) exploring the existence and strength of perceptual visual simulations during L2 comprehension, focusing on proficient unbalanced late bilinguals, who have learned their L2 formally in the L1 country; and by (2) testing the biological infrastructure that supports such simulation-based processing, focusing on the relative contribution of the two cerebral hemispheres to perceptual visual simulations. Notably, this study revealed that visual simulations during language comprehension are reduced in the L2 relative to the L1; and are more extensively generated in the RH than in the LH. These results further suggest that under typical (central) reading conditions, the RH is more involved in L1 processing than in L2 processing, and this may explain why the visual embodiment of the L2, in this type of bilinguals, is reduced, relative to their L1. In the following I discuss these findings in more detail.

4.1. Visual simulations are reduced in the L2 relative to the L1

Late bilinguals, living in their native-tongue environment, usually acquire their L2 in a formal setting. Thus, the learning and use of their L2 may be less associated with real-world experiences, in comparison to their L1. Therefore, the present study tested the possibility that the L2 of these bilinguals may be less embodied relative to their L1 or may not even evoke embodied simulations. To this end, native speakers of Hebrew (L1) who acquired their L2 (English) in the L1 country (Israel) after the age of 6, performed two tasks that tested their ability to simulate visual features (i.e., shape and spatial location) of verbally described objects – the sentence picture verification task (Zwaan et al., 2002) and the semantic judgment task (Zwaan & Yaxley, 2003a).

Exp. 1 employed the sentence picture verification task to test the activation of implied shape information during L1 and L2 sentence reading. In this task, participants read sentences describing an object in a given location (e.g., “The boy saw the balloon in the air”). After each sentence, a picture of the object (e.g., balloon) was presented and participants had to decide whether or not the object had been mentioned in the preceding sentence. Critically, the shape of the object in the picture could have either matched (i.e., a picture of an inflated balloon) or mismatched (i.e., a picture of a deflated balloon) the shape implied by the sentence. Faster responses in the match, relative to the mismatch condition (i.e., the shape effect), indicate that implied visual knowledge about the shape of objects is spontaneously activated during sentence comprehension.

Consistent with our initial predictions, while L1 sentences led to significant activations of implied visual shape information, L2 sentences resulted in a non-significant shape effect, indicating that, as opposed to the L1, the L2 did not substantially evoke the visual shape of mentioned objects. These findings are in line with previous studies, showing limited activation of perceptual (e.g., Chen et al., 2020), motor (e.g., Vukovic & Shtyrov, 2014), and affective (e.g., Hsu et al., 2015) knowledge during L2 reading, relative to L1 reading, and support the assumption that, in this type of bilinguals, the embodiment of the L2 is reduced, relative to the L1.

This L1-L2 difference in the degree of embodiment, is consistent with theories that postulate a distinction between linguistic-based and simulation-based comprehension processes (e.g., Paivio, 1991; Barsalou et al., 2008). For example, Barsalou and his colleagues (Barsalou et al., 2008) have proposed the linguistic and situated simulation theory as a model for the representation of knowledge in the brain. In this model, meanings of words are represented in two different systems – a linguistic system that uses word association to represent meaning, and a simulation system that uses non-verbal sensorimotor knowledge. Importantly, the model assumes that these two systems are connected, such that during language comprehension, lexical representations in the linguistic system (e.g., the written form of the word “dog”) evoke sensorimotor representations in the simulation system (e.g., the visual image of a dog). The results of Exp. 1 suggest that these intersystem connections are stronger in an L1 than in an L2. As a result, L1 comprehension involves substantial simulation processes, whereas L2 comprehension relies mainly on linguistic representations. This difference may be attributed to the fundamentally distinct settings in which these two languages have been acquired and used – early, natural, informal learning of the L1, in which linguistic information is constantly related to the physical world; and formal, un-immersive learning of the L2, in which linguistic information is far less related to non-verbal, multimodal information.

Interestingly, Exp. 1 also revealed cross-language influences on visual simulation processes, in both languages. Specifically, it was found that the immediate recent experience in performing the same task in the other language (i.e., either the L1 or the L2), significantly affected the strength of the shape effect in the L1 and in the L2, but in opposite directions.

Thus, in the L1, the shape effect was smaller when the L1 block was performed immediately after the L2 block (in comparison to when it was performed first), assumingly because of the immediate recent experience with L2 sentence reading, which does not involve simulations. Conversely, in the L2, the shape effect was larger when the L2 block was performed immediately after the L1 block (in comparison to when it was performed first), assumingly due to the immediate recent experience with L1 sentence reading, in which simulation processes are extensively employed (see Figure 2). These findings are in line with previous studies, which have also observed an effect of recent experience in the L1/L2 on task performance in the other language (e.g., Ben-Dror et al., 1995). Thus, when the same task is performed in both the L1 and the L2 successively, the specific processing patterns, usually employed in each language, may become more similar to the processing pattern of the other language.

Despite these cross-language influences, the results of Exp. 1 clearly indicate that visual simulations characterize L1, but not L2 processing, as visual effects were observed only in the L1-Hebrew block (when it was performed first, before the L2-English block, and thus, could not have been affected by the processing pattern of the L2). These findings are consistent with the notion that a formally learned L2 is less embodied, and its comprehension does not involve the construction of visual simulations.

Exp. 2 employed a semantic judgment task to test the activation of spatial information during L1 and L2 word reading. In this task, participants were asked to decide whether or not two words, presented one above the other, are semantically related. Critically, these word-pairs denoted referents with a typical spatial-vertical relation (e.g., car-road) and were presented in two spatial conditions. In the match condition, the spatial arrangement of the two words on the screen matched the typical spatial relation of their referents (e.g., “car” was displayed above “road”). In the mismatch condition, the visual spatial arrangement of the two words did not match the typical spatial relation of their referents (e.g., “road” was displayed above “car”). Faster responses in the match, relative to the mismatch condition (i.e. the spatial effect), indicate that visual knowledge about the typical spatial location of objects is spontaneously activated during word comprehension.

Interestingly, the results of Exp. 2 did not demonstrate the spatial effect, neither in the L1 nor in the L2. That is, no significant evidence for the activation of implied visual spatial information during word reading was found. Thus, in contrast to previous L1 studies, which demonstrated significant spatial effects using the same semantic judgment task (Louwerse, 2008; Zwaan & Yaxley, 2003a), here we did not observe a significant facilitation when the vertical spatial position of the two words matched the relative spatial location of their referents.

This suggests that the activation of implied visual knowledge during language comprehension may be task-related, as the sentence picture verification task produced a significant visual shape effect, whereas the semantic judgment task failed to significantly exhibit visual spatial effects. Indeed, it seems that the shape effect is more robust than the spatial effect, since numerous studies have consistently exhibited a significant shape effect (e.g., Peleg et al., 2018; Zwaan et la., 2002), whereas the spatial effect has not been reliably evident in all previous studies (e.g., Louwerse & Jeuniaux, 2010; Van Elk & Blanke, 2011).

Moreover, this task-related difference in the exhibited visual effects, supports the claim that visual simulations are subjected to several modulating factors (e.g., Lebois et al., 2015). One such factor may be the perceptual orientation of the task. Namely, it is possible that visual knowledge is more likely to be activated in tasks that emphasize the visual properties of the linguistic content. Indeed, the sentence picture verification task, which incorporated non-verbal visual stimuli (i.e., pictures of objects) in addition to the verbal stimuli (i.e., sentences), yielded substantial evidence for the activation of visual features, assumingly because the involvement of pictures in the task focuses participants on the perceptual aspects of verbally described objects. However, the semantic judgment task, which consisted of merely verbal stimuli (i.e., word-pairs), failed to present significant evidence for the activation of visual knowledge, assumingly because it was more linguistically oriented, and thus, may focus participants on the abstract linguistic characteristics of the verbal content.

Similar findings were obtained by Louwerse and Jeuniaux (2010). They demonstrated that when the semantic judgment task incorporated non-verbal visual stimuli (picture-pairs), rather than verbal stimuli (word-pairs), the spatial effect was evident, and the size of the effect significantly correlated with the extent to which the referent's spatial relation in the real world is constant. Likewise, Rommers, Meyer, and Huettig (2013) obtained a stronger shape effect in the sentence picture verification task when participants were explicitly asked to use mental imagery while reading the sentences. Thus, when the task directs language comprehenders to pay more attention to the visual aspect of the verbally described situation, visual information is more extensively activated.

Another modulating factor may be the intrinsicness of the visual property that was examined by each task. That is, prominent perceptual features may be simulated more extensively and result in stronger visual effects, relative to other, less distinguishable visual characteristics that may result in weaker effects. Indeed, previous studies have demonstrated that intrinsic visual properties, such as size and shape, are more likely to be activated, than extrinsic features, such as spatial information (De Koning et al., 2017b; Koster et al., 2018; Zwaan & Pecher, 2012).

Still, since Exp. 2, which employed a linguistically oriented task, did not yield significant visual effects, neither in the L1 nor in the L2, the degree to which perceptual visual knowledge is spontaneously activated during L1 and L2 comprehension as well as the conditions under which these activations occur, should be further verified in future studies, by using other tasks that do not direct participants to the perceptual visual aspects of the linguistic content.

Taken together, the results of Set A (Exp. 1 and 2) suggest a substantial difference between L1 and L2 processing, such that visual simulations during language comprehension occur only in the L1. Moreover, even in the case of an L1, visual simulations were observed only in the sentence picture verification task and only when the L1 block was performed before the L2 block. These results can be explained by embodied theories of language processing, which distinguish between comprehension processes that merely employ the linguistic system and deeper comprehension processes that employ the simulation system as well (Paivio 1991; Barsalou et al., 2008). Accordingly, an L2 that is learned formally, does not establish strong links between these two systems, and thus, relies primarily on the linguistic system. On the other hand, a naturally learned L1 is characterized by a strong connection between the two systems, and therefore enables both types of processing – shallower processing that employs only the linguistic system (Glaser, 1992), and deeper processing that includes the activation of perceptual visual representations in the simulation system (Solomon & Barsalau, 2004).

4.2. Visual simulations are more extensively generated in the RH than in the LH

A complementary issue that was examined in the current study relates to the neural mechanisms that support the construction of these visual simulations. Studies on hemispheric specialization suggest a RH advantage in visual processing and a LH advantage in linguistic processing (Corballis, 2003; Hugdahl, 2000). However, only a few studies have examined asymmetries in the activation of visual information during language comprehension, and these have focused only on L1 comprehension (e.g., Berndt et al., 2019; Lincoln et al., 2007; 2008; Zwaan & Yaxley, 2003b). Therefore, the second aim of the present study was to examine the ability of the two cerebral hemispheres to activate perceptual visual knowledge during L1 and L2 reading. If the LH specializes in language processing and the RH specializes in non-verbal visual processing, then visual simulation processes should be more pronounced in the RH than in the LH.

The experiments conducted in Set B (Exp. 3 and 4) tested these assumptions by employing the same two tasks that were used in Set A, in conjunction with a DVF technique. Thus, in both tasks, target stimuli were presented either in the LVF to the RH or in the RVF to the LH, allowing the assessment of the separate ability of each hemisphere to activate the visual shape (Exp. 3) and the spatial location (Exp. 4) of verbally mentioned objects, in both the L1 and the L2. This set of experiments have yielded substantial evidence for RH-LH difference in the construction of perceptual visual simulations during language comprehension.

Consistent with our initial predictions, Exp. 3 revealed that irrespective of the language involved, the shape effect was significant only when the target stimuli were presented in the LVF to the RH. Furthermore, although Exp. 4 did not yield significant visual effects, in neither the L1 nor the L2, a similar trend was observed in the L2. These findings are in line with previous studies, showing a RH advantage in activating perceptual visual features, such as shape (e.g., Lincoln et al., 2008) and spatial location (e.g., Zwaan & Yaxley, 2003b), during L1 reading.

This RH-LH difference in the ability to construct a perceptual simulation of the described event is consistent with hemispheric theories which predict RH involvement in language comprehension when processing linguistic stimuli (e.g., concrete nouns), which are encoded both verbally and perceptually, and thus, engage linguistic mechanisms located mainly in the LH, and simulation mechanisms located in both hemispheres (Paivio, 1990; 2010; 2014). Furthermore, although simulation processes may involve both hemispheres, the results of the current study are consistent with the notion that the RH is more crucial than the LH in activating perceptual visual knowledge during language comprehension, assumingly because of its better ability to process non-verbal visual information (e.g., Whitehouse, 1981). Finally, this hemispheric asymmetry in the construction of visual simulations can explain findings demonstrating a RH advantage in generating elaborative inferences during language comprehension (e.g., Metusalem et al., 2016), which may be supported by simulation processes.

4.3. The RH is more involved in L1 processing than in L2 processing

Although Exp. 3 did not reveal a significant three-way interaction between the shape condition (match/mismatch), visual field condition (RVF/LVF), and language condition (L1-Hebrew/L2-English), planned comparisons conducted separately for each language showed that the hemispheric asymmetry described above was more pronounced in the L2-English than in the L1-Hebrew. Specifically, in the L1-Hebrew, a similar pattern of results was obtained in both hemispheres – responses were faster in the match than in the mismatch condition, but this difference did not reach significance. However, in the L2-English, a significant shape effect was obtained in the RH, whereas, in the LH, the effect was not evident at all. This, together with the results of Exp. 1 (a significant shape effect only in the L1 under CVF presentation), suggests that the two hemispheres may be differently engaged during L1 and L2 sentence processing.

To investigate this possibility, additional analyses were conducted, in which performance patterns (i.e., the shape effect) that were observed under CVF presentation were compared with those observed under LVF or RVF presentations. These comparisons revealed that both hemispheres may be involved, at least to some extent, in natural (central) reading of both languages. Nevertheless, it appears that in each language, the two hemispheres are involved to different degrees.

Specifically, in the L1, the pattern of the shape effect that was obtained in the CVF (i.e., a significant effect) was different from the pattern obtained in the LVF/RH and in the RVF/LH (i.e., non-significant effects), suggesting that in natural (central) L1 reading, the RH and the LH are more similarly engaged in processing, since both additively contribute to the construction of visual shape simulations. Conversely, in the L2, the pattern of the shape effect that was obtained in the CVF (i.e., a non-significant effect) was different than the pattern obtained in the LVF/RH (i.e., a significant effect), and was more similar to the pattern obtained in the RVF/LH (i.e., a non-significant effect), suggesting that in natural (central) L2 reading, the RH is far less implicated in processing, since its significant contribution to the construction of visual shape simulations, shown under separate LVF/RH processing, is not evident when both hemispheres are presented with the stimuli.

This suggestion somewhat contradicts with several L2 studies that have reported greater RH involvement in L2 processing, relative to L1 processing, assumingly because the neural computation of the L2 is more effortful (e.g., Cieślicka & Heredia, 2011; Leonard et al., 2010; Xiang et al., 2015). However, this contradiction may be explained by differences in participants' L2 proficiency, in the level of complexity of the task and/or the stimuli, and in the research method employed. Nevertheless, the current results indicate that visual simulations during sentence comprehension are more substantially generated in the RH than in the LH under unilateral presentation and are more robust in the L1 than in the L2 under central presentation.

In sum, the comparison of the central (Exp. 1) and unilateral (Exp. 3) experiments suggests that while L1 reading is more balanced in terms of hemispheric involvement, L2 reading relies more heavily on the LH, at least when the L2 is acquired formally. This left lateralized nature of L2 processing among late bilinguals, who have learned and used their L2 in a formal manner, outside of the natural L2 speaking environment, is consistent with the predictions made by the manner of L2 acquisition hypothesis (Galloway, 1981; Galloway & Krashen 1980; Galloway, & Scarcella, 1982), which emphasizes the difference between formal and informal late L2 learning. This hypothesis predicts that formal L2 learning should result in greater LH involvement during L2 processing, because in this learning mode, L2 learners/users are consciously monitoring their L2 performance, by analytically using their metalinguistic knowledge in the LH. Conversely, immersive and informal L2 acquisition, which does not stress linguistic structures and rules, but rather emphasizes communication and daily interaction with other speakers, should result in greater involvement of the RH during L2 processing. Thus, according to this hypothesis, if the mode of acquisition and use is predominantly a formal one, greater LH involvement is predicted. Alternatively, informal and immersive language acquisition is associated with greater RH involvement (Hull & Vaid, 2005). These predictions should be further examined by directly comparing the L1 and the L2 of these two types of late L2 learners.

Yet, an alternative explanation for the different pattern of hemispheric involvement found in each language, relates to the specific languages that were investigated in this study. Namely, it is possible that differences in hemispheric involvement between the processing of Hebrew and English, in either Hebrew-English or English-Hebrew bilinguals, may reflect cross-language differences in specific linguistic characteristics (e.g., the morphological structure of words), rather than processing differences between the L1 and the L2 (e.g., Eviatar & Ibrahim, 2007). Likewise, it can be argued that the greater involvement of the RH in L1-Hebrew reading, than in L2-English reading, which was evident in the current study, may be the result of the difference in reading direction between Hebrew and English and not because of L1-L2 processing differences. Thus, it is possible that the right-to-left reading direction in Hebrew gives an advantage to the RH because readers' attention is directed to the

LVF. In contrast, the left-to-right reading direction in English gives an advantage to the LH because readers' attention is directed to the RVF.

However, this possibility seems less plausible since in Set B, in both tasks, the LH exhibited an overall significant processing advantage, relative to the RH, irrespective of the language involved. Furthermore, previous findings indicate that the typically found LH-advantage in language processing is also evident in Hebrew (e.g., Faust, Kravetz, & Babkoff, 1993). Thus, the differences in hemispheric involvement between the two languages in the current study, are more likely to be the result of L1-L2 processing differences, rather than the result of Hebrew-English processing difference. Still, to further confirm this conclusion, future investigations should test English-Hebrew bilinguals in the same task, as well as bilinguals whose two languages are read in the same direction (e.g., Arabic-Hebrew or English-Spanish bilinguals).

Taken together, the present study demonstrated a relationship between the manner of language acquisition, the pattern of hemispheric involvement, and the ability to evoke visual simulations during language comprehension. In particular, in the case of an L1, which is acquired in a natural and experiential fashion, processing relies on both hemispheres, and therefore involves not only linguistic representations, but also non-verbal visual representations. However, in the case of an L2, which is acquired in a formal and un-immersive fashion, processing relies mainly on the LH, and therefore involves only linguistic representations.

These differences may have critical implications on the nature of comprehension in each language, because simulation-based comprehension is assumed to involve deep conceptual information, which enable higher-level processing functions, whereas linguistic-based comprehension is assumed to be relatively shallow, because it relies on superficial low-level processing strategies, which may not be sufficient for some tasks (Solomon & Barsalau, 2004; Barsalau et al., 2008). The current study presented evidence for L1-L2 differences in hemispheric processing and simulation abilities. Further studies are needed in order to establish a causal relationship between simulation abilities and language comprehension abilities in both the L1 and the L2.

4.4. Conclusions

The prevalence of nonnative language users over the world requires a deeper understating of the processes involved in a nonnative language use. Specifically, uncovering points of divergence between native and non-native language processing may be an important step towards understating the factors crucial for mastering a non-native language. Therefore, the purpose of the current study was to uncover neural and cognitive differences between L1 and L2 processing. Indeed, this study has revealed that the two languages of proficient unbalanced late bilinguals, who have learned and used their L2 in a formal and un-immersive manner, are processed differently, such that each language is embodied to a different extent and each language involves a distinct pattern of hemispheric processing.

It appears that L1 reading substantially evokes perceptual visual knowledge, assumingly because a native language is acquired and used in natural settings, in which linguistic information is regularly related to the physical world. On the contrary, it seems that L2 reading does not significantly involve the activation of this type of embodied knowledge, assumingly because during formal learning and usage of an L2, linguistic information is far less related to non-verbal multimodal information. Thus, among this type of bilinguals, L1 comprehension involves visual simulation processes, which may enable deeper conceptual encoding and more complex processing, because their L1 is highly embodied. However, L2 comprehension mainly involves linguistic processes, which may result in a more superficial conceptual encoding, and may support more basic linguistic tasks, since the embodiment of their L2 is restricted.

Additionally, even though the ability to visually simulate the linguistic content appears to be stronger in the RH than in the LH, in both the L1 and the L2, it looks as if interhemispheric interaction, which allows the contribution of both hemispheres to processing, occurs more extensively during L1 reading, than during L2 reading. Specifically, our data points to a greater involvement of the RH in L1 reading, than in L2 reading, which can explain the reduced visual embodiment of the L2 under central viewing. Namely, the reduced ability of bilinguals in the current study to visually simulate the linguistic content in their L2, may be the result of the specific pattern of hemispheric involvement that characterizes natural L2 reading, in which the LH is mainly involved.

These conclusions may have important theoretical and practical implications. First, they can inform theories of embodied cognition in regard to the conditions under which language is embodied, as well as theories of bilingual language processing, both in regard to the way late bilinguals conceptually represent the linguistic content in their two languages and in regard to the interplay between the two hemispheres during L1 and L2 processing. Second, they may encourage educational language programs to adopt less-formal and more-embodied and natural teaching methods, which directly relate linguistic information in the L2 to multimodal knowledge. These methods may allow a more native-like activation of non-verbal embodied representations during L2 comprehension, and perhaps, more native-like comprehension abilities.

REFERENCES

Adams, A. M. (2016). How language is embodied in bilinguals and children with specific language impairment. *Frontiers in psychology*, *7*, 1209.

Ahn, S., & Jiang, N. (2018). Automatic semantic integration during L2 sentential reading. *Bilingualism: Language and Cognition*, *21*(2), 375-383.

Alario, F. X., & Ferrand, L. (1999). A set of 400 pictures standardized for French: Norms for name agreement, image agreement, familiarity, visual complexity, image variability, and age of acquisition. *Behavior Research Methods, Instruments, & Computers, 31*(3), 531-552.

Anderson , M. L. (2003). Embodied cognition: A field guide. Artificial Intelligence, 149 (1), 91–103.

Banich, M. T. (2003). The divided visual field technique in laterality and interhemispheric integration. In *Experimental methods in neuropsychology* (pp. 47-63). Springer, Boston, MA.

Bar, M. (2004). Visual objects in context. *Nature Reviews Neuroscience*, *5*(8), 617-629.

Barsalou, L. W. (1999). Perceptions of perceptual symbols. *Behavioral and brain sciences, 22*(04), 637-660.

Barsalou, L. W. (2008). Grounded cognition. *Annu. Rev. Psychol.*, *59*, 617-645.

Barsalou, L. W., Santos, A., Simmons, W. K., & Wilson, C. D. (2008). Language and simulation in conceptual processing. *Symbols, embodiment, and meaning*, 245-283.

Baumeister, J. C., Foroni, F., Conrad, M., Rumiati, R. I., & Winkielman, P. (2017). Embodiment and emotional memory in first vs. second language. *Frontiers in psychology*, *8*, 394.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of memory and language*, *59*(4), 390-412.

Beeman, M. (1993). Semantic processing in the right hemisphere may contribute to drawing inferences from discourse. *Brain and language*, *44*, 80-80.

Beeman, M. (1998). Coarse semantic coding and discourse comprehension. *Right hemisphere language comprehension: Perspectives from cognitive neuroscience*, 255-284.

Beeman, M. J., Bowden, E. M., & Gernsbacher, M. A. (2000). Right and left hemisphere cooperation for drawing predictive and coherence inferences during normal story comprehension. *Brain and language*, *71*(2), 310-336.

Beeman, M., Friedman, R. B., Grafman, J., Perez, E., Diamond, S., & Lindsay, M. B. (1994). Summation priming and coarse semantic coding in the right hemisphere. *Journal of cognitive neuroscience, 6*(1), 26-45.

Bedny, M., & Caramazza, A. (2011). Perception, action, and word meanings in the human brain: the case from action verbs. *Annals of the New York Academy of Sciences*, *1224*(1), 81-95.

Beilock, S. L., Lyons, I. M., Mattarella-Micke, A., Nusbaum, H. C., & Small, S. L. (2008). Sports experience changes the neural processing of action language. *Proceedings of the National Academy of Sciences*, *105*(36), 13269-13273.

Ben-Dror, I., Bentin, S., & Frost, R. (1995). Semantic, phonologic, and morphologic skills in reading disabled and normal children: Evidence from perception and production of spoken Hebrew. *Reading Research Quarterly*, 876-893.

Bergen, B. (2015). Embodiment, simulation and meaning. *The Routledge handbook of semantics*, 142-157.

Bergen, B., Lau, T. T. C., Narayan, S., Stojanovic, D., & Wheeler, K. (2010). Body part representations in verbal semantics. *Memory & cognition*, *38*(7), 969-981.

Bergen, B. K., Lindsay, S., Matlock, T., & Narayanan, S. (2007). Spatial and linguistic aspects of visual imagery in sentence comprehension. *Cognitive science*, *31*(5), 733-764.

Berndt, E., Dudschig, C., Miller, J., & Kaup, B. (2019). A replication attempt of hemispheric differences in semantic-relatedness judgments (Zwaan & Yaxley, 2003). *Acta Psychologica*, *198*, 102871.

Binder, J. R., Westbury, C. F., McKiernan, K. A., Possing, E. T., & Medler, D. A. (2005). Distinct brain systems for processing concrete and abstract concepts. *Journal of cognitive neuroscience*, *17*(6), 905-917.

Bourne, V. J. (2006). The divided visual field paradigm: Methodological considerations. *Laterality*, *11*(4), 373-393.

Brederoo, S. G., Nieuwenstein, M. R., Cornelissen, F. W., & Lorist, M. M. (2019). Reproducibility of visual-field asymmetries: Nine replication studies investigating lateralization of visual information processing. *Cortex*, *111*, 100-126.

Broca, P. (1863). Localisation des fonctions cérébrales: Siége de langage articulé. *Bulletins de la Société d'Anthropologie de Paris*, *4*, 200-208.

Brownell, H. H., Carroll, J. J., Rehak, A., & Wingfield, A. (1992). The use of pronoun anaphora and speaker mood in the interpretation of conversational utterances by right hemisphere brain-damaged patients. *Brain and Language*, *43*(1), 121-147.

Brownell, H. H., Potter, H. H., Bihrle, A. M., & Gardner, H. (1986). Inference deficits in right brain-damaged patients. *Brain and language*, *27*(2), 310-321.

Brunyé, T. T., Ditman, T., Mahoney, C. R., Walters, E. K., & Taylor, H. A. (2010). You heard it here first: Readers mentally simulate described sounds. *Acta psychologica, 135*(2), 209-215.

Buccino, G., Marino, B. F., Bulgarelli, C., & Mezzadri, M. (2017). Fluent speakers of a second language process graspable nouns expressed in L2 like in their native language. *Frontiers in psychology*, *8*, 1306.

Burgess, C., & Simpson, G. B. (1988). Cerebral hemispheric mechanisms in the retrieval of ambiguous word meanings. *Brain and language*, *33*(1), 86-103.

Chen, D., Wang, R., Zhang, J., & Liu, C. (2020). Perceptual Representations in L1, L2 and L3 Comprehension: Delayed Sentence–Picture Verification. *Journal of Psycholinguistic Research*, *49*(1), 41-57.

Cieślicka, A. B., & Heredia, R. R. (2011). Hemispheric asymmetries in processing L1 and L2 idioms: Effects of salience and context. *Brain and Language*, *116*(3), 136-150.

Citron, F. M. (2012). Neural correlates of written emotion word processing: a review of recent electrophysiological and hemodynamic neuroimaging studies. *Brain and language*, *122*(3), 211-226.

Collins, A. M., & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological review*, *82*(6), 407.

Connell, L. (2007). Representing object colour in language comprehension. *Cognition, 102*(3), 476-485.

Connell, L., & Lynott, D. (2014). Principles of representation: Why you can't represent the same concept twice. *Topics in Cognitive Science*, *6*(3), 390-406.

Conrad, M., Recio, G., & Jacobs, A. M. (2011). The time course of emotion effects in first and second language processing: a cross cultural ERP study with German–Spanish bilinguals. *Frontiers in psychology*, *2*, 351.

Coppens, L. C., Gootjes, L., & Zwaan, R. A. (2012). Incidental picture exposure affects later reading: evidence from the N400. *Brain and Language*, *122*(1), 64-69.

Corballis, P. M. (2003). Visuospatial processing and the right-hemisphere interpreter. *Brain and cognition*, *53*(2), 171-176.

Corballis, P. M., Funnell, M. G., & Gazzaniga, M. S. (2002). Hemispheric asymmetries for simple visual judgments in the split brain. *Neuropsychologia*, *40*(4), 401-410.

Costa, A., Foucart, A., Arnon, I., Aparici, M., & Apesteguia, J. (2014). "Piensa" twice: On the foreign language effect in decision making. *Cognition*, *130*(2), 236-254.

Costa, A., Foucart, A., Hayakawa, S., Aparici, M., Apesteguia, J., Heafner, J., & Keysar, B. (2014). Your morals depend on language. *PloS one*, *9*(4), e94842.

Costa, A., Vives, M. L., & Corey, J. D. (2017). On language processing shaping decision making. *Current Directions in Psychological Science*, *26*(2), 146-151.

Coulson, S., Federmeier, K. D., Van Petten, C., & Kutas, M. (2005). Right hemisphere sensitivity to word- and sentence-level context: evidence from event-related brain potentials. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(1), 129.

Coulson, S., & Wu, Y. C. (2005). Right hemisphere activation of joke-related information: An event-related brain potential study. *Journal of cognitive neuroscience*, *17*(3), 494-506.

Cutica, I. (2005). Neuropsychological evidence for linguistic and extralinguistic paths in communication. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 27, No. 27).

Cutica, I., Bucciarelli, M., & Bara, B. G. (2006). Neuropragmatics: Extralinguistic pragmatic ability is better preserved in left-hemisphere-damaged patients than in right-hemisphere-damaged patients. *Brain and language*, *98*(1), 12-25.

Degani, T., Kreiner, H., Ataria, H., & Khateeb, F. (2020). The impact of brief exposure to the second language on native language production: Global or item specific?. *Applied Psycholinguistics*, *41*(1), 153-183.

De Groot, A. M. (1992). Determinants of word translation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(5), 1001.

De Grauwe, S., Willems, R. M., Rueschemeyer, S. A., Lemhöfer, K., & Schriefers, H. (2014). Embodied language in first-and second-language speakers: Neural correlates of processing motor verbs. *Neuropsychologia*, *56*, 334-349.

De Koning, B. B., Wassenburg, S. I., Bos, L. T., & Van der Schoot, M. (2017a). Size does matter: Implied object size is mentally simulated during language comprehension. *Discourse processes*, *54*(7), 493-503.

De Koning, B. B., Wassenburg, S. I., Bos, L. T., & van der Schoot, M. (2017b). Mental simulation of four visual object properties: similarities and differences as assessed by the sentence–picture verification task. *Journal of Cognitive Psychology*, *29*(4), 420-432.

Dekker, T. M., Mareschal, D., Johnson, M. H., & Sereno , M. I. (2014). Pictuirng words? Sensorimotor cortex activation for printed words in child and adult readers. *Brain & Language*, *139*, 58-67.

Dhond, R. P., Witzel, T., Dale, A. M., & Halgren, E. (2007). Spatiotemporal cortical dynamics underlying abstract and concrete word reading. *Human brain mapping*, *28*(4), 355-362.

Dijkstra, K., Yaxley, R. H., Madden, C. J., & Zwaan, R. A. (2004). The role of age and perceptual symbols in language comprehension. *Psychology and aging*, *19*(2), 352.

Dong, Y., Gui, S., & MacWhinney, B. (2005). Shared and separate meanings in the bilingual mental lexicon. *Bilingualism: Language and Cognition*, *8*(3), 221-238.

Dudschig, C., de la Vega, I., & Kaup, B. (2014). Embodiment and second-language: Automatic activation of motor responses during processing spatially associated L2 words and emotion L2 words in a vertical Stroop paradigm. *Brain and language*, *132*, 14-21.

Dudschig, C., Souman, J., Lachmair, M., de la Vega, I., & Kaup, B. (2013). Reading "sun" and looking up: The influence of language on saccadic eye movements in the vertical dimension. *PloS one*, *8*(2), e56872.

Eilola, T. M., Havelka, J., & Sharma, D. (2007). Emotional activation in the first and second language. *Cognition and Emotion*, *21*(5), 1064-1076.

Eilola, T. M., & Havelka, J. (2011). Behavioural and physiological responses to the emotional and taboo Stroop tasks in native and non-native speakers of English. *International Journal of Bilingualism*, *15*(3), 353-369.

Engelen, J. A., Bouwmeeste, S., & de Bruin, A. b. (2011). Perceptual simulation in developing language comprehension. *Journal of Experimental Child Psychology*, *110*(4), 659-675.

Estes, Z., Verges, M., & Barsalou, L. W. (2008). Head up, foot down: Object words orient attention to the objects' typical location. *Psychological Science*, *19*(2), 93-97.

Estes, Z., Verges, M., & Adelman, J. S. (2015). Words, objects, and locations: Perceptual matching explains spatial interference and facilitation. *Journal of Memory and Language*, *84*, 167-189.

Eviatar, Z., & Ibrahim, R. (2007). Morphological structure and hemispheric functioning: The contribution of the right hemisphere to reading in different languages. *Neuropsychology*, *21*(4), 470.

Eviatar, Z., Hellige, J. B., & Zaidel, E. (1997). Individual differences in lateralization: Effects of gender and handedness. *Neuropsychology*, *11*(4), 562.

Faust, M., & Chiarello, C. (1998). Sentence context and lexical ambiguity resolution by the two hemispheres. *Neuropsychologia*, *36*(9), 827-835.

Faust, M. E., & Gernsbacher, M. A. (1996). Cerebral mechanisms for suppression of inappropriate information during sentence comprehension. *Brain and language*, *53*(2), 234.

Faust, M., Kravetz, S., & Babkoff, H. (1993). Hemispheric specialization or reading habits: Evidence from lexical decision research with Hebrew words and sentences. *Brain and Language*, *44*(3), 254-263.

Federmeier, K. D. (2007). Thinking ahead: The role and roots of prediction in language comprehension. *Psychophysiology*, *44*(4), 491-505.

Flores d'Arcais, G. B., Schreuder, R., & Glazenborg, G. (1985). Semantic activation during recognition of referential words. *Psychological Research*, *47*(1), 39-49.

Foroni, F. (2015). Do we embody second language? Evidence for 'partial'simulation during processing of a second language. *Brain and cognition*, *99*, 8-16.

Francken, J. C., Kok, P., Hagoort, P., & De Lange, F. P. (2015). The behavioral and neural effects of language on motion perception. *Journal of cognitive neuroscience*, *27*(1), 175-184.

Ferré, P., Anglada-Tort, M., & Guasch, M. (2018). Processing of emotional words in bilinguals: Testing the effects of word concreteness, task type and language status. *Second Language Research*, *34*(3), 371-394.

Fodor, J., (1975). *The Language of Thought*, Harvard University Press, Cambridge, Mass, USA, 1975.

Gallese, V., & Lakoff, G. (2005). The brain's concepts: The role of the sensory-motor system in conceptual knowledge. *Cognitive neuropsychology*, *22*(3-4), 455-479.

Galloway, L. M. (1981). The convolutions of second language: A theoretical article with a critical review and some new hypotheses towards a neuropsychological model of bilingualism and second language performance. *Language Learning*, *31*(2), 439-464.

Galloway, L., & Krashen, S. (1980). Cerebral organization in bilingualism and second language. *Research in second language acquisition*, 74-80.

Galloway, L. M., & Scarcella, R. (1982). Cerebral organization in adult second language acquisition: Is the right hemisphere more involved? *Brain and Language*, *16*(1), 56-60.

Gazzaniga, M. S., Bogen, J. E., & Sperry, R. W. (1962). Some functional effects of sectioning the cerebral commissures in man. *Proceedings of the National Academy of Sciences*, *48*(10), 1765-1769.

Gazzaniga, M. S. (2005). Forty-five years of split-brain research and still going strong. *Nature Reviews Neuroscience*, *6*(8), 653.

Geipel, J., Hadjichristidis, C., & Surian, L. (2015). How foreign language shapes moral judgment. *Journal of Experimental Social Psychology*, *59*, 8-17.

Gentner, D. (2010). Bootstrapping the mind: Analogical processes and symbol systems. *Cognitive Science*, *34*(5), 752-775.

Glaser, W. R. (1992). Picture naming. *Cognition*, *42*(1-3), 61-105.

Glenberg, A. M. (2015). Few believe the world is flat: How embodiment is changing the scientific understanding of cognition. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *69*(2), 165.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic bulletin & review*, *9*(3), 558-565.

González, J., Barros-Loscertales, A., Pulvermüller, F., Meseguer, V., Sanjuán, A., Belloch, V., & Ávila, C. (2006). Reading cinnamon activates olfactory brain regions. *Neuroimage*, *32*(2), 906-912.

Grosjean, F. (2010). *Bilingual*. Harvard university press.

Gullick, M. M., Mitra, P., & Coch, D. (2013). Imagining the truth and the moon: An electrophysiological study of abstract and concrete word processing. *Psychophysiology*, *50*(5), 431-440.

Harpaz, Y., Levkovitz, Y., & Lavidor, M. (2009). Lexical ambiguity resolution in Wernicke's area and its right homologue. *Cortex*, *45*(9), 1097-1103.

Harris, C. L., Ayçíçeğí, A., & Gleason, J. B. (2003). Taboo words and reprimands elicit greater autonomic reactivity in a first language than in a second language. *Applied Psycholinguistics*, *24*(4), 561-579.

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron*, *41*(2), 301-307.

Hayakawa, S., & Keysar, B. (2018). Using a foreign language reduces mental imagery. *Cognition*, *173*, 8-15.

Hausmann, M., Brysbaert, M., van der Haegen, L., Lewald, J., Specht, K., Hirnstein, M., Willemin, J., Barton, J., Buchilly, D., Chmetz, F. & Roch, M. (2019). Language lateralisation measured across linguistic and national boundaries. *Cortex*, *111*, 134-147.

Havas, D. A., Glenberg, A. M., & Rinck, M. (2007). Emotion simulation during language comprehension. *Psychonomic bulletin & review*, *14*(3), 436-441.

Hebb, D. O. (1949). The organization of behavior; a neuropsycholocigal theory. *A Wiley Book in Clinical Psychology.*, 62-78.

Hines, D. (1976). Recognition of verbs, abstract nouns and concrete nouns from the left and right visual half-fields. *Neuropsychologia*, *14*(2), 211-216.

Hirschfeld, G., & Zwitserlood, P. (2011). How vision is shaped by language comprehension - top-down feedback based on low-spatial frequencies. *Brain research, 1377*, 78-83.

Hirschfeld, G., Zwitserlood, P., & Dobel, C. (2011). Effects of language comprehension on visual processing–MEG dissociates early perceptual and late N400 effects. *Brain and Language, 116*(2), 91-96.

Hoenig, K., Müller, C., Herrnberger, B., Sim, E. J., Spitzer, M., Ehret, G., & Kiefer, M. (2011). Neuroplasticity of semantic representations for musical instruments in professional musicians. *NeuroImage*, *56*(3), 1714-1725.

Hoenig, K., Sim, E. J., Bochev, V., Herrnberger, B., & Kiefer, M. (2008). Conceptual flexibility in the human brain: dynamic recruitment of semantic maps from visual, motor, and motion-related areas. *Journal of Cognitive Neuroscience*, *20*(10), 1799-1814.

Holt, L. E., & Beilock, S. L. (2006). Expertise and its embodiment: Examining the impact of sensorimotor skill expertise on the representation of action-related text. *Psychonomic bulletin & review*, *13*(4), 694-701.

Hsu, C. T., Jacobs, A. M., & Conrad, M. (2015). Can Harry Potter still put a spell on us in a second language? An fMRI study on reading emotion-laden literature in late bilinguals. *Cortex*, *63*, 282-295.

Huang, H. W., & Federmeier, K. D. (2015). Imaginative language: What event-related potentials have revealed about the nature and source of concreteness effects. *Language and linguistics*, *16*(4), 503-515.

Huang, H. W., Lee, C. L., & Federmeier, K. D. (2010). Imagine that! ERPs provide evidence for distinct hemispheric contributions to the processing of concrete and abstract concepts. *NeuroImage*, *49*(1), 1116-1123.

Hugdahl, K. (2000). Lateralization of cognitive processes in the brain. *Acta psychologica, 105*(2-3), 211-235.

Hull, R., & Vaid, J. (2005). Clearing the cobwebs from the study of the bilingual brain. *Handbook of bilingualism: Psycholinguistic approaches*, 480-496.

Hunter, Z. R., & Brysbaert, M. (2008). Visual half-field experiments are a good measure of cerebral language dominance if used properly: Evidence from fMRI. *Neuropsychologia*, *46*(1), 316-325.

Jared, D., Poh, R. P. Y., & Paivio, A. (2013). L1 and L2 picture naming in Mandarin–English bilinguals: A test of bilingual dual coding theory. *Bilingualism: Language and Cognition*, *16*(2), 383-396.

Johns, C. L., Tooley, K. M., & Traxler, M. J. (2008). Discourse impairments following right hemisphere brain damage: A critical review. *Language and linguistics compass*, *2*(6), 1038-1062.

Jung-Beeman, M. (2005). Bilateral brain processes for comprehending natural language. *Trends in cognitive sciences*, *9*(11), 512-518.

Kaplan, J. A., Brownell, H. H., Jacobs, J. R., & Gardner, H. (1990). The effects of right hemisphere damage on the pragmatic interpretation of conversational remarks. *Brain and language*, *38*(2), 315-333.

Kaschak, M. P., Madden, C. J., Therriault, D. J., Yaxley, R. H., Aveyard, M., Blanchard, A. A., & Zwaan, R. A. (2005). Perception of motion affects language processing. *Cognition*, *94*, B79-B89.

Kaup, B., Yaxley, R. H., Madden, C. J., Zwaan, R. A., & Lüdtke, J. (2007). Experiential simulations of negated text information. *The Quarterly Journal of Experimental Psychology*, *60*(7), 976-990.

Kellenbach, M. L., Wijers, A. A., & Mulder, G. (2000). Visual semantic features are activated during the processing of concrete words: Event-related potential evidence for perceptual semantic priming. *Cognitive Brain Research*, *10*(1-2), 67-75.

Kelley, W. M., Miezin, F. M., McDermott, K. B., Buckner, R. L., Raichle, M. E., Cohen, N. J., Ollinger, J. M., Akbudak, E., Conturo, T. E., Snyder, A. Z., & Petersen, S. E. (1998). Hemispheric specialization in human dorsal frontal cortex and medial temporal lobe for verbal and nonverbal memory encoding. *Neuron*, *20*(5), 927-936.

Keysar, B., Hayakawa, S. L., & An, S. G. (2012). The foreign-language effect: Thinking in a foreign tongue reduces decision biases. *Psychological science*, *23*(6), 661-668.

Kiefer, M., & Pulvermüller, F. (2012). Conceptual representations in mind and brain: theoretical developments, current evidence and future directions. *cortex*, *48*(7), 805-825.

Kiefer, M., Sim, E. J., Herrnberger, B., Grothe, J., & Hoenig, K. (2008). The sound of concepts: four markers for a link between auditory and conceptual brain systems. *Journal of Neuroscience*, *28*(47), 12224-12230.

Kitterle, F. L., Hellige, J. B., & Christman, S. (1992). Visual hemispheric asymmetries depend on which spatial frequencies are task relevant. *Brain and cognition*, *20*(2), 308-314.

Koster, D., Cadierno, T., & Chiarandini, M. (2018). Mental simulation of object orientation and size: A conceptual replication with second language learners. *Journal of the European Second Language Association*, *2*(1).

Kounios, J., & Holcomb, P. J. (1994). Concreteness effects in semantic processing: ERP evidence supporting dual-coding theory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*(4), 804.

Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations *Journal of memory and language*, *33*(2), 149-174.

Kreiner, H., & Degani, T. (2015). Tip-of-the-tongue in a second language: The effects of brief first-language exposure and long-term use. *Cognition*, *137*, 106-114.

Kühne, K., & Gianelli, C. (2019). Is Embodied Cognition Bilingual? Current Evidence and Perspectives of the Embodied Cognition Approach to Bilingual Language Processing. *Frontiers in psychology*, *10*.

Lachmair, M., Dudschig, C., De Filippis, M., de la Vega, I., & Kaup, B. (2011). Root versus roof: automatic activation of location information during word processing. *Psychonomic bulletin & review*, *18*(6), 1180-1188.

Laeng, B., Zarrinpar, A., & Kosslyn, S. M. (2003). Do separate processes identify objects as exemplars versus members of basic-level categories? Evidence from hemispheric specialization. *Brain and Cognition*, *53*(1), 15-27.

Lam, K. J., Dijkstra, T., & Rueschemeyer, S. A. (2015). Feature activation during word recognition: action, visual, and associative-semantic priming effects. *Frontiers in psychology*, *6*, 659.

Landauer, T. K., & Dumais, S. T. (1997). A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological review*, *104*(2), 211.

Lebois, L. A., Wilson-Mendenhall, C. D., & Barsalou, L. W. (2015). Are automatic conceptual cores the gold standard of semantic processing? The context-dependence of spatial meaning in grounded congruency effects. *Cognitive science*, *39*(8), 1764-1801.

Lemhöfer, K., & Broersma, M. (2012). Introducing LexTALE: A quick and valid lexical test for advanced learners of English. *Behavior research methods*, *44*(2), 325-343.

Leonard, M. K., Brown, T. T., Travis, K. E., Gharapetian, L., Hagler Jr, D. J., Dale, A. M., Elman, J. L. & Halgren, E. (2010). Spatiotemporal dynamics of bilingual word processing. *Neuroimage, 49*(4), 3286-3294.

Lincoln, A. E., Long, D. L., & Baynes, K. (2007). Hemispheric differences in the activation of perceptual information during sentence comprehension. *Neuropsychologia, 45*, 397–405.

Lincoln, A. E., Long, D. L., Swick, D., Larsen, J., & Baynes, K. (2008). Hemispheric asymmetries in the perceptual representations of words. *Brain research, 1188*, 112-121.

Long, D. L., & Baynes, K. (2002). Discourse representation in the two cerebral hemispheres. *Journal of Cognitive Neuroscience, 14*(2), 228-242.

Louwerse, M. M. (2008). Embodied relations are encoded in language. *Psychonomic Bulletin & Review, 15*(4), 838-844.

Louwerse, M. M., & Jeuniaux, P. (2010). The linguistic and embodied nature of conceptual processing. Cognition, 114, 96–104.

Luh, K. E., & Levy, J. (1995). Interhemispheric cooperation: Left is left and right is right, but sometimes the twain shall meet. *Journal of Experimental Psychology: Human perception and performance, 21*(6), 1243.

Madden, C. J., & Dijkstra, K. (2010). Contextual constraints in situation model construction: An investigation of age and reading span. *Aging, Neuropsychology, and Cognition, 17*(1), 19-34.

Madden, C. J., & Zwaan, R. A. (2006). Perceptual representation as a mechanism of lexical ambiguity resolution: An investigation of span and processing time. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(6), 1291.

Mahon, B. Z. (2015). The burden of embodied cognition. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *69*(2), 172.

Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of physiology-Paris, 102*(1), 59-70.

Male, A. G., & Gouldthorp, B. (2020). Hemispheric differences in perceptual integration during language comprehension: An ERP study. *Neuropsychologia*, 107353.

Mannaert, L. N. H., Dijkstra, K., & Zwaan, R. A. (2017). Is color an integral part of a rich mental simulation? *Memory & cognition*, *45*(6), 974-982.

Marian, V., Blumenfeld, H. K., & Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech, Language, and Hearing Research*.

Marsolek, C. J. (1999). Dissociable neural subsystems underlie abstract and specific object recognition. *Psychological Science*, *10*(2), 111-118.

Martin, A. (2007). The representation of object concepts in the brain. *Annu. Rev. Psychol.*, *58*, 25-45.

Mashal, N., Faust, M., Hendler, T., & Jung-Beeman, M. (2007). An fMRI investigation of the neural correlates underlying the processing of novel metaphoric expressions. *Brain and language*, *100*(2), 115-126.

Meteyard, L., Bahrami, B., & Vigliocco, G. (2007). Motion detection and motion verbs: Language affects low-level visual perception. *Psychological Science*, *18*(11), 1007-1013.

Meteyard, L., Cuadrado, S. R., Bahrami, B., & Vigliocco, G. (2012). Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex*, *48*(7), 788-804.

Metusalem, R., Kutas, M., Urbach, T. P., & Elman, J. L. (2016). Hemispheric asymmetry in event knowledge activation during incremental language comprehension: A visual half-field ERP study. *Neuropsychologia*, *84*, 252-271.

Monaco, E., Jost, L. B., Gygax, P. M., & Annoni, J. M. (2019). Embodied semantics in a second language: critical review and clinical implications. *Frontiers in human neuroscience*, *13*, 110.

Morrow, D. G., & Clark, H. H. (1988). Interpreting words in spatial descriptions. *Language and Cognitive Processes*, *3*(4), 275-291.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113.

Opitz, B., & Degner, J. (2012). Emotionality in a second language: It's a matter of time. *Neuropsychologia*, *50*(8), 1961-1967.

Ostarek, M., & Vigliocco, G. (2017). Reading sky and seeing a cloud: On the relevance of events for perceptual simulation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(4), 579.

Paivio, A. (1990). Mental representations: A dual coding approach. Oxford University Press.

Paivio, A. (1991). Dual coding theory: Retrospect and current status. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *45*(3), 255.

Paivio, A. (2010). Dual coding theory and the mental lexicon. *The Mental Lexicon*, *5*(2), 205-230.

Paivio, A. (2014). *Mind and its evolution: A dual coding theoretical approach*. Psychology Press.

Paivio, A., & Desrochers, A. (1980). A dual-coding approach to bilingual memory. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *34*(4), 388.

Paivio, A., & Te Linde, J. (1982). Imagery, memory, and the brain. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *36*(2), 243.

Pavlenko, A. (2009). Conceptual representation in the bilingual lexicon and second language vocabulary learning. *The bilingual mental lexicon: Interdisciplinary approaches*, 125-160.

Pavlenko, A. (2012). Affective processing in bilingual speakers: Disembodied cognition? *International Journal of Psychology*, *47*(6), 405-428.

Pecher, D., Zeelenberg, R., & Raaijmakers, J. G. (1998). Does pizza prime coin? Perceptual priming in lexical decision and pronunciation. *Journal of Memory and Language*, *38*(4), 401-418.

Pecher, D., van Dantzig, S., Zwaan, R. A., & Zeelenberg, R. (2009). Short article: Language comprehenders retain implied shape and orientation of objects. *Quarterly Journal of Experimental Psychology*, *62*(6), 1108-1114.

Peleg, O., & Eviatar, Z. (2008). Hemispheric sensitivities to lexical and contextual information: Evidence from lexical ambiguity resolution. *Brain and Language*, *105*(2), 71-82.

Peleg, O., & Eviatar, Z. (2009). Semantic asymmetries are modulated by phonological asymmetries: Evidence from the disambiguation of homophonic versus heterophonic homographs. *Brain and Cognition*, *70*(1), 154-162.

Peleg, O., & Eviatar, Z. (2012). Understanding written words: Phonological, lexical, and contextual effects in the cerebral hemispheres. *The handbook of the neuropsychology of language*, 59-76.

Peleg, O., & Eviatar, Z. (2017). Controlled semantic processes within and between the two cerebral hemispheres. *Laterality: Asymmetries of Body, Brain and Cognition*, *22*(1), 1-16.

Peleg, O., Markus, A., & Eviatar, Z. (2012). Hemispheric asymmetries in meaning selection: Evidence from the disambiguation of homophonic vs. heterophonic homographs. *Brain and cognition*, *80*(3), 328-337.

Peleg, O., Ozer, R., Norman, T., & Segal, O. (2018). Perceptual simulations during sentence comprehension: A comparison between typical adolescents and adolescents with autism spectrum disorder. *Journal of Neurolinguistics, 45*, 36-44.

Pexman, P. M. (2019). The role of embodiment in conceptual development. *Language, Cognition and Neuroscience*, *34*(10), 1274-1283.

Peyrin, C., Chauvin, A., Chokron, S., & Marendaz, C. (2003). Hemispheric specialization for spatial frequency processing in the analysis of natural scenes. *Brain and cognition*, *53*(2), 278-282.

Piazza, E. A., & Silver, M. A. (2014). Persistent hemispheric differences in the perceptual selection of spatial frequencies. *Journal of cognitive neuroscience*, *26*(9), 2021-2027.

Pulvermüller, F. (1999). Words in the brain's language. *Behavioral and brain sciences*, *22*(2), 253-279.

Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature reviews neuroscience*, *6*(7), 576-582.

Pulvermüller, F. (2013). How neurons make meaning: brain mechanisms for embodied and abstract-symbolic semantics. *Trends in cognitive sciences, 17*(9), 458-470.

Rey, A. E., Riou, B., Vallet, G. T., & Versace, R. (2017). The automatic visual simulation of words: A memory reactivated mask slows down conceptual access. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *71*(1), 14.

Richardson, D. C., Spivey, M. J., Barsalou, L. W., & McRae, K. (2003). Spatial representations activated during real-time comprehension of verbs. *Cognitive science*, *27*(5), 767-780.

Rommers, J., Meyer, A. S., & Huettig, F. (2013). Object shape and orientation do not routinely influence performance during language processing. *Psychological science*, *24*(11), 2218-2225.

Sabsevitz, D. S., Medler, D. A., Seidenberg, M., & Binder, J. R. (2005). Modulation of the semantic system by word imageability. *Neuroimage*, *27*(1), 188-200.

Sato, M., Schafer, A. J., & Bergen, B. K. (2013). One word at a time: mental representations of object shape change incrementally during sentence processing. *Language and Cognition*, *5*(4), 345-373.

Schneiderman, E. I., Murasugi, K. G., & Saddy, J. D. (1992). Story arrangement ability in right brain-damaged patients. *Brain and Language*, *43*(1), 107-120.

Schreuder, R., d'Arcais, G. B. F., & Glazenborg, G. (1984). Effects of perceptual and conceptual similarity in semantic priming. *Psychological Research, 45*(4), 339-354.

Scorolli, C., & Borghi, A. M. (2007). Sentence comprehension and action: Effector specific modulation of the motor system. *Brain research*, *1130*, 119-124.

Segalowitz, N., Trofimovich, P., Gatbonton, E., & Sokolovskaya, A. (2008). Feeling affect in a second language: The role of word recognition automaticity. *The Mental Lexicon*, *3*(1), 47-71.

Sheikh, N. A., & Titone, D. (2016). The embodiment of emotional words in a second language: An eye-movement study. *Cognition and Emotion*, *30*(3), 488-500.

Simmons, W. K., Ramjee, V., Beauchamp, M. S., McRae, K., Martin, A., & Barsalou, L. W. (2007). A common neural substrate for perceiving and knowing about color. *Neuropsychologia*, *45*(12), 2802-2810.

Simons, J. S., Koutstaal, W., Prince, S., Wagner, A. D., & Schacter, D. L. (2003). Neural mechanisms of visual object priming: evidence for perceptual and semantic distinctions in fusiform cortex. *Neuroimage*, *19*(3), 613-626.

Solomon, K. O., & Barsalou, L. W. (2001). Representing properties locally. *Cognitive psychology*, *43*(2), 129-169.

Solomon, K. O., & Barsalou, L. W. (2004). Perceptual simulation in property verification. *Memory & cognition*, *32*(2), 244-259.

Sperry, R. (1982). Some effects of disconnecting the cerebral hemispheres. *Bioscience reports*, *2*(5), 265-276.

Spivey, M. J., & Geng, J. J. (2001). Oculomotor mechanisms activated by imagery and memory: Eye movements to absent objects. *Psychological research*, *65*(4), 235-241.

Stanfield, R. A., & Zwaan, R. A. (2001). The effect of implied orientation derived from verbalcontext on picture recognition. *Psychological Sience*, *12*(2), 153-156.

Tettamanti, M., Buccino, G., Saccuman, M. C., Gallese, V., Danna, M., Scifo, P., Fazio, F., Rizzolatti, G., Cappa, S. F. & Perani, D. (2005). Listening to action-related sentences activates fronto-parietal motor circuits. *Journal of cognitive neuroscience*, *17*(2), 273-281.

Van Elk, M., & Blanke, O. (2011). The relation between body semantics and spatial body representations. *Acta psychologica*, *138*(3), 347-358.

Vukovic, N., & Shtyrov, Y. (2014). Cortical motor systems are involved in second-language comprehension: Evidence from rapid mu-rhythm desynchronization. *NeuroImage*, *102*, 695-703.

Vukovic, N., & Williams, J. N. (2014). Automatic perceptual simulation of first language meanings during second language sentence processing in bilinguals. *Acta psychologica*, *145*, 98-103.

Wassenburg, S. I., & Zwaan, R. A. (2010). Rapid Communication: readers routinely represent implied object rotation: the role of visual experience. *Quarterly Journal of Experimental Psychology*, *63*(9), 1665-1670.

Wennekers, T., Garagnani, M., & Pulvermüller, F. (2006). Language models based on Hebbian cell assemblies. *Journal of Physiology-Paris*, *100*(1-3), 16-30.

Wernicke, C. (1874). *Der aphasische Symptomencomplex: eine psychologische Studie auf anatomischer Basis*. Cohn.

West, W. C., & Holcomb, P. J. (2000). Imaginal, semantic, and surface-level processing of concrete and abstract words: an electrophysiological investigation. Journal of Cognitive Neuroscience, 12(6), 1024-1037.

Weylman, S. T., Brownell, H. H., Roman, M., & Gardner, H. (1989). Appreciation of indirect requests by left-and right-brain-damaged patients: The effects of verbal context and conventionality of wording. *Brain and language*, *36*(4), 580-591.

Whitehouse, P. J. (1981). Imagery and verbal encoding in left and right hemisphere damaged patients. *Brain and Language*, *14*(2), 315-332.

Willemin, J., Hausmann, M., Brysbaert, M., Dael, N., Chmetz, F., Fioravera, A., Gieruc, K. & Mohr, C. (2016). Stability of right visual field advantage in an international lateralized lexical decision task irrespective of participants' sex, handedness or bilingualism. *Laterality: Asymmetries of Body, Brain and Cognition*, *21*(4-6), 502-524.

Willems, R. M., & Casasanto, D. (2011). Flexibility in embodied language understanding. *Frontiers in psychology*, *2*, 116.

Willems, R. M., Hagoort, P., & Casasanto, D. (2010). Body-specific representations of action verbs: Neural evidence from right-and left-handers. *Psychological Science*, *21*(1), 67-74.

Winter, B., & Bergen, B. (2012). Language comprehenders represent object distance both visually and auditorily. *Language and Cognition*, *4*(1), 1-16.

Xiang, H., Van Leeuwen, T. M., Dediu, D., Roberts, L., Norris, D. G., & Hagoort, P. (2015). L2-proficiency-dependent laterality shift in structural connectivity of brain language pathways. *Brain Connectivity*, *5*(6), 349-361.

Xu, J., Kemeny, S., Park, G., Frattali, C., & Braun, A. (2005). Language in context: emergent features of word, sentence, and narrative comprehension. *Neuroimage, 25*(3), 1002-1015.

Yee, E., & Thompson-Schill, S. L. (2016). Putting concepts into context. *Psychonomic bulletin & review*, *23*(4), 1015-1027.

Yee, E., Ahmed, S. Z., & Thompson-Schill, S. L. (2012). Colorless green ideas (can) prime furiously. *Psychological science*, *23*(4), 364-369.

Zhang, Y. (2014). Online tool for handedness assessment. Retrieved from http://zhanglab.wikidot.com/handedness

Zwaan, R. A. (2004). The immersed experiencer: Toward an embodied theory of language comprehension. *Psychology of learning and motivation*, *44*, 35-62.

Zwaan, R. A., & Madden, C. J. (2005). Embodied sentence comprehension. *Grounding cognition: The role of perception and action in memory, language, and thinking*, 224-245.

Zwaan, R. A., Madden, C. J., Yaxley, R. H., & Aveyard, M. E. (2004). Moving words: Dynamic representations in language comprehension. *Cognitive Science, 28*(4), 611-619.

Zwaan, R. A., & Pecher, D. (2012). Revisiting mental simulation in language comprehension: Six replication attempts. *PLoS One, 7*(12), e51382. doi:10.1371/journal.pone.0051382

Zwaan, R. A., Stanfield, R. A., & Yaxley, R. H. (2002). Language comprehenders mentally represent the shapes of objects. *Psychological Sience, 13*(2), 168-171.

Zwaan, R. A., & Yaxley, R. H. (2003a). Spatial iconicity affects semantic relatedness judgments. *Psychonomic bulletin & review, 10*(4), 954-958.

Zwaan, R. A., & Yaxley, R. H. (2003b). Hemispheric differences in semantic-relatedness judgments. *Cognition*, *87*(3), B79-B86.

Zwaan, R. A., & Yaxley, R. H. (2004). Lateralization of object-shape information in semantic processing. *Cognition*, *94*(2), B35-B43.

APPENDICES

Appendix 1: Ethical approval from Tel Aviv University ethics committee

Academic Secretariat
Senate Office

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

המזכירות האקדמית
מדור הסנאט

19 ביוני 2018

לכבוד
פרופ׳ אורנה פלג
ביה״ס למדעי התרבות
הפקולטה למדעי הרוח
כ א ן

שלום רב,

הנדון: עבודת מחקר בנושא: הבנת שפה

הצעת המחקר הנ״ל עומדת בקריטריונים של ועדת האתיקה של אוניברסיטת תל-אביב.

לידיעת החוקר: האישור הוא אישור אתי בלבד.

אני מאחל לך הצלחה בהמשך המחקר.

תוקף האישור: 18.6.19.

*** לתשומת לב החוקרים: בקשות להארכת אישור יוגשו חודש לפני פקיעת תוקפו של האישור.**

ב ב ר כ ה,

פרופ׳ מאיר להב
יו״ר ועדת אתיקה אוניברסיטאית

העתק:
גב׳ טל נורמן, הפקולטה למדעי הרוח

אוניברסיטת תל-אביב
ועדת האתיקה האוניברסיטאית

Appendix 2: Critical stimuli in experiments 1 and 3

<u>Hebrew and English Sentences</u>

Version 1

Objects	L1-Hebrew Sentences	L2-English Sentences
balloon	הילד ראה את הבלון באריזה	The boy saw the balloon in the package
bat	האיש ראה את העטלף באוויר	The man saw the bat in the air
book	הילד ראה את הספר בתיק	The boy saw the book in the bag
cheese	האיש ראה את הגבינה בקופסה	The man saw the cheese in the box
cigarette	האישה ראתה את הסיגריה בזבל	The woman saw the cigarette in the trash
eagle	הילדה ראתה את העייט בשמיים	The girl saw the eagle in the sky
shirt	האיש ראה את החולצה על הדוגמן	The man saw the shirt on the model
towel	האישה ראתה את המגבת על החוף	The woman saw the towel on the beach
spaghetti	האיש ראה את הספגטי באריזה	The man saw the spaghetti in the package
corn	הילד ראה את התירס בשדה	The woman saw the corn in the field
lemon	הילדה ראתה את הלימון בגינה	The girl saw the lemon in the garden
airplane	הילד ראה את המטוס בנמל התעופה	The boy saw the airplane at the airport
apple	הילדה ראתה את התפוח בפח האשפה	The girl saw the apple in the garbage can
bread	האישה ראתה את הלחם במאפיה	The woman saw the bread in the bakery
pineapple	האישה ראתה את האננס על העוגה	The woman saw the pineapple on the cake
onion	האיש ראה את הבצל בסלסלה	The man saw the onion in the basket
mushroom	הילד ראה את הפטריה באריזה	The boy saw the mushroom in the package
tomato	הילדה ראתה את העגבניה בכריך	The girl saw the tomato in the sandwich
watermelon	האיש ראה את האבטיח על הצלחת	The man saw the watermelon on the plate
chicken	הילד ראה את העוף בתנור	The boy saw the chicken in the oven
gum	הילד ראה את המסטיק בחפיסה	The boy saw the gum in the pack
glasses	האישה ראתה את המשקפיים בתיק	The woman saw the glasses in the bag
banana	הילדה ראתה את הבננה בסלט הפירות	The girl saw the banana in the fruit salad
sock	הילדה ראתה את גרב על כף הרגל שלה	The girl saw the sock on her foot
toilet paper	הילדה ראתה את נייר הטואלט באריזה	The girl saw the toilet paper in the package
potato	האיש ראה את תפוח האדמה בשדה	The man saw the potato in the field
cake	האיש ראה את העוגה על הצלחת	The man saw the cake on the plate
scarf	האישה ראתה את הצעיף על הצוואר	The woman saw the scarf on the neck
cucumber	הילד ראה את המלפפון בשקית הקניות	The boy saw the cucumber in the shopping bag
carrot	האישה ראתה את הגזר במרק	The woman saw the carrot in the soup
green pepper	האישה ראתה את הפלפל הירוק בשקית הקניות	The woman saw the green pepper in the shopping bag
melon	האיש ראה את המלון בשקית הקניות	The man saw the melon in the shopping bag
jeans	הילד ראה את הג'ינס על המדף	The boy saw the jeans on the shelf
sleeping bag	הילדה ראתה את שק השינה על החוף	The girl saw the sleeping bag on the beach
mango	האיש ראה את המנגו בשקית הקניות	The man saw the mango in the shopping bag
umbrella	הילד ראה את המטריה במכונית	The boy saw the umbrella in the car
kiwi	הילדה ראתה את הקיווי בסלט הפירות	The girl saw the kiwi in the fruit salad
peach	האישה ראתה את האפרסק על העוגה	The woman saw the peach on the cake

dog	הילד ראה את הכלב על השביל	The boy saw the dog on the walkway
duck	הילדה ראתה את הברווז באגם	The girl saw the duck in the lake
avocado	הילד ראה את האבוקדו בכריך	The boy saw the avocado in the sandwich
leaf	הילד ראה את העלה על העץ	The boy saw the leaf on the tree
strawberry	האיש ראה את התות בשדה	The man saw the strawberry in the field
flowers	האישה ראתה את הפרחים בגינה	The woman saw the flowers in the garden
train	האיש ראה את הרכבת בתחנה	The man saw the train at the station
wine bottle	האישה ראתה את בקבוק היין בחנות	The woman saw the wine bottle at the store
cat	הילד ראה את החתול על הספה	The boy saw the cat on the sofa
runner	הילדה ראתה את האצנית בקו הזינוק	The girl saw the runner at the starting line
sweet potato	האיש ראה את הבטטה בשדה	The man saw the sweet potato in the field
swimmer	הילד ראה את השחיין בבריכת השחיה	The boy saw the swimmer in the swimming pool
broccoli	הילדה ראתה את הברוקולי בפסטה	The girl saw the broccoli in the pasta
steak	האישה ראתה את הסטייק בחנות	The woman saw the steak at the store
man	הילדה ראתה את האיש ברחוב	The girl saw the man in the street
ice cream	האיש ראה את הגלידה בכוס	The man saw the ice cream in the cup
candle	האיש ראה את הנר בקופסה	The man saw the candle in the box
carpet	הילדה ראתה את השטיח על הרצפה	The girl saw the carpet on the floor

Version 2

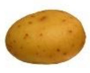
Objects	**L1-Hebrew Sentences**	**L2-English Sentences**
balloon	הילד ראה את הבלון באוויר	The boy saw the balloon in the air
bat	האיש ראה את העטלף במערה	The man saw the bat in the cave
book	הילד ראה את הספר במכונת הצילום	The boy saw the book in the photocopier
cheese	האיש ראה את הגבינה בכריך	The man saw the cheese in the sandwich
cigarette	האישה ראתה את הסיגרייה בחפיסה	The woman saw the cigarette in the pack
eagle	הילדה ראתה את העייט על העץ	The girl saw the eagle on the tree
shirt	האיש ראה את החולצה על המדף	The man saw the shirt on the shelf
towel	האישה ראתה את המגבת על המדף	The woman saw the towel on the shelf
spaghetti	האיש ראה את הספגטי בקערה	The man saw the spaghetti in the bowl
corn	האישה ראתה את התירס במרק	The woman saw the corn in the soup
lemon	הילדה ראתה את הלימון בתה	The girl saw the lemon in the tea
airplane	הילד ראה את המטוס בשמיים	The boy saw the airplane in the sky
apple	הילדה ראתה את התפוח בסלסלת הפירות	The girl saw the apple in the fruit basket
bread	האישה ראתה את הלחם בטוסטר	The woman saw the bread in the toaster
pineapple	האישה ראתה את האננס בשקית הקניות	The woman saw the pineapple in the shopping bag
onion	האיש ראה את הבצל בכריך	The man saw the onion in the sandwich
mushroom	הילד ראה את הפטריה בסלט	The boy saw the mushroom in the salad
tomato	הילדה ראתה את העגבניה בשקית הקניות	The girl saw the tomato in the shopping bag
watermelon	האיש ראה את האבטיח על הרצפה	The man saw the watermelon on the floor
chicken	הילד ראה את העוף בחצר	The boy saw the chicken in the yard
gum	הילד ראה את המסטיק בזבל	The boy saw the gum in the trash
glasses	האישה ראתה את המשקפיים על הראש	The woman saw the glasses on the head
banana	הילדה ראתה את הבננה בשקית הקניות	The girl saw the banana in the shopping bag

sock	הילדה ראתה את הגרב על המיטה שלה	The girl saw the sock on her bed
toilet paper	הילדה ראתה את נייר הטואלט בזבל	The girl saw the toilet paper in the trash
potato	האיש ראה את תפוח האדמה בתנור	The man saw the potato in the oven
cake	האיש ראה את העוגה בקופסה	The man saw the cake in the box
scarf	האישה ראתה את הצעיף בארון	The woman saw the scarf in the closet
cucumber	הילד ראה את המלפפון בסלט	The boy saw the cucumber in the salad
carrot	האישה ראתה את הגזר בשדה	The woman saw the carrot in the field
green pepper	האישה ראתה את הפלפל הירוק בסלט	The woman saw the green pepper in the salad
melon	האיש ראה את המלון על הצלחת	The man saw the melon on the plate
jeans	הילד ראה את הג'ינס על הדוגמן	The boy saw the jeans on the model
sleeping bag	הילדה ראתה את שק השינה על המדף	The girl saw the sleeping bag on the shelf
mango	האיש ראה את המנגו על הצלחת	The man saw the mango on the plate
umbrella	הילד ראה את המטריה באוויר	The boy saw the umbrella in the air
kiwi	הילדה ראתה את הקיווי בשקית הקניות	The girl saw the kiwi in the shopping bag
peach	האישה ראתה את האפרסק בשקית הקניות	The woman saw the peach in the shopping bag
dog	הילד ראה את הכלב על הספה	The boy saw the dog on the sofa
duck	הילדה ראתה את הברווז על האדמה	The girl saw the duck on the ground
avocado	הילד ראה את האבוקדו בשקית הקניות	The boy saw the avocado in the shopping bag
leaf	הילד ראה את העלה על האדמה	The boy saw the leaf on the ground
strawberry	האיש ראה את התות ביוגורט	The man saw the strawberry in the yogurt
flowers	האישה ראתה את הפרחים באגרטל	The woman saw the flowers in the vase
train	האיש ראה את הרכבת על הגשר	The man saw the train on the bridge
wine bottle	האישה ראתה את בקבוק היין בזבל	The woman saw the wine bottle in the trash
cat	הילד ראה את החתול על הכביש	The boy saw the cat on the road
runner	הילדה ראתה את האצנית בקו הסיום	The girl saw the runner at the finish line
sweet potato	האיש ראה את הבטטה בתנור	The man saw the sweet potato in the oven
swimmer	הילד ראה את השחיין בנקודת הזינוק	The boy saw the swimmer at the starting point
broccoli	הילדה ראתה את הברוקולי בשקית הקניות	The girl saw the broccoli in the shopping bag
steak	האישה ראתה את הסטייק במסעדה	The woman saw the steak at the restaurant
man	הילדה ראתה את האיש במכונית	The girl saw the man in the car
ice cream	האיש ראה את הגלידה במקפיא	The man saw the ice cream in the freezer
candle	האיש ראה את הנר על העוגה	The man saw the candle on the cake
carpet	הילדה ראתה את השטיח על המשאית	The boy saw the carpet on the truck

Pictures of Objects

Object	Version 1	Version 2	Object	Version 1	Version 2
balloon			cucumber		
bat			carrot		
book			green pepper		
cheese			melon		
cigarette			jeans		
eagle			sleeping bag		
shirt			mango		
towel			umbrella		
spaghetti			kiwi		
corn			peach		

lemon	
airplane	
apple	
bread	
pineapple	
onion	
mushroom	
tomato	
watermelon	
chicken	
gum	
dog	
duck	
avocado	
leaf	
strawberry	
flowers	
train	
wine bottle	
cat	
runner	
sweet potato	

glasses			swimmer		
banana			broccoli		
sock			steak		
toilet paper			man		
potato			ice cream		
cake			candle		
scarf			carpet		

Appendix 3: Critical Stimuli in experiments 2 and 4

<u>Hebrew and English Word-Pairs</u>

L1-Hebrew Word-Pairs		L2-English Word-Pairs	
Up Referent	**Down Referent**	**Up Referent**	**Down Referent**
צוואר	כתפיים	neck	shoulders
מכונית	כביש	car	road
רכבת	מסילה	train	railroad
סירה	ים	boat	sea
שמיכה	מיטה	blanket	bed
כובע	ראש	hat	head
גשר	נהר	bridge	river
ענף	שורש	branch	root
רוכב	סוס	rider	horse
שחקן	במה	actor	stage
אנטנה	רדיו	antenna	radio
חולצה	חצאית	shirt	skirt
ספר	מדף	book	shelf
גנן	דשא	gardener	grass
שמש	עננים	sun	clouds
מטריה	מגפיים	umbrella	boots
חגורה	נעליים	belt	shoes
עגילים	שרשרת	earrings	necklace
גבות	עיניים	eyebrows	eyes
להבה	נר	flame	candle
גג	בית	roof	house
עץ	אדמה	tree	ground
שפם	שפתיים	mustache	lips
טרקטור	שדה	tractor	field
דבש	פנקייק	honey	pancake
מרפק	ברך	elbow	knee
יד	רגל	hand	leg
תקרה	רצפה	ceiling	floor

מצח	אף	forehead	nose
מסך	מקלדת	screen	keyboard
פה	סנטר	mouth	chin
פרחים	אגרטל	flowers	vase
חזה	בטן	chest	belly
עוגה	מגש	cake	tray
אופניים	שביל	bicycle	trail
עשן	ארובה	smoke	chimney
ציפור	קן	bird	nest
אוניה	אוקיינוס	ship	ocean
הר	עמק	mountain	valley
שיער	קרקפת	hair	scalp
סוודר	מכנסיים	sweater	pants
מגדלור	חוף	lighthouse	beach
בשר	מנגל	meat	grill
ברז	כיור	tap	sink
מחבת	כיריים	pan	stove
סדין	מזרן	sheet	mattress
קרסול	עקב	ankle	heel
כדור	מגרש	ball	court
רמזור	מדרכה	stoplight	sidewalk
מכסה	סיר	cover	pot
קצף	בירה	foam	beer
אצן	מסלול	runner	track
ארטיק	מקל	popsicle	stick
ממטרה	מדשאה	sprinkler	lawn
אדים	קומקום	steam	teapot
מפרש	סיפון	sail	deck

Appendix 4: Experiment 5

Method

Exp. 5 was identical to Exp. 2, except that word-pairs were presented for 3500 ms, the list of critical stimuli included only 48 items (out of 56 that were used in Exp. 2) that had the highest English-Hebrew translation scores in the post-test, and 56 participants were tested (16 more than in Exp. 2). Thus, in the current experiment, 56 participants responded to 48 critical items presented in the center of the screen for 3500 ms.

Results

Data Cleanup

The entire data set, a total of 8064 trials (2688 critical trials and 5376 filler trials), was inspected in terms of accuracy rates per-participant as well as per-item, vocabulary knowledge of critical L2-items per-participant, and RT outliers.

First, accuracy rates were examined for each participant and item in each language. Participants and items that had a mean accuracy rate lower than 60%, in either the L1-Hebrew or the L2-English task, were excluded from analyses. Based on this criterion, 3 items were excluded from the data, resulting in a total loss of 168 trials (2.1%).

Next, 130 English trials that were incorrectly translated in the post-test vocabulary check were removed, 64 trials with RT greater than 3000 ms or lower than 200 ms were removed, and 39 trials that fell outside the range of acceptable latencies (i.e., +/− 3.5 SD from participant's mean RT) were removed. This trimming procedure accounted for a total loss of 233 trials (3.0%). Finally, filler trials were excluded from the data.

RT Data

For the RT analyses, additional 150 critical trials (6.4%) were removed due to incorrect responses. The final RT dataset consisted of correct critical trials only. Thus, 2204 data points (1190 in L1-Hebrew and 1014 in L2-English) that 56 participants produced by responding to 45 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 3 fitted the RT data significantly better than Model 1 and 2 ($\chi^2(8)=53.49$, $p<.001$). Therefore, Model 3, which included the fixed main effects of Spatial Condition, Target Language, Experimental Block, and English Proficiency Score, the interactions between them, and the random effects of

Subject and Item, was selected for further analysis. Mean correct RTs (in ms) by Spatial Condition, Target Language, Experimental Block, and English Proficiency Group (‘high-score’/’low-score’; See footnote 4) are illustrated in Table 10.

Table 10: Mean correct RTs (in ms) by Spatial Condition, Target Language, Experimental Block, and English Proficiency Group in Exp. 5

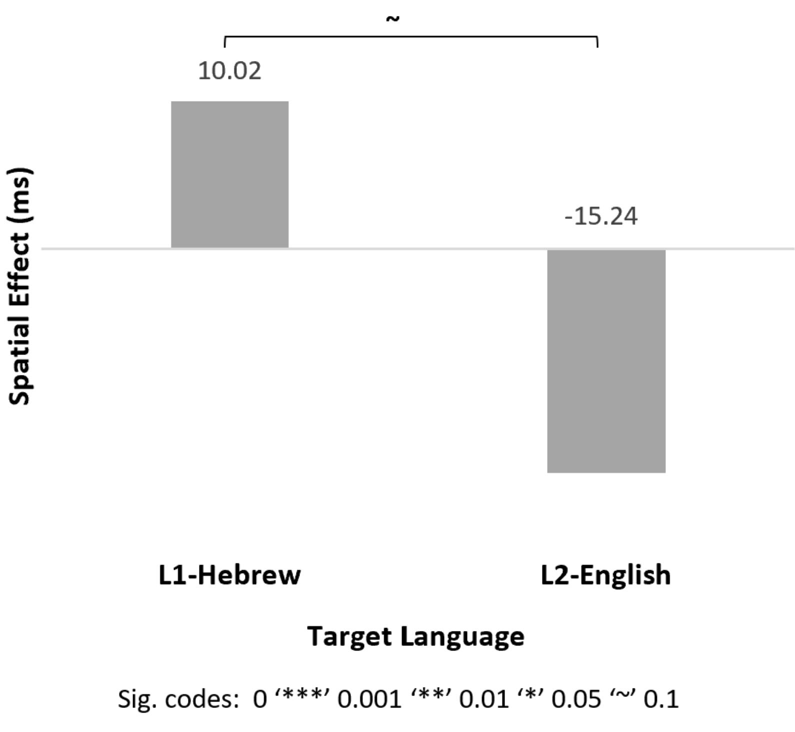
ExpBlock	Language	EnProfGrou	SpatialCond	RT.mean	RT.sd	Effect
First	He	High	match	864.99	201.27	
First	He	High	mismatch	877.98	246.25	12.99
First	He	Low	match	972.49	256.60	
First	He	Low	mismatch	1014.21	262.99	41.72
First	En	High	match	1318.58	335.33	
First	En	High	mismatch	1325.08	370.20	6.50
First	En	Low	match	1389.56	438.14	
First	En	Low	mismatch	1333.14	363.55	-56.42
Second	He	High	match	1000.99	259.94	
Second	He	High	mismatch	989.68	281.91	-11.31
Second	He	Low	match	909.96	284.26	
Second	He	Low	mismatch	906.93	261.02	-3.03
Second	En	High	match	1175.94	323.58	
Second	En	High	mismatch	1164.33	322.80	-11.61
Second	En	Low	match	1467.80	401.26	
Second	En	Low	mismatch	1442.52	315.99	-25.28

Within Model 3, the main effect of Target Language was significant ($\chi^2(1)=1133.65$, $p<.001$), indicating that overall, responses to ‘L1-Hebrew’ trials (Mean=938.77, SD=262.46) were faster than responses to ‘L2-English’ trials (Mean=1316.00, SD=372.82).

In addition, the main effect of English Proficiency Score was significant ($\chi^2(1)=5.64$, $p<.05$), as was the two-way interaction between English Proficiency Score and Target Language ($\chi^2(1)=39.58$, $p<.001$). Thus, only ‘L2-English’ trials were influenced by the effect of English Proficiency Score ($\chi^2(1)=15.13$, $p<.001$), such that higher scores (Mean=1241.58, SD=345.45) led to faster responses, relative to lower scores (Mean=1404.50, SD=385.03). Indeed, examination of the effect of English Proficiency Score, separately in each Target Language, revealed that the difference between participants with ‘high-score’ (i.e., half of the participants with the highest proficiency scores) and ‘low-score’ (i.e., the other half of the participants with the lowest proficiency scores) was not significant in the 'L1-Hebrew' ($\chi^2(1)$=.36, p=1.00), but was highly significant in the 'L2-English' ($\chi^2(1)$=15.13, p<.001).

Importantly, the two-way interaction between Spatial Condition and Target Language was marginally significant ($\chi^2(1)$=2.78, p=.096). Thus, while in the 'L1-Hebrew', responses to 'match' trials (Mean=933.75, SD=256.81) were faster than responses to 'mismatch' trials (Mean=943.77, SD=268.10), in the 'L2-English', responses to 'match' trials (Mean=1323.69, SD=388.10) were slower than responses to 'mismatch' trials (Mean=1308.45, SD=357.67). Yet, examination of the effect of Spatial Condition separately in each Target Language, revealed that the difference between 'match and 'mismatch' trials was not significant neither in the 'L1-Hebrew' ($\chi^2(1)$=.26, p=1.00) nor in the 'L2-English' ($\chi^2(1)$=3.12, p=.16), indicating that the effect of Spatial Condition on speed performance was weak, in both languages. The spatial effect (in ms) by Target Language is illustrated in Figure 15.

Figure 15: The spatial effect (in ms) by Target Language in Exp. 5



Error Data

The final Error dataset consisted of critical trials only. Thus, 2354 data points (1257 in L1-Hebrew and 1097 in L2-English) that 56 participants produced by responding to 45 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 3 fitted the Error data significantly better than Model 1 and 2 ($\chi^2(8)=21.30$, $p<.01$). Therefore, Model 3, which included the fixed main effects of Spatial Condition, Target Language, Experimental Block, and English Proficiency Score, the interactions between them, and the random effects of Subject and Item, was selected for further analysis.

Within Model 3, the main effect of Target Language was significant ($\chi^2(1)=7.05$, $p<.01$), indicating that overall, 'L1-Hebrew' trials (Mean=.05, SD=.23) resulted in a lower Error rate than 'L2-English' trials (Mean=.08, SD=.27). In addition, the main effect of Experimental Block was marginally significant ($\chi^2(1)=2.74$, $p=.098$), indicating that overall, 'first-block' trials (Mean=.08, SD=.26) resulted in a higher Error rate than 'second-block' trials (Mean=.05, SD=.22).

Furthermore, the two-way interaction between English Proficiency Score and Target Language was significant ($\chi^2(1)=7.69$, $p<.01$). Thus, only 'L2-English' trials were influenced by the effect of English Proficiency Score, such that higher scores (Mean=.06, SD=.23) led to lower Error rate, relative to lower scores (Mean=.10, SD=.30). Yet, examination of the effect of English Proficiency Score separately in each Target Language, revealed that the difference between participants with 'high-score' (i.e., half of the participants with the highest proficiency scores) and 'low-scores' (i.e., the other half of the participants with the lowest proficiency scores) was not significant neither in the 'L1-Hebrew' ($\chi^2(1)=.00$, $p=1.00$) nor in the 'L2-English' ($\chi^2(1)=2.57$, $p=.23$), indicating that the effect of English Proficiency Score on accuracy performance was weak, in both languages. Finally, the three-way interaction between English Proficiency Score, Target Language, and Experimental Block was significant as well ($\chi^2(1)=5.44$, $p<.05$).

Appendix 5: Analysis of first- and second-block trials in Exp. 3

Data analysis protocol

The procedure of data analysis was identical to the one employed in Exp. 1, except that the independent variable Visual Field (RVF/LVF) was added to the LME models that were fitted to the RT data and error data. Thus, three LME models were fitted to the RT and error data of Exp. 3 (the entire dataset of first- and second-block trials). Model 1 included the fixed main effects of Shape Condition, Target Language, and Visual Field, the interaction between them, and the random effects of Participants and Items. Model 2 included the fixed main effects of Shape Condition, Target Language, Visual Field, and Experimental Block, the interactions between them, and the random effects of Participants and Items. Model 3 included the fixed main effects of Shape Condition, Target Language, Visual Field, Experimental Block, and English Proficiency Score, the interactions between them, and the random effects of Participants and Items.

Data Cleanup

The entire dataset, a total of 26880 trials (8960 critical trials and 17920 filler trials), was inspected in terms of accuracy rates per-participant as well as per-item, vocabulary knowledge of critical L2-items per-participant, and RT outliers.

First, accuracy rates were examined for each participant and item in each language. Participants and items that had a mean accuracy rate lower than 60%, in either the Hebrew or the English task, were excluded from analyses. None of the participants or items in Exp. 3 was rejected based on this criterion.

Next, 111 English trials that were incorrectly translated in the English-Hebrew translation post-test were removed, 51 trials with RT greater than 3000 ms or lower than 200 ms were removed, and 313 trials that fell outside the range of acceptable latencies (i.e., +/− 3.5 SD from participant's mean RT) were removed. This trimming procedure accounted for a total loss of 475 trials (1.8%). Finally, filler trials were excluded from the data.

RT Data

For the RT analysis, additional 264 critical trials (3%) were removed due to incorrect responses, and the final RT dataset consisted of correct critical trials only. Thus, 8451 data points (4266 in L1-Hebrew and 4185 in L2-English) that 160 participants produced by responding to 56 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 2 fitted the RT data significantly better than Model 1 ($\chi^2(8)=121.14$, $p<.001$) and Model 3 did not fit the data significantly better than Model 2 ($\chi^2(16)=9.47$, $p=.89$). Therefore, Model 2, which included the fixed main effects of Shape Condition, Target Language, Visual Field, and Experimental Block, the interactions between them, and the random effects of Participants and Items, was selected for further analysis. Mean correct RTs (in ms) by Shape Condition, Visual Field, Target Language, and Experimental Block are presented in Table 11.

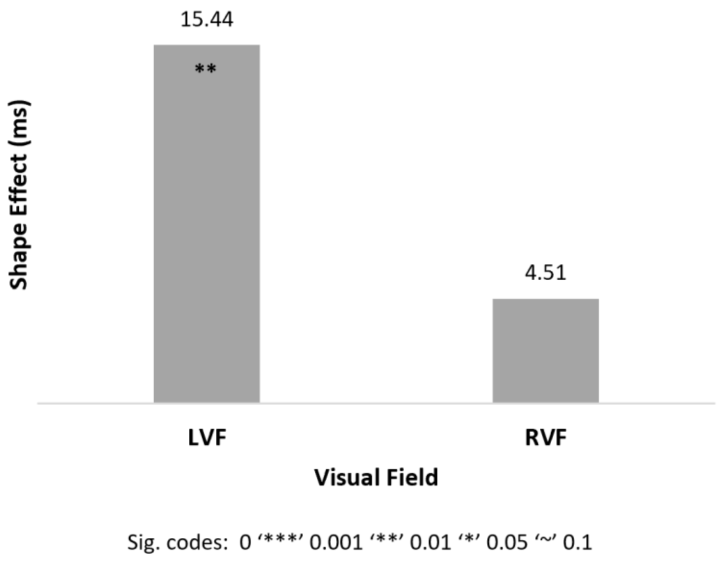
Table 11: Mean correct RTs (in ms) by Shape Condition, Visual Field, Target Language, and Experimental Block in Exp. 3

ExpBlock	Language	VF	ShapeCond	RT.mean	RT.sd	Effect
First	He	LVF	match	672.8311	205.2246	
First	He	LVF	mismatch	695.9263	218.9182	23.10
First	He	RVF	match	669.2532	209.0332	
First	He	RVF	mismatch	673.2838	208.2047	4.03
First	En	LVF	match	679.3441	203.7261	
First	En	LVF	mismatch	698.6679	227.1919	19.33
First	En	RVF	match	670.5514	223.5937	
First	En	RVF	mismatch	674.8184	223.5877	4.27
Second	He	LVF	match	647.3750	217.8551	
Second	He	LVF	mismatch	647.1269	185.2389	-0.25
Second	He	RVF	match	632.9369	197.1684	
Second	He	RVF	mismatch	634.4754	193.2400	1.54
Second	En	LVF	match	629.5568	192.3597	
Second	En	LVF	mismatch	649.0956	202.3671	19.54
Second	En	RVF	match	631.4225	216.8573	
Second	En	RVF	mismatch	640.2433	210.5206	8.82

Within Model 2, the main effect of Shape Condition was significant ($\chi^2(1)=9.00$, $p<.01$), indicating that responses to 'match' trials (Mean=654.28, SD=209.26) were faster than responses to 'mismatch' trials (Mean=664.24, SD=210.24). In addition, the main effect of Visual Field was significant ($\chi^2(1)=11.31$, $p<.001$), indicating that responses to ‘RVF’ trials (Mean=653.47, SD=211.15) were faster than responses to ‘LVF’ trials (Mean=665.01, SD=208.29). Moreover, the main effect of Experimental Block was also significant ($\chi^2(1)=118.08$, $p<.001$), indicating that responses to ‘first-block’ trials (Mean=679.25, SD=215.16) were slower than responses to ‘second-block’ trials (Mean=639.06, SD=202.28).

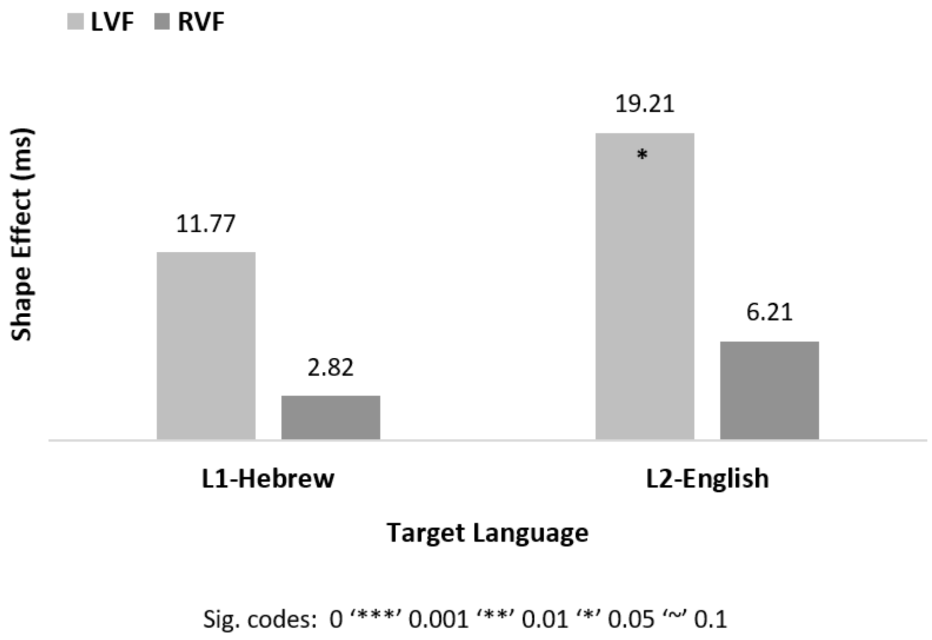
Planned chi-square tests: Even though the Visual Field variable did not significantly interact with Shape Condition ($\chi^2(1)=2.2$, $p=.14$), planned chi-square tests were performed to examine the effect of Shape Condition separately for each Visual Field. This was done since it was initially hypothesized that the shape effect would be modulated by Visual Field, such that it would be stronger in the ‘LVF’ relative to the ‘RVF’. Indeed, this examination revealed that while on ‘RVF’ trials the shape effect was not reliable ($\chi^2(1)=1.17$, $p=.56$), on ‘LVF’ trials the effect was significant ($\chi^2(1)=10.06$, $p<.01$). The shape effect (in ms) by Visual Field is illustrated in Figure 16.

Figure 16: The shape effect (in ms) by Visual Field in Exp. 3 (first- and second- trials)



In addition, even though the three-way interaction between Target Language, Shape Condition, and Visual Field was not significant ($\chi^2(1)=.06$, $p=.81$), planned chi-square tests were performed to examine the interaction between Visual Field and Shape Condition as well as the effect of Shape Condition in each Visual Field, separately for each Target Language. This was done since it was initially hypothesized (and was also supported by the results of Exp. 1), that the shape effect would be modulated by Target Language, such that it would be stronger in the ‘L1-Hebrew’ relative to the ‘L2-English’. These examinations revealed that the interaction between Visual Field and Shape Condition was not significant neither in the ‘L1-Hebrew’ ($\chi^2(1)$=.78, p=.76) nor in the ‘L2-English’ ($\chi^2(1)$=1.47, p=.45). In addition, in the ‘L1-Hebrew’, the shape effect did not reach significance, neither on ‘RVF’ trials ($\chi^2(1)$=.26, p=1.00) nor on ‘LVF’ trials ($\chi^2(1)$=3.07, p=.32). However, in the ‘L2-English’, while on ‘RVF’ trials the shape effect was not reliable ($\chi^2(1)$=1.03, p=1.00), on ‘LVF’ trials a significant shape effect was demonstrated ($\chi^2(1)$=7.46, p<.05), such that responses to ‘match’ trials (Mean=654.62, SD=199.63) were faster than responses to ‘mismatch trials (Mean=673.83, SD=216.44). These results indicate that the significant influence of Shape Condition on speed performance was most strongly apparent on ‘LVF-L2-English’ trials. The shape effect (in ms) by Visual Field and Target Language is illustrated in Figure 17.

Figure 17: The shape effect (in ms) by Visual Field and Target Language in Exp. 3 (first- and second- trials)



<u>Error Data</u>

The final Error dataset consisted of critical trials only. Thus, 8715 data points (4407 in L1-Hebrew and 4308 in L2-English) that 160 participants produced by responding to 56 critical items were analyzed.

The comparison of Models 1, 2, and 3 revealed that Model 2 did not fit the error data significantly better than Model 1 ($\chi^2(8)$=7.99, p=.43), and Model 3 did not fit the data significantly better than Model 2 ($\chi^2(16)=11.79$, $p=.76$). Therefore, Model 1, which included the fixed main effects of Shape Condition, Target Language, and Visual Field, the interactions between them, and the random effects of Participants and Items, was selected for further analysis.

Within Model 1, only the main effect of Shape Condition was significant ($\chi^2(1)=13.17$, $p<.001$), indicating that overall 'match' trials (Mean=.02, SD=.15) resulted in a lower error rate than 'mismatch' trials (Mean=.04, SD=.19).

Planned chi-square tests: Even though Visual Field did not significantly interact with Shape Condition ($\chi^2(1)=.03$, $p=.87$), planned chi-square tests were performed to examine the effect of Shape Condition separately for each Visual Field. This was done since it was initially hypothesized that the shape effect would be modulated by Visual Field, such that it would be stronger in the 'LVF' relative to the 'RVF'. This examination revealed that the shape effect was significant on both 'RVF' trials ($\chi^2(1)=6.95$, $p<.05$) and 'LVF' trials ($\chi^2(1)=6.15$, $p<.05$).

In addition, even though the three-way interaction between Target Language, Shape Condition, and Visual Field was not significant ($\chi^2(1)=.62$, $p=.37$), planned chi-square tests were performed to examine the interaction between Visual Field and Shape Condition as well as the effect of Shape Condition in each Visual Field, separately for each Target Language. This was done since it was initially hypothesized (and was also supported by the results of Exp. 1), that the shape effect would be modulated by Target Language, such that it would be stronger in the 'L1-Hebrew' relative to the 'L2-English'. These examinations revealed that the interaction between Visual Field and Shape Condition was not significant neither in the 'L1-Hebrew' ($\chi^2(1)=.24$, $p=1.00$) nor in the 'L2-English' ($\chi^2(1)=.57$, $p=.90$). In addition, in the 'L1-Hebrew', while on 'RVF' trials the shape effect was not reliable ($\chi^2(1)=2.84$, $p=.37$), on 'LVF' trials, a marginally significant effect was demonstrated ($\chi^2(1)=5.77$, $p=.065$). Yet, in the 'L2-English', the shape effect was not significant, neither on 'RVF' trials ($\chi^2(1)=4.18$, $p=.16$) nor on 'LVF' trials ($\chi^2(1)=1.28$, p=.1.00), indicating that the significant effect of Shape Condition on accuracy performance was most strongly evident on 'L1-Hebrew-LVF' trials.

In sum, both the RT data and error data of Exp. 3 (the entire dataset of first- and second-block trials) demonstrated a significant shape effect irrespective of Target Language. Thus, as opposed to Exp. 1, the shape effect in Exp. 3 was not modulated by Target Language. Furthermore, the shape effect was most strongly pronounced in the RH, in both languages. While in the RT data it was most strongly exhibited on 'LVF-L2-English' trials, in the error data it was most strongly evident on 'LVF-L1-Hebrew' trials.

תקציר

תיאוריות מודאליות של עיבוד שפה מניחות כי הבנת שפה כרוכה בסימולציה מולטי-מודאלית של הסיטואציה המתוארת בקלט הלשוני. כלומר, אותן מערכות סנסוריות, מוטוריות, ורגשיות שמופעלות כאשר אנחנו חווים אירוע מסוים, מופעלות גם כאשר אנחנו קוראים או שומעים על האירוע. הבנת שפה, לפיכך, מערבת לא רק ייצוגים לשוניים, אלא גם ייצוגים מודאליים מסוגים שונים (למשל, ייצוגים ויזואליים) הקשורים באובייקטים ובמצבים המתוארים (Anderson, 2003; Barsalou, 2008; Glenberg, 2015).

על בסיס הנחה זו, בארסלו ועמיתיו (Barsalou, Santos, Simmons, & Wilson, 2008) הציעו מודל היברידי, לפיו משמעויות מיוצגות בשתי מערכות נפרדות: מערכת לשונית המקודדת משמעויות באמצעות אסוציאציות בין מילים, ומערכת סימולציה המקודדת משמעויות באמצעות ידע מודאלי לא-לשוני. באופן חשוב, המודל מניח קשר בין שני סוגי הייצוגים כך שבמהלך הבנת שפה, הקלט הלשוני מפעיל ייצוגים לשוניים במערכת הלשונית (למשל, הצורה הכתובה של המילה "כלב"), ואלה מפעילים ייצוגים קשורים במערכת הסימולציה (למשל, דימוי ויזואלי של כלב).

מחקרים רבים מראים התעוררות של ייצוגים סנסוריים, מוטוריים, ורגשיים במהלך הבנת שפה (לסקירה ראו Barsalou, 2008), אולם אלה התמקדו בעיקר בשפה ראשונה. בשונה משפה ראשונה, הנרכשת באופן טבעי וחוויתי, רכישת שפה שנייה עשויה להיות מנותקת מהחוויות שלנו במציאות, בעיקר כאשר השפה נלמדת במסגרת פורמלית והשימוש בה נעשה בהקשרי חיים מוגבלים יחסית. במקרה כזה, הקשר בין ייצוגים לשוניים במערכת הלשונית לייצוגים סנסוריים-מוטוריים במערכת הסימולציה עשוי להיות חלש יותר. לכן, ייתכן כי אחד ההבדלים המהותיים הקיימים בין הבנת שפה ראשונה ושנייה, בנסיבות כאלה, הוא ביכולת לבנות באופן ספונטני סימולציה עשירה ומורכבת של המצבים המתוארים בתוכן הלשוני.

לפיכך, המטרה הראשונה של עבודה זו הייתה לבדוק האם תהליכי הבנה של שפה שנייה, בהשוואה לשפה ראשונה, כרוכים בהתעוררות של ייצוגים מודאליים הקשורים לתוכן הלשוני. באופן ספציפי, המחקר הנוכחי התמקד ביכולת לעורר סימולציות ויזואליות במהלך קריאה בשפה ראשונה ובשפה שנייה. אם אופן רכישת השפה וצורת השימוש בה אכן משפיעים על יכולת זו, נצפה שמידע ויזואלי הקשור לתוכן הסמנטי של המילים יתעורר בעוצמה רבה יותר בזמן עיבוד שפה ראשונה, בהשוואה לעיבוד שפה שנייה.

המטרה השנייה של המחקר הייתה לבחון את התשתית הביולוגית של סימולציות ויזואליות אלה, תוך התמקדות בתרומה היחסית של כל אחת מהמיספרות המוח לתהליך זה. מחקרים קודמים שבדקו הבדלים בין שתי המיספרות המוח, הן במהלך עיבוד שפתי והן במהלך עיבוד ויזואלי, הראו יתרון שפתי להמיספרה השמאלית ויתרון ויזואלי להמיספרה הימנית (Corballis, 2003; Hugdahl, 2000). עם זאת, רק מחקרים בודדים בדקו את מידת המעורבות של שתי ההמיספרות בבניית סימולציות ויזואליות במהלך הבנת שפה, ואלה התמקדו רק בשפה ראשונה (למשל, Lincoln, Long & Baynes, 2007). לפיכך, המחקר הנוכחי בחן את היכולת הנפרדת והמשותפת של שתי המיספרות המוח לעורר ידע ויזואלי במהלך הבנת שפה ראשונה ושנייה. אם המיספרה שמאל מתמחה בעיבוד לשוני והמיספרה ימין מתמחה בעיבוד ויזואלי לא-לשוני, נצפה שתהליכי סימולציה ויזואלית ישענו

בעיקר על המיספרה ימין. יתרה מכך, אם עיבוד שפה ראשונה מערב את מערכת הסימולציה, ואילו עיבוד שפה שנייה, הנלמדת באופן פורמלי, נשען בעיקר על המערכת הלשונית, נצפה למעורבות גדולה יותר של המיספרה ימין בעיבוד שפה ראשונה לעומת עיבוד שפה שנייה.

על מנת לבחון השערות אלה, בוצעו שני סטים של ניסויים. בכל הניסויים המשתתפים היו דוברי עברית ילידיים (עברית שפה ראשונה), שגרו בישראל כל חייהם, ולמדו את שפתם השנייה-אנגלית אחרי גיל 6 בבתי ספר בישראל. נבדקים אלה ביצעו מטלות זהות בשפתם הראשונה-עברית ubשפתם השנייה-אנגלית. המטלה הראשונה - מטלת התאמת תמונה למשפט (Zwaan, Stanfield & Yaxley, 2002) בחנה את היכולת של הנבדקים לעורר באופן ספונטני ידע לגבי הצורה המרומזת של האובייקטים המוזכרים בקלט הלשוני (ניסויים 1, 3). המטלה השנייה - מטלת שיפוט קשר סמנטי בין שתי מילים (Zwaan & Yaxley, 2003a) בדקה את היכולת של הנבדקים לעורר ידע ויזואלי לגבי המיקום המרחבי האופייני של האובייקטים המוזכרים (ניסויים 2, 4). בסט הניסויים הראשון (ניסויים 1, 2) גירויי המטרה (ראו תיאור בהמשך) הוצגו במרכז המסך לשתי המיספרות המוח. בסט הניסויים השני (ניסויים 3, 4), אותם גירויים הוצגו בשדה הראייה השמאלי להמיספרה הימנית או בשדה הראייה הימני להמיספרה השמאלית.

ניסויים 1 ו-3 עשו שימוש במטלת התאמת תמונה למשפט. במטלה זו הנבדקים קראו משפטים שתיארו אובייקט במיקום מסוים ("הילד ראה את הבלון באוויר/באריזה"). משפטים אלה הוצגו בעברית (שפה ראשונה) או באנגלית (שפה שנייה). מיד אחרי קריאת המשפט, הוצגה לנבדקים תמונה של אובייקט (למשל, בלון) והם התבקשו להחליט האם האובייקט שהוצג בתמונה, הוזכר במשפט שקראו (כן/לא). בכל הצעדים הקריטיים, האובייקט שבתמונה אכן הוזכר במשפט, אך צורתו יכלה להיות תואמת או לא תואמת לצורה המשתמעת מהמשפט. למשל, המשפט "הילד ראה את הבלון באוויר" מרמז על בלון מנופח, ולכן אחרי משפט זה, בתנאי התואם הוצגה תמונה של בלון מנופח, ובתנאי הלא-תואם הוצגה תמונה של בלון לא מנופח (ולהפך במשפט "הילד ראה את הבלון באריזה"). תגובות מהירות יותר בתנאי התואם בהשוואה לתנאי הלא-תואם (האפקט הצורני), מעידות על התעוררות ספונטנית של ידע ויזואלי לגבי צורת האובייקט במהלך הבנת המשפט. ניסוי 1 בחן התעוררות של ידע ויזואלי-צורני כאשר התמונות מוצגות במרכז המסך לשתי המיספרות המוח. ניסוי 3 בחן התעוררות של ידע ויזואלי-צורני כאשר התמונות מוצגות בשדה הראייה השמאלי להמיספרה הימנית או בשדה הראייה הימני להמיספרה השמאלית.

ניסויים 2 ו-4 עשו שימוש במטלת שיפוט קשר סמנטי. במטלה זו, הנבדקים התבקשו להחליט בכל צעד האם שתי מילים שהוצגו אחת מעל השנייה על גבי המסך קשורות במשמעותן (כן/לא). בשני הניסויים המילים הוצגו בעברית (שפה ראשונה) או באנגלית (שפה שנייה). בצעדים הקריטיים, שתי המילים היו קשורות סמנטית, ובנוסף ייצגו אובייקטים בעלי יחס מרחבי-אנכי אופייני, כך שבמציאות אובייקט אחד ממוקם בדרך כלל מעל האובייקט השני (מכונית-כביש). זוגות המילים הוצגו בשני תנאי תצוגה מרחביים: בתנאי התואם, הסידור המרחבי של שתי המילים על גבי המסך היה זהה למיקום המרחבי האופייני לרפרנטים שאותם הן מציינות ("מכונית" מעל "כביש"); ואילו בתנאי הלא-תואם, הסידור המרחבי של המילים היה הפוך מהיחס המרחבי שקיים בין הרפרנטים שלהן במציאות ("כביש" מעל "מכונית"). תגובות מהירות יותר בתנאי התואם, בהשוואה לתנאי הלא-תואם (האפקט המרחבי), מעידות על התעוררות ספונטנית של ידע ויזואלי לגבי המיקום המרחבי האופייני של

האובייקטים במהלך הבנת המילים. ניסוי 2 בחן התעוררות של ידע ויזואלי-מרחבי כאשר המילים מוצגות במרכז המסך לשתי המיספרות המוח. ניסוי 4 בחן התעוררות של ידע ויזואלי-מרחבי כאשר המילים מוצגות בשדה הראייה השמאלי להמיספרה הימנית או בשדה הראייה הימני להמיספרה השמאלית.

ההשערות הספציפיות של המחקר היו כדלקמן: (א) בסט הניסויים הראשון (תצוגה מרכזית) צפינו שיימצא הבדל בין עיבוד שפה ראשונה לעיבוד שפה שנייה, כך שקריאת מילים ומשפטים בשפה שנייה תעורר במידה מופחתת, או לא תעורר כלל, ידע ויזואלי הקשור לצורה או למיקום המרחבי של האובייקטים המתוארים בקלט הלשוני. זאת עקב ההבדלים המהותיים הקיימים בין אופן הרכישה והשימוש של שתי השפות בקרב נבדקי המחקר. כלומר, האפקטים הויזואליים בשתי המטלות (האפקט הצורני והאפקט המרחבי) היו צפויים להיות חלשים יותר באופן מובהק בניסויים בשפה השנייה, בהשוואה לניסויים בשפה הראשונה. (ב) בסט הניסויים השני (תצוגה צידית) צפינו שתהליכי סימולציה במהלך קריאת מילים ומשפטים יערבו את שתי ההמיספרות. כלומר, אם ידע ויזואלי (צורני ומרחבי) אכן מתעורר במהלך הקריאה, הוא יתעורר בשתי המיספרות המוח, זאת משום שמנגנונים ויזואליים קיימים בשתיהן. אולם, צפינו כי ידע זה יתעורר במידה חזקה יותר בהמיספרה ימין מאשר בהמיספרה שמאל, עקב היתרון שיש להמיספרה ימין בעיבוד מידע ויזואלי לא-לשוני. כלומר, צפינו שהאפקטים הויזואליים (האפקט הצורני והאפקט המרחבי) שיתקבלו בהמיספרה ימין יהיו חזקים יותר, בהשוואה להמיספרה שמאל.

בהתאם להשערת המחקר הראשונה, בסט הראשון (תצוגה מרכזית), אפקטים ויזואליים התקבלו רק במקרה של שפה ראשונה (ורק במקרה של מטלת התאמת תמונה למשפט – ראו פירוט בהמשך). בניסוי 1 (מטלת התאמת תמונה למשפט), התקבלה אינטראקציה מובהקת בין תנאי הצורה (תואם/לא-תואם) לבין תנאי השפה (ראשונה/שנייה). בעוד שבשפה הראשונה האפקט הצורני היה מובהק, בשפה השנייה ההבדל בין התנאי התואם לתנאי הלא-תואם היה זניח. ממצא זה מעיד על כך שדו-לשוניים מהסוג שנבדק במחקר זה, בונים סימולציות ויזואליות בשפתם הראשונה, אך לא בשפתם השנייה. כלומר, בעוד הבנת שפה ראשונה שנלמדה באופן טבעי מערבת תהליכי סימולציה, נראה כי הבנת שפה שנייה שנלמדה בצורה פורמלית נסמכת בעיקר על תהליכי עיבוד לשוניים.

באופן מעניין, בשתי השפות, האפקט הצורני הושפע מסדר הבלוקים (שפה ראשונה אחרי שפה שנייה/שפה שנייה אחרי שפה ראשונה). בשפה הראשונה (עברית), האפקט הצורני היה חלש יותר כאשר הניסוי בשפה זו בוצע מיד לאחר הניסוי בשפה השנייה (אנגלית). לעומת זאת, בשפה השנייה (אנגלית), האפקט הצורני היה חזק יותר כאשר הניסויי בשפה זו בוצע מיד לאחר הניסוי בשפה הראשונה (עברית). ממצא זה מעיד על כך שאופן עיבוד המשפטים בכל אחת מהשפות בניסוי הראשון (עברית-סימולציה/אנגלית-לשוני בלבד), השפיע על אופן עיבוד המשפטים בכל אחת מהשפות בניסוי השני.

בנוסף, נמצא כי האפקטים הויזואליים הושפעו מסוג המטלה. בעוד שבמטלת התאמת תמונה למשפט (ניסוי 1) התקבל אפקט ויזואלי מובהק בשפה הראשונה, במטלת השיפוט הסמנטי (ניסוי 2) לא נמצאו אפקטים ויזואליים מובהקים, לא בשפה הראשונה ולא בשפה השנייה. ממצא זה מצביע על כך שמידת המעורבות של מערכת הסימולציה, גם במהלך הבנת שפה ראשונה, עשויה להיות מושפעת מגורמים שונים כגון: אופי המטלה (התאמת תמונה למשפט/שיפוט סמנטי), סוג הגירויים (עם תמונות/ללא תמונות), או סוג המידע הויזואלי שנבדק (צורני/מרחבי).

לסיכום, התוצאות שהתקבלו מסט הניסויים הראשון מרמזות על הבדל בין עיבוד שפה ראשונה ושנייה, כך שסימולציות ויזואליות במהלך הבנת שפה מתרחשות רק בשפה ראשונה. מעבר לכך, גם במקרה של שפה ראשונה, סימולציות ויזואליות נצפו רק במטלת התאמת תמונה למשפט, ורק כאשר הניסוי בשפה הראשונה נערך לפני הניסוי בשפה השנייה. תוצאות אלה יכולות להיות מוסברות במסגרת תיאוריות מודאליות המבחינות בין תהליכי עיבוד המבוססים על המערכת הלשונית בלבד, לתהליכי הבנה עמוקים יותר המערבים גם את מערכת הסימולציה (Barsalou et al., 2008). לפי הסבר זה, שפה שנייה, הנלמדת באופן פורמלי, אינה מייצרת קשרים חזקים בין שתי המערכות, ולכן נשענת בעיקר על המערכת הלשונית. שפה ראשונה, לעומת זאת, מאופיינת בקשר חזק בין שתי המערכות, ולכן מאפשרת את שני סוגי העיבודים - עיבוד רדוד יותר המערב רק את המערכת הלשונית (Glaser, 1992) ועיבוד עמוק יותר הכולל גם אקטיבציה של ייצוגים מודאליים (ויזואליים) במערכת הסימולציה (Solomon & Barsalou, 2004).

בהתאם להשערת המחקר השנייה, בסט השני (תצוגה צידית) האפקט הויזואלי הצורני היה חזק יותר כאשר הגירויים הוצגו בשדה הראייה השמאלי ישירות להמיספרה הימנית. גם בסט זה, אפקטים ויזואליים התקבלו רק במטלת התאמת תמונה למשפט (ניסויים 3א-3ב). בניסויים אלה נמצאה אינטראקציה שולית בין תנאי הצורה (תואם/לא-תואם) לתנאי שדה הראייה (ימני/שמאלי), כך שבלי קשר לשפה המעורבת, האפקט הצורני היה מובהק רק כאשר הגירויים הוצגו בשדה הראייה השמאלי להמיספרה הימנית. ממצא זה מעיד על כך שמעבר לסוג השפה (ראשונה/שנייה), ידע ויזואלי לא-לשוני מתעורר במידה חזקה יותר בהמיספרה הימנית, ככל הנראה עקב יתרונה של המיספרה ימין בעיבוד ויזואלי (Corballis, 2003; Hugdahl, 2000).

למרות שלא נמצאה אינטראקציה משולשת בין תנאי השפה (ראשונה-עברית/שנייה-אנגלית), תנאי הצורה (תואם/לא-תואם), ותנאי שדה הראייה (ימני/שמאלי), השוואות מתוכננות שבוצעו בכל שפה בנפרד הראו שההבדל בין שתי ההמיספרות, מבחינת האפקט הצורני, היה גדול יותר בשפה השנייה-אנגלית. באופן ספציפי, כאשר הניסוי בוצע בעברית, בשתי ההמיספרות התקבלו תוצאות דומות: התנאי התואם היה מהיר יותר מהתנאי הלא-תואם, אך הבדל זה לא הגיע לידי מובהקות. לעומת זאת, כאשר הניסוי בוצע באנגלית, ההבדל בין התנאי התואם לתנאי הלא-תואם היה מובהק בהמיספרה הימנית ולא קיים בהמיספרה השמאלית. ממצאים אלה, יחד עם ממצאי הניסוי הראשון (תצוגה מרכזית), מרמזים על מעורבות שונה של שתי ההמיספרות במהלך קריאת משפטים בשפה ראשונה ושנייה.

בכדי להמשיך ולבדוק את מידת המעורבות של שתי ההמיספרות במהלך קריאה טבעית בכל אחת מהשפות, נערכה השוואה בין האפקט הצורני שהתקבל כאשר התמונות הוצגו בשדה הראייה המרכזי לשתי ההמיספרות, לאפקט שהתקבל כאשר התמונות הוצגו בשדה הראייה הימני להמיספרה השמאלית או בשדה הראייה השמאלי להמיספרה הימנית. השוואות אלה הראו ששתי ההמיספרות מעורבות בתהליכי הקריאה של שתי השפות. עם זאת, מידת המעורבות של כל אחת מההמיספרות משתנה כתלות בשפה. בשפה ראשונה, דפוס האפקט הצורני שהתקבל בשדה הראייה המרכזי (אפקט מובהק), היה שונה מהדפוס שהתקבל בשדה הראייה הימני או השמאלי (בשני המקרים, האפקט הצורני לא הגיע לידי מובהקות). ממצא זה מעיד על כך שבמהלך קריאה טבעית בשפה ראשונה, שתי ההמיספרות תורמות באופן מצטבר לאפקט הצורני, ומכאן ששתיהן מעורבות בתהליכי ההבנה של משפטים כתובים בשפה ראשונה. לעומת זאת, בשפה שנייה, דפוס האפקט הצורני שהתקבל בשדה הראייה המרכזי

(אפקט לא מובהק) היה דומה לזה שהתקבל בשדה הראייה הימני (אפקט לא מובהק) ושונה מזה שהתקבל בשדה הראייה השמאלי (אפקט מובהק). ממצא זה מעיד על כך שקריאה טבעית בשפה שנייה נשענת בעיקר על המיספרה שמאל (עיבוד לשוני בלבד), ולכן למרות שמשפטים בשפה שנייה יכולים לעורר ידע ויזואלי בהמיספרה ימין, ידע זה אינו משפיע על תהליכי העיבוד בתנאי קריאה רגילים (תצוגה מרכזית).

לסיכום, ממצאי הסט השני מצביעים על מעורבות גדולה יותר של המיספרה ימין בתהליכי סימולציה ויזואלית. ממצאים אלה עולים בקנה אחד עם הטענה לפיה עיבוד ויזואלי מתבצע בעיקר בצד ימין של המוח ואילו עיבוד לשוני מתבצע בעיקר בצד שמאל של המוח. בנוסף, השוואה בין התוצאות שהתקבלו בשדה הראייה המרכזי לתוצאות שהתקבלו בשדות הראייה הפריפריאליים, מלמדת על אינטראקציה שונה בין שתי המיספרות המוח בכל אחת מהשפות, כך שעיבוד שפה ראשונה נשען על שתי ההמיספרות, ואילו עיבוד שפה שנייה מתבצע בעיקר בהמיספרה שמאל.

יחד, ממצאי המחקר הנוכחי מצביעים על קשר בין אופן רכישת השפה, דפוס העיבוד ההמיספריאלי, והיכולת לעורר סימולציות ויזואליות במהלך הבנת שפה. באופן ספציפי, הממצאים מציעים כי במקרה של שפה ראשונה, הנרכשת באופן טבעי וחווייתי, העיבוד נשען על שתי המיספרות המוח, ולכן מערב לא רק ייצוגים לשוניים אלא גם ייצוגים ויזואליים לא-לשונים הקשורים לתוכן הלשוני. לעומת זאת, במקרה של שפה שנייה, הנלמדת באופן פורמלי, העיבוד נשען בעיקר על ההמיספרה השמאלית של המוח, ולכן מערב ייצוגים לשוניים בלבד.

להבדלים אלה עשויות להיות השלכות על טיב ההבנה של כל אחת מהשפות, משום שתהליכי הבנה המערבים סימולציה עשויים להוביל לעיבוד קונספטואלי עמוק יותר, המאפשר תהליכי עיבוד גבוהים הכוללים הסקת מסקנות וניבויים, ואילו תהליכי עיבוד לשוניים נוטים להיות שטחיים יותר ואף לא מספיקים עבור מטלות מסוימות (Solomon & Barsalau, 2004; Barsalau et al., 2008). המחקר הנוכחי הציג הבדל מהותי בין שפה ראשונה לשפה שנייה בכל הנוגע לעיבוד המיספריאלי וליכולת סימולציה. נחוצים מחקרים נוספים על מנת לבחון את הקשר הסיבתי בין יכולת סימולציה ליכולת הבנה בשפה ראשונה ושנייה.

עבודה זו נעשתה בהדרכת

פרופסור אורנה פלג

אוניברסיטת תל-אביב
הפקולטה למדעי הרוח ע"ש לסטר וסאלי אנטין
בית הספר למדעי התרבות ע"ש שירלי ולסלי פורטר
התוכנית ללימודים קוגניטיביים של השפה ושימושיה

סימולציה תפיסתית ויזואלית בשתי המיספרות המוח במהלך הבנת שפה ראשונה ושנייה

חיבור לשם קבלת התואר "דוקטור לפילוסופיה"

מאת

טל נורמן

הוגש לסנאט של אוניברסיטת תל-אביב
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