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The Lester & Sally Entin Faculty of Humanities

The Shirley & Leslie Porter School of Cultural Studies

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**Visual simulations in the two cerebral hemispheres**

**during first and second language comprehension**

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**Tal Norman**

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**Prof. Orna Peleg**

**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.