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Hemispheric processing of mental representations during text comprehension: Evidence for inhibition of inconsistent shape information

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ABSTRACT

To successfully understand a text, readers often mentally represent the shape of an object described in a text (e.g., creating a mental image of a sliced tomato when reading about a tomato on a pizza). However, it is currently unclear how the cerebral hemispheres contribute to these mental images during reading. In the current study, participants were presented with sentences consistent with the shape of an object (i.e., the match condition), sentences inconsistent with the shape of an object (i.e., the mismatch condition), or sentences that did not specify the shape of an object (i.e., the neutral condition). Participants read each sentence and then viewed an image of an object that was quickly presented to either the right visual field-left hemisphere (rvf-LH) or the left visual field-right hemisphere (lvf-RH). Results indicate that when the shape of an object was implicitly described in the text (in Experiment 1), response times for images presented to the rvf-LH were longer in the mismatch condition than in the neutral or match conditions. However, no response time differences were evident in the lvf-RH. When the shape of an object was explicitly described in the text (in Experiment 2), response times were longer in the mismatch condition than in the neutral and match conditions in both hemispheres. Thus, hemispheric involvement in mental representation depends on how explicit information is described in a text. Furthermore, these findings suggest that readers inhibit information that does not match an object's shape described in a text.

1. Introduction

During text comprehension, readers often encounter information about different objects described in a text and form mental representations about the shape of these objects. For example, when reading the sentence "There was a tomato on the pizza," readers are likely to form a mental image of a tomato that is consistent with the information presented in the sentence (i.e., a sliced tomato rather than a whole tomato) (Zwaan, Stanfield, & Yaxley, 2002). Thus, mental representation is crucial to the successful comprehension of a text (van den Broek, 2010; Verhoeven & Perfetti, 2008). However, it is currently unclear how the left and right cerebral hemispheres produce and maintain these mental representations during text comprehension. In addition, little is known about how the cerebral hemispheres process text when the shape of an object mentioned in a sentence is implicitly described (e.g., "There was a tomato on the pizza") compared to when the shape of an object is explicitly described (e.g., "A slice of tomato topped the salad"; Lincoln, Long, & Baynes, 2007). Therefore, the current study investigates how the left and right cerebral hemispheres process information about the shape of an object that is both explicitly and implicitly described in a text. In addition, this study examines how the cerebral hemispheres process images of objects that are consistent or inconsistent with the shape of an object described in the text.

Theoretical accounts of how readers form mental representations during text comprehension can provide support for the specific cognitive processes that occur as readers mentally represent the shapes of objects encountered during reading. For example, the Perceptual Symbols Theory (Barsalou, 1999; 2012) can help account for how readers likely form mental representations of objects mentioned in a text. This theory states that readers mentally represent objects by activating their sensory systems, and that these same systems are active when readers both perceive an object and when they remember or mentally represent that object. This theory is consistent with a variety of research findings showing that when readers encounter descriptions of objects in a text, they mentally represent those objects based on

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previous experiences with similar objects and shapes (e.g., Madden & Zwaan, 2006; Pecher, Zeelenberg, & Barsalou, 2004; Richardson, Spivey, Barsalou, & McRae, 2003; Spivey, Tyler, Richardson, & Young, 2000). For example, a reader who encounters the text “there was a lemon in the drink” would likely generate a mental representation of a slice of lemon based on that reader's previous experience that sliced lemons are more commonly found in drinks than whole lemons. Therefore, the Perceptual Symbols Theory predicts that readers will utilize their prior knowledge about the shape of an object that usually occurs in a familiar context when they mentally represent the shapes of those objects during text comprehension.

Although previous research has shown that readers form mental representations of the shape of objects encountered during reading, less is known about how the cerebral hemispheres generate and maintain these mental representations during text comprehension. For example, participants in one series of studies viewed objects followed by similar or slightly altered versions of those objects (e.g., an image of a grand piano followed by an image of a smaller upright piano) in either the left visual field- right hemisphere or the right visual field- left hemisphere (Marsolek 1995; 1999). Response times showed that the right hemisphere was more sensitive than the left hemisphere at detecting differences between the objects in these images. In addition, other researchers have demonstrated that the right fusiform cortex shows decreased levels of activation when participants are presented with visual images they have seen previously compared to novel images (Koutstaal et al. 2001). This finding has been interpreted as an evidence that the right fusiform cortex processes visual information about the shape of objects depicted in images (Lincoln, Long, & Baynes, 2007). Further, participants are more likely to confirm that two objects have similar shapes (e.g., ladders and railroad tracks) when visual stimuli are presented to the right hemisphere than when visual stimuli are presented to the left hemisphere (Zwaan & Yaxley 2004). In sum, previous research suggests that the right hemisphere may have an advantage compared to the left hemisphere when readers encounter information that requires discrimination between the shapes of different objects.

Although the right hemisphere likely has a processing advantage when readers perform tasks that require shape discrimination, the left hemisphere may have an advantage when readers form mental representations of objects they read about during text comprehension. A recent account of word retrieval posits that the left hemisphere has a processing advantage when individuals retrieve and maintain information about categories of objects (such as tools or furniture) and the shapes that those objects normally take (Damasio, Tranel, Grabowski, Adolphs, & Damasio 2004). This account details the sequence in which the cerebral hemispheres likely process information related to the shape of the object. Specifically, these researchers propose that viewing an object and then naming it initially activates the visual cortices in both hemispheres. Information about the object's shape is then processed in the inferior temporal left cortex. Finally, information about the object and its shape are processed in the language areas of the left hemisphere if the participant is required to name the object. Perhaps more important for the current study, Damasio et al. (2004) suggest that this processing sequence takes place in the reverse order when readers form mental representations of objects during reading. Specifically, readers who encounter these objects in a text first activate the left hemisphere language areas, which in turn activate the inferior left temporal cortex, which then leads to processing of sensorimotor information about the object's shape (Damasio et al., 2004). This processing model is consistent with research showing that patients who have disconnected hemispheres perform better at letter-sorting tasks (which require mental imagery) when stimuli are presented to the left hemisphere than when stimuli are presented to the right hemisphere (Farah, Gazzaniga, Holtzman, & Kosslyn 1984). Taken together, these findings suggest that the left hemisphere may have an advantage when readers form mental representations of the shapes of objects during reading.

Although the left hemisphere may be active when readers form mental representations of an object's shape during reading, it is possible that the cerebral hemispheres process mental representations of objects described in a text differently depending on whether the shape of an object is either explicitly described in the text or if the shape of an object must be inferred from the text. For example, much of the previous behavioral research on the mental representation of objects mentioned in a text has focused on texts in which the object's shape is implied rather than texts that explicitly describe the object's shape. For example, in the sentence “There was a lemon in the tree,” a reader needs to infer that the sentence refers to a whole lemon rather than a sliced lemon because this information is implied in the text (Zwaan et al., 2002). However, recent findings suggest that the right hemisphere is particularly sensitive to the shapes of objects when the text explicitly describes those shapes (e.g., “There was a whole lemon in the tree”; Lincoln et al., 2007). In contrast, response time results indicate that the left hemisphere is sensitive to the shape of an object during reading, regardless of whether the object's shape is implicitly or explicitly described in the text. These findings suggest that the left hemisphere may have an advantage when readers construct mental representations of an object's shape when the shape must be inferred during reading; however, both the left and the right hemispheres may process mental representations of an object when the shape of an object is explicitly described in a text.

Previous researchers have explored the hemispheric involvement in the mental representation of objects during reading, but it is not yet clear what processes in the hemispheres contribute to these specific mental representations. For example, it is possible that when readers encounter an object described in a text, this information leads to the generation of mental representations that are consistent with (or match) the object's shape described in the text. Conversely, it is possible that when readers encounter an object in a text, this leads to the inhibition of mental representations of the object that are inconsistent with (or do not match) the object's shape in the text. Finally, it is possible that some combination of these activation and inhibition processes underlie the creation of these mental representations of objects during reading. Previous research has yet to demonstrate if these mental representations are driven by the facilitation of mental representations that match the object's description in a text, by inhibition of mental representations that do not match the object's description in a text, or if this process occurs due to a combination of these processes during reading.

Much of the previous research on the creation of mental representations during reading has focused on presenting participants with a description of an object in a text, followed by an image of an object in which the shape either matches or mismatches the description in the text (Lincoln et al., 2007; Zwaan et al., 2002). These previous studies demonstrate that images that match the shape of an object described in a text are recognized more quickly than images that do not match the shape of an object described in a text. Although this evidence suggests that readers do mentally represent the shapes of objects during reading, researchers have yet to investigate the specific mechanisms underlying this mental representation. However, if a neutral condition, in which the shape of an object is not specified in the text, were included in these experiments it could serve as a useful baseline condition against which researchers could directly compare response times in the match and mismatch conditions.

Specifically, a neutral condition would include the same object as in the match and mismatch condition, but this condition would not describe the exact shape of an object (e.g., “The tomato was in the recipe.”). Thus, the inclusion of a neutral condition would allow researchers to investigate both how readers process mental representations of objects for textual information that is activated during text comprehension (i.e., facilitation) and information that is suppressed (i.e., inhibition) during text comprehension. Specifically, faster response times in the match condition than in the neutral condition would be evidence for hemispheric facilitation, whereas slower response times in the mismatch condition than in the neutral condition would be an evidence for hemispheric inhibition of information during reading.

Although little research has been conducted on the activation and inhibition mechanisms underlying the mental representation of objects during reading, one previous study provides some evidence for how readers likely process mismatches between an object's shape described in a text and the object's shape in a specific image. In this study (Zwaan et al., 2002, Experiment 2) participants read a text in which the shape of an object described in a text matched the shape of an object in an image (i.e., the match condition), a text in which the shape of the object described in a text did not match the shape of the object in the image (i.e., the mismatch condition), and a text that did not describe the object's shape and thus did not match or mismatch the shape of the object in the image (i.e., the neutral condition). These researchers predicted that faster response times in the match condition compared to the neutral condition would be evidence for facilitation of perceptual matches during reading. Further, slower response times in the mismatch condition than in the neutral condition would be evidence for inhibition of perceptual mismatches during reading. This study did not find significant response time differences between conditions, but importantly, the magnitude of the response time differences between the mismatch and neutral conditions was greater than the magnitude of the response time differences between the match and neutral conditions. Therefore, these previous results suggest that perceptual mismatches may be inhibited when readers form mental representations about the shape of an object during reading.

If the mental representation of objects encountered during reading involves the inhibition of specific information that contradicts the shape of an object described in a text, then this inhibition would be consistent with predictions of current theories of sensory information processing. In particular, the Indexical Hypothesis (Glenberg, 1997; Glenberg & Robertson, 2000) suggests that individuals tend to inhibit information from their external environment when that information conflicts with processes in working memory. For example, when individuals read “There was a slice of tomato on the pizza,” and form a mental representation of a slice of tomato, the Indexical Hypothesis predicts that these individuals would likely experience difficulty processing information that conflicts with this mental image in working memory (e.g., if readers encountered an image of a whole tomato instead of a slice of tomato). Thus, gaining more knowledge about the facilitative and inhibitory processes involved during the presentation of objects mentioned in a text will contribute to theoretical frameworks involved with mental representations and perceptual processing during text comprehension.

In the current set of experiments, we investigate how the cerebral hemispheres process information related to objects mentioned in a text, and further we investigate how these processes facilitate or inhibit information about the shape of an object as described in a text. Specifically, participants read sentences that describe the shape of an object (i.e., the match condition), sentences that do not describe the shape of an object (i.e., the mismatch condition), and sentences that contain no information about the object's shape (i.e., the neutral condition). After reading each sentence, participants viewed an image of an object presented quickly to either the right visual field-left hemisphere (rvf-LH) or the left visual field-right hemisphere (lvf-RH), and then indicated by a button press if the image was previously mentioned in the sentence. By calculating response time differences between the match condition and the neutral condition, and between the mismatch condition and the neutral condition, we can directly compare the left and right hemisphere's sensitivity to processing information related to the shape of an object described in a text. Specifically, if the information about the shape of an object described in a text is driven by the activation of information, response times will be faster for the match condition than for the neutral and mismatch conditions. In addition, if the information related to the shape of an object described in a text is driven by the inhibition of information, then response times will be slower for the mismatch condition than for the neutral and match conditions.

We also explored a secondary question regarding evidence for a strong version of the Perceptual Symbols Theory, which would postulate that readers generate detailed visual information from a text. Specifically, if we observe faster response times in the match condition than in the neutral condition, and slower response times in the mismatch condition than in the neutral condition, these simultaneous differences could provide evidence for a strong version of the Perceptual Symbols Theory, which claims that visual simulations are generated when individuals read and, that readers do not need recourse to amodal non-sensory computational processing when generating these representations (e.g., Bergen, 2012). However, if we observe facilitation of matches only, or inhibition of mismatches only, these results would support a less strong version of the Perceptual Symbols Theory, and would suggest that amodal, non-sensory computation may play a role in forming these representations, as amodal computations would not necessarily lead to sensory facilitation or inhibition during reading.

2. Experiment 1

The goal of Section 2 is to investigate how the left and right hemispheres process information related to the shape of an object mentioned in a text when the text implicitly describes the shape of an object.

2.1. Method

2.1.1. Participants

One hundred thirty one undergraduate students (96 females, 35 males) at an urban university in the Midwest participated in this experiment in exchange for course credit. All participants had normal or corrected-to-normal vision, were native speakers of English, and had no history of neurological damage or disorder. All participants were right handed (mean laterality quotient: 0.77), and ranged between 0.30 and 1.00 on the Edinburgh Handedness Inventory (Oldfield, 1971).

2.1.2. Materials

Forty eight images served as the experimental stimuli for this study. Consistent with previous research (Lincoln et al., 2007; Zwaan et al., 2002), we selected images that featured inanimate objects, food, or animals. These images were presented in color, and care was taken to ensure that the colors of the objects in the images were typical for that type of object. Images ranged in size from 250×250 pixels to 325×325 pixels. For each of the 48 experimental images, a *match* sentence, a *mismatch* sentence, and a *neutral* sentence were constructed. In the match sentences, the shape of the object implied by the sentence matched the shape of the object in the image. In the mismatch sentences, the shape of the object implied by the sentence was different from the shape of the object in the image. In the neutral sentences, no shape of an object was implied or described by the text. Because no shape is mentioned in the neutral sentences, readers should be expected to generate perceptual matches or mismatches roughly half of the time (Zwaan et al., 2002). See Fig. 1 for an example image with a corresponding match, mismatch, and neutral sentence.

To ensure that the sentences are aligned with their intended condition (i.e., the match, mismatch, or neutral condition), a pilot study was conducted. In this pilot study, 48 participants (who did not participate in the main experiment) rated how closely the shape of the objects mentioned in each sentence matched the shape of the objects in the images on a scale of 1 (not a very close match at all) to 7 (an extremely close match). Similarity judgments were significantly higher for the match condition (M=4.63, SE =.16) than for the neutral condition, (M=3.64, SE =.19), $t(47)$= 4.36, $p<.001$. Similarity judgments were higher for the match condition than for the mismatch condition (M=2.45, SE =.09), $t(47)$=11.03, $p<.001$. Similarity judgments were also higher for the neutral condition than for the mismatch condition $t(47)$=5.23, $p<.001$. These results indicate that individuals were able to discriminate between the object shapes in the match, mismatch, and neutral conditions.

In addition, 48 images and sentences were included in the materials as filler. The sentences in these fillers mentioned an object that was unrelated to the object in the image. A sentence was constructed for each of the 48 filler images. When filler images were presented, participants needed to make a "no" response. These fillers help ensure that readers did not develop a bias to respond "yes" to all stimuli.

2.1.3. Procedure

The experiment was run on a PC using E-Prime software (Schneider, Eschman, & Zuccolotto, 2002). Participants were seated 50 cm from a computer screen, and rested their head in a chin rest to maintain this distance throughout the experiment. This chin rest prevented the participants from moving their heads during the procedure, ensuring that the position and angle at which participants viewed the computer remained consistent throughout the experiment.

Participants were instructed to read each sentence for comprehension, and to press a button on a response box once they had finished reading the sentence. Each sentence was presented horizontally, in its entirety, and in the center of the screen. After reading the sentence, participants were then presented with a plus sign in the middle of the screen, which served as the central fixation point. This plus sign remained on the screen for 750 ms. Participants were instructed to focus both their eyes on this fixation point the entire time it was on the screen. Immediately after the plus sign disappeared, participants were presented with an image presented to either the left or right visual field for 176 ms. This short presentation was necessary so that participants did not have enough time to move their eyes away from the central fixation point and towards the image, thus ensuring that each image was initially presented to either the left or right visual field. These images appeared at a visual angle of 2.51° the left or right of the central fixation point. The center of each image was 5.5 cm from the central fixation point on average, and the inside edge of each image was at least 2.2 cm from the central fixation point's outer edge.

Participants were instructed to decide whether the presented image had appeared in the previous sentence. For the sentence-image match, sentence-image mismatch, and neutral conditions, the correct answer was "yes," and for the filler condition, the correct answer was "no." Participants were instructed to make their decision by pressing the buttons marked "yes" or "no" on the response box. These specific instructions were given in the current study to remain consistent with several previous studies that also investigate mental representation during reading (Holt & Beilock, 2006; Kaup & Zwaan, 2003; Lincoln et al., 2007; Yaxley & Zwaan, 2007; Zwaan et al., 2002). Half of the participants used their left hand to respond, and the other half used their right hand. The "yes" and "no" buttons were arranged perpendicular to the computer screen. This was done to prevent participants from developing a horizontal response bias (Bourne, 2006). In total, each participant read 16 matching sentences, 16 mismatching sentences, 16 neutral sentences, and 48 filler sentences. Each participant viewed only one version of the sentence per item. Prior to participating in the main experiment, participants underwent a practice session in which they had to score 80% correct or better to continue on to the main experiment. During both the practice session and the main experiment, participants received feedback after each trial as to whether or not their decision was correct. Items were presented in a random order to minimize the effects of presentation order.

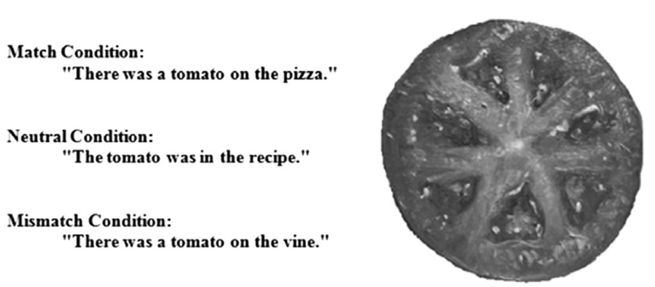

Fig. 1. Example image and corresponding match, neutral, and mismatch condition sentences from Experiment 1.

2.2. Results

Means and standard errors for response time and accuracy can be found in Table 1. Analyses were conducted for both participants (F_1) and items (F_2). The top and bottom 1% of the response times were removed prior to analyses to minimize the influence of outliers (see Ratcliff, 1993 for a description of this procedure). The between-subjects variables of gender and hand used to respond did not produce significant differences, so we collapsed across those categories in these analyses.

2.2.1. Response time

To explore the effect of matching condition and visual field presentation on response time, we conducted 3 (matching condition: match, mismatch, neutral) by 2 (visual field-hemisphere: rvf-LH, lvf-RH) repeated measures ANOVA. No significant main effects

Table 1
Mean response time (in ms) and accuracy (in proportion correct) for target words in the match, neutral, and mismatch conditions by visual field-hemisphere for Experiment 1.

Condition	rvf-LH		lvf-RH	
	RT	AC	RT	AC
Match	668.25 (14.14)	0.94 (0.08)	671.83 (15.43)	0.94 (0.08)
Neutral	669.97 (14.54)	0.93 (0.10)	672.52 (15.74)	0.94 (0.08)
Mismatch	697.19 (15.58)	0.93 (0.10)	680.09 (14.47)	0.93 (0.08)

Note. Right visual field-left hemisphere is abbreviated: rvf-LH and left visual field-right hemisphere is abbreviated: lvf-RH. RT refers to response times and AC refers to Accuracy. Values in parentheses represent standard errors.

were observed for matching condition $F_1(2, 130)=2.90$, $MSe=7069.92$, $p=.06$; $F_2(2, 94)=2.54$, $MSe=5578.56$, $p=.08$. No significant main effect was observed for visual field presentation (F_1 and $F_2<1$). Importantly, however, there was a significant interaction between visual field presentation and match condition by subjects, $F_1(2, 130)=3.53$, $MSe=6350.11$, $p=.03$; $F_2(1, 94)=1.72$, $MSe=5739.21$, $p=.18$.

To investigate this interaction, we conducted a set of planned follow-up comparisons with a significance level set to .025 to correct for multiple comparisons. Within rvf-LH, response times were longer for the mismatch condition than for the match condition, $t_1(130)=2.99$, $p<.001$, $t_2(47)=2.72$, $p=.009$; and the neutral condition, $t_1(130)=2.38$, $p=.02$, $t_2(47)=1.27$, $p=.21$. Further, there was a trend for response times in the mismatch condition to be longer in the left hemisphere than in the right hemisphere, $t_1(130)=2.23$, $p=.03$; $t_2(47)=1.61$, $p=.11$. All other comparisons were nonsignificant ($t<2$ in all cases).

2.2.2. Accuracy

A 3 (matching condition: match, mismatch, neutral) by 2 (visual field-hemisphere: rvf-LH, lvf-RH) repeated measures ANOVA was conducted on the response accuracy rates. No significant main effects or interactions were detected. Therefore we did not find evidence that the response time effects were due to tradeoffs between speed and accuracy.

2.3. Discussion

In Section 2, we investigated how the cerebral hemispheres processed mental representations of objects described in a text when the shape of the object was implicitly described. Response time differences between the match, mismatch, and neutral conditions were observed only in the rvf-LH. Specifically, the left hemisphere showed significantly longer response times for the mismatch condition than for both the match condition and the neutral condition. Further, the response times in the mismatch condition tended to be longer when presented to the rvf-LH than to the lvf-RH. These findings are consistent with previous research showing that response times are slower for mismatches than matches in the left hemisphere (but not in the right hemisphere) when the text implies the shape of an object (Lincoln et al., 2007). Our findings also suggest a specific mechanism for the left hemisphere's sensitivity to shape: inhibition of irrelevant mental representations or irrelevant external stimuli, as also predicted by theories of perceptual processing (Barsalou, 1999; Glenberg, 1997).

Interestingly, response times for the match condition did not differ from response times of the neutral condition in either hemisphere. We therefore did not find response time evidence that mental representation is driven by facilitation of mental representations similar to those described in a text. This lack of a match effect is somewhat surprising, as the implications of the Perceptual Symbols Theory (Barsalou, 1999) would suggest that the compatibility between the shape of the object described in the text and the shape of the object depicted in the image should facilitate processing time. It is difficult to draw conclusions from lack of effects. However, previous researchers (e.g., Zwaan et al., 2002) have not yet specified whether mental representation during reading occurs due to the facilitation of text-image matches or the inhibition of text-image mismatches. Although the results of Experiment 1 do not contradict previous findings (e.g., Zwaan et al., 2002), they fail to support the possibility that faster response times between matches and mismatches typically found in these studies (Lincoln et al. 2007; Zwaan et al., 2002) are influenced by congruity between a reader's mental representation of the object's shape and its depiction in these images.

One possible reason that we did not find facilitation effects in the matching condition for this study is that readers may experience difficulty generating a mental representation of an object during reading when the object's shape must be inferred from the text. Here, by “difficult,” we mean that participants may experience a delay in detecting a perceptual match between the reader's mental representation of the object described in the text and the actual depiction of that object in the presented image in the current study. For example, a reader may generate an accurate mental representation of the text description in the sense that it does not contradict the information presented in the text. However, there may be subtle differences between how participants envision the object and how the image is actually presented in the current study, especially when the shape of the object must be inferred from the text. Thus, when objects' shapes are only implicitly described in the text, the contrast between the shape in the text and the shape in the image may require less time to detect than the overlap between one's mental representation of an object and a similarly shaped object in the image. If a lack of difference in response times between the match and neutral conditions is due to readers needing to infer the shape of the object during reading in Experiment 1, response times may be faster for sentence-image matches if the object in the sentence is explicitly described. Thus, Section 3 focuses on the cerebral hemispheric processing of shapes of objects that are explicitly described in a text.

3. Experiment 2

The goal of Section 3 is to investigate how the left and right cerebral hemispheres process information related to the shape of an object mentioned in a text when the text explicitly describes the shape of an object. To increase the power of our by-item analyses and to ensure that participants did not view the same object both in the implicit condition and the explicit condition, we chose to test explicit descriptions in a separate experiment rather than compare implicit versus explicit descriptions in one experiment.

3.1. Method

3.1.1. Participants

Ninety one undergraduate students (72 female, 19 male) participated in this study in exchange for course credit at an urban Midwestern university. All participants had normal or corrected-to-normal vision, were native speakers of English, and had no history of neurological damage or disorder. All participants were right handed (mean laterality quotient: .82), and ranged between .4 and 1.00 on the Edinburgh Handedness Inventory.

3.1.2. Materials

Forty eight images served as the experimental stimuli for Section 3. For each of the 48 experimental images, a *match* sentence, a *mismatch* sentence, and a *neutral* sentence were constructed. In the match condition, the text explicitly described the same shape of the object in the image. In the mismatch condition, the text explicitly described a different shape of the object in the image. In the neutral sentence, the text did not describe the shape of the object in the image. To ensure that the sentences aligned with their intended condition (i.e., the match, mismatch, or neutral condition), a separate pilot study was conducted. In this study, 48 participants (who did not participate in the main experiment) rated how closely the shape of the objects mentioned in each sentence matched the shape of the objects in the images, on a scale of 1 (not a very close match at all) to 7 (an extremely close match). Similarity judgments were significantly higher for the match condition (M=5.51, SE =.11) than in the neutral condition (M=3.29, SE =.09), $t(47)=15.41$, $p<.001$. Similarity judgments were also higher for the match condition than for the mismatch condition (M=1.48, SE =.05), $t(47)=30.61$, $p<.001$. Similarity judgments were also higher for the neutral condition than for the mismatch condition $t(47)=17.74$, $p<.001$. See Fig. 2 for an example image and the match, mismatch, and neutral sentences. These results indicate that individuals were able to discriminate between the object shapes in the match, mismatch, and neutral conditions in this study.

The same 48 filler texts and images from Experiment 1 were also used in Experiment 2.

3.1.3. Procedure

The procedure for Experiment 2 was identical to that of Experiment 1 (Section 2.1.3).

3.2. Results

Means and standard errors for response time and accuracy are shown in Table 2. Analyses were conducted for both participants (F_1) and items (F_2). The top and bottom 1% of the response times were removed prior to analyses to minimize the influence of outliers (see Ratcliff, 1993 for a description of this procedure). The between-subjects variables of gender and hand used to respond did not produce significant differences, so we collapsed across these categories in these analyses.

3.2.1. Response times

To explore the effect of the match condition and visual field presentation on response time, we conducted 3 (matching condition: match, mismatch, neutral) by 2 (visual field-hemisphere: rvf-LH, lvf-RH) repeated measures ANOVA.

The main effect of the matching condition was significant by subjects and by items, $F_1(2, 180)=59.70$, $MSe=10{,}570.22$, $p<.001$; $F_2(2, 94)=57.85$, $MSe=6845.16$, $p<.001$. There was no significant main effect of visual field-hemisphere, and there was no significant interaction between matching condition and visual field-hemisphere.

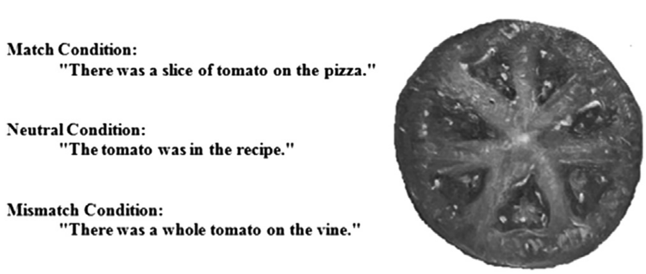

Fig. 2. Example image and corresponding match, neutral, and mismatch condition sentences from Experiment 2.

Table 2
Mean response time (in ms) and accuracy (in proportion correct) for target words in the match, neutral, and mismatch conditions by visual field-hemisphere for Experiment 2.

Condition	rvf-LH		lvf-RH	
	RT	AC	RT	AC
Match	666.15 (18.88)	0.96 (0.01)	666.88 (20.92)	0.98 (0.01)
Neutral	682.50 (18.90)	0.94 (0.01)	670.02 (20.92)	0.95 (0.01)
Mismatch	767.98 (24.59)	0.89 (0.01)	778.07 (24.59)	0.87 (0.02)

Note. Right visual field-left hemisphere is abbreviated: rvf-LH and left visual field-right hemisphere is abbreviated: lvf-RH. RT refers to response times and AC refers to Accuracy. Values in parentheses represent standard errors.

3.2.2. Accuracy

A 3 (matching condition: match, mismatch, neutral) by 2 (visual field-hemisphere: rvf-LH, lvf-RH) repeated measures ANOVA was conducted on the responses' accuracy rates. There was a significant main effect of matching condition by subjects and by items, $F_1(2, 89)=35.74$, MSe =.01, $p<.001$; $F_2(2, 94)=22.34$, MSe =.01, $p<.001$. Within both hemispheres, accuracy was higher in the match condition than in the neutral condition ($p<.001$) or the mismatch condition ($p>.001$), and accuracy was higher in the neutral condition than in the mismatch condition, ($p>.001$). There was no significant main effect of visual field-hemisphere and no significant interaction between matching condition and visual field-hemisphere.

Because we observed accuracy differences but not response time differences between the match and neutral conditions in both hemispheres, we explored whether these accuracy differences were due to an increase in participants' accuracy occurring as their response times decreased (i.e., a speed-accuracy tradeoff). Pearson correlations of the response times and accuracy scores were all nonsignificant ($r<.10$ in all comparisons), suggesting that these accuracy differences were not driven by a speed-accuracy tradeoff (Boer & Keuss, 1982; Mazard et al. 2002).

3.3. Discussion

In Section 3, we investigated how the hemispheres processed mental representations of objects mentioned during reading when the shape of the object was explicitly described in the text. Our results indicate different patterns of hemispheric activation from Section 2, in which the text implicitly described the shape of an object. Specifically, in Section 3 the mismatch condition showed longer response times than the neutral condition and the match condition in both visual field-hemispheres. However, no response time differences were observed between the match and neutral conditions in either visual field-hemisphere. These results replicate Lincoln et al.'s (2007) finding that both hemispheres are sensitive to the shape of an object described in a text when the shapes of those objects are explicitly described in the text. Furthermore, our response time findings suggest that readers inhibit mental representations of shapes that are inconsistent with the shape of the object mentioned in the text.

As with Section 2, the lack of response time differences between the match and neutral conditions fails to support a strong version of the Perceptual Symbols Theory (Barsalou, 1999). A strong version of this theory would predict differences between the match and neutral conditions as well as between the neutral and mismatch conditions. Although this lack of a matching effect does not itself constitute evidence against the Perceptual Symbols Theory, it is interesting to note that the lack of a matching effect is evident even when the objects' shapes are explicitly described, which was thought to have created a more detailed mental image for the reader to draw upon when making decisions about the images.

Interestingly, accuracy was greater in the match condition than in both the neutral and the mismatch conditions in both hemispheres, whereas accuracy was lower in the mismatch condition than in both the neutral and match conditions for the lvf-RH. These findings suggest that mental representation of objects encountered during reading may involve both facilitative and inhibitory processes. It is curious however, that we observed greater accuracy in the match condition than in the neutral condition, but we did not observe response time differences between these two conditions. One would expect to find similar patterns in the accuracy and response time data, as both of these variables should likely tap into similar cognitive processes. However, the lack of a correlation between the response times and accuracy rates points to a mechanism other than a speed-accuracy tradeoff to account for the accuracy rate differences in this experiment.

4. General discussion

The current set of studies contributes to our knowledge of how the right and left hemispheres generate and maintain mental representations of the shapes of objects encountered during sentence comprehension. The results of these two experiments replicate previous findings that the left hemisphere is sensitive to the shapes of objects encountered during reading when the shape is either implicitly or explicitly described in the text. However, the right hemisphere appears to be particularly sensitive to the information about an object's shape during reading when the shape of an object is explicitly described in the text (Lincoln et al. 2007). Our results are also consistent with previous findings that the left hemisphere has an advantage compared to the right hemisphere when readers mentally represent objects mentioned in the text (Damasio et al., 2004; Zwaan & Yaxley, 2003). In sum, these findings suggest that although many types of mental representations may be processed through right hemisphere mechanisms (e.g. Zwaan & Yaxley, 2003), information about an object's shape derived from text comprehension can involve the left hemisphere as well.

Our results suggest that the processing of shape information during reading is influenced by the implicit or explicit nature of the description of the object in a text. When an object's shape must be inferred in the text, readers may utilize conceptual information available to the left hemisphere to make inferences about the object's shape. Such an account is supported by Damasio et al. (2004) suggestion that the processing network for visualizing objects mentioned during text comprehension begins, and is largely focused, in the left hemisphere. Conversely, the right hemisphere exhibited sensitivity to object shape information only when the text explicitly described the shape of the object. This suggests an interesting possibility that the right hemisphere may be more sensitive to an object's shape when the object's visual characteristics are more immediately available in the text.

Our findings contribute to the current understanding of how the cerebral hemispheres process mental representations of the shapes of objects encountered during reading by directly comparing conditions in which the shape of the object in the text either matched or mismatched the shape of the object in the images in a neutral condition (which contains no object shape information in the text). Previously, it was unclear whether the "sensitivity to spatial information" described by Lincoln et al. (2007) was due to the facilitation of mental representations that match the shape of the object described in the text, or due to the inhibition of mental representations that did not match the shape of the object described in the text. Our results suggest that sensitivity to information that does not match the shape of an object described in a text is a key factor in how the hemispheres carry out this process. These findings are also consistent with the pattern of results from a previous behavioral study showing that the magnitude of differences in response times between the mismatch and neutral conditions was greater than the magnitude of differences in response times between the match and the neutral conditions (Zwaan et al., 2002). The inhibitory effects observed in this study contribute to the existing body of research describing how readers visualize information during text comprehension. According to several theories about how mental representations are processed and maintained, inhibition of irrelevant sensory information is thought to be crucial for successful mental representation (Barsalou, 1999; Glenberg, 1997). In the current set of studies, the response times in the mismatch condition were significantly slower than response times in the neutral condition of the rvf-LH (in Sections 2 and 3) and in the lvf-RH (in Section 3). However, participants did not respond to images in the match condition faster than the neutral condition in either hemisphere or experiment. Our findings therefore lend further support for the idea that the hemispheres may be sensitive to mismatches between an object's description in a text and its depiction in an image, especially when the text explicitly describes the object's shape.

One potential explanation for the current set of findings is that the conceptual processing of shape-related information during text comprehension may be influenced, but not entirely dependent, on sensorimotor processes. For example, the *Grounded Interaction* hypothesis (Mahon & Caramazza, 2008) states that sensory information in a text influences conceptual processing, but that conceptual processing is not necessarily dependent on sensorimotor systems for readers to form mental representations during text comprehension. Such an account is consistent with the current findings, as sensory information that conflicts with conceptual information (i.e., the mismatch condition) may have a larger effect on processing time than sensory information that is compatible with the readers' mental representations (i.e., the match condition). Specifically, consistency between the text and images in the matching condition may not have provided any additional information upon which readers build their conceptual representations, but the conflicting sensory information in the mismatch condition may have caused a conflict leading to increased response times.

The Grounded Interaction hypothesis could explain why stronger mismatch effects were observed in Section 3 (i.e., where the shape of the object was explicitly given in a text) than in Section 2 (where the shape of the objects was implicitly described in a text). Interestingly, there has been debate as to whether readers routinely generate shape information during reading (Rommers, Meyer, & Heuttig, 2013; Zwaan, 2014). The current set of results suggest that the frequency or strength with which readers generate shape information during reading, may in part depend on whether the shape of the object is explicitly described in the text. In other words, explicit descriptions may serve as stronger retrieval cues for sensorimotor information during reading than implicit descriptions, leading to stronger sensorimotor activation during text comprehension.

Although the Grounded Interaction hypothesis is consistent with the current set of results, there is another potential explanation for these findings which relates to variations in how individuals generate mental representations from a text. Consider that when the shape of an object is explicitly described in a text in Section 3, accuracy differences were evident between the match and neutral conditions, but were not evident in response time differences. It is possible that these accuracy scores may reflect the fact that readers generated mental representations of the objects during reading that contained some overlap with the shape of the objects in the images in the match condition (importantly, we found no evidence that these accuracy scores indicated a speed-accuracy tradeoff). However, there may have been slight differences between the reader's mental representation of the shape and the shape as presented in the matching image. This is possible because textual descriptions of objects frequently contain less specific information about an object's shape than visual depictions (Schnotz, 2005). Thus, readers may recognize the overlap between their mental representation generated during reading and the shape of the object depicted in the image, leading to increased accuracy for the match condition, but not necessarily decreased response time for the matched condition, as the reader likely needs additional time to revise their mental representation to conform to the specific image of the object presented in the study. This is not to suggest that accuracy and response times are measuring different cognitive processes, but rather that the interference between a reader's mental representation and a closely-matching (but perhaps not identical) depiction of that same object in a text may be more evident when measuring response time than when measuring accuracy in the current study. The reader may be able to accurately verify that the object in the image matches their mental representation, but that verification may require extra processing time, leading to more noise in the response time data than in the accuracy data. Such interference and revision might explain why we find match effects for accuracy but not response times in Section 3.

If readers need additional time to revise their mental representations to conform to the specific shape of the object depicted in the match condition's images, then this revision process could account for why responses were more accurate in the match condition than in the neutral condition only when the shapes were explicitly described in the text. Specifically, the explicit description of the object's shape in the text could create more overlap between a reader's mental representation and the matching image, whereas participants who had to infer the object's shape in Section 2 may have generated a mental representation of an image that required more revision upon viewing the image in the study. This revision process could also account for why accuracy difference between matches and mismatches was greater when the shape of objects were explicitly rather than implicitly described in previous research studies (Lincoln et al., 2007). Thus, further research is needed to investigate this revision hypothesis and will help determine whether this hypothesis accurately accounts for the patterns we observed in accuracy and response time.

Future research could test this revision hypothesis by varying the level of specificity in the description of an object's shape in a text. For example, descriptions of the objects in a text could be varied by mentioning either the shape, color, or both, following recent evidence that descriptions of shape and color multiplicatively contribute to the mental representation of objects (Richter & Zwaan, 2010). If images are recognized more quickly and accurately when preceded by a sentence with greater specificity compared to a sentence with less specificity, this finding would support the hypothesis that readers may need to revise their mental representations of the shape of objects derived from a text to resolve any discrepancies between their mental representation of the object and any accompanying images of the object.

Another direction for future research focuses on how participants interpret the specific instructions in this experiment. In the current set of experiments, and others that examine mental representations during reading (Holt & Beilock, 2006; Lincoln et al., 2007; Zwaan et al., 2002), participants are instructed to indicate whether the object in the image was mentioned in the previous sentence. Although these instructions are widely used in research investigating mental representations, it is not entirely clear how participants interpret these instructions. For example, it is possible that the delays observed in the mismatch condition arise because the shape of the object conflicts with the reader's mental representation, but it is also possible that participants may be slower to respond to mismatches because they are expecting to see an image that matches the exact context of the sentence rather than an image whose shape matches or mismatches. To mitigate the possibility of students generating a strategy of seeking out images that matched the sentence exactly rather than matching the shape of the object, in the current study we provided constant feedback about the accuracy of participants′ responses, thus discouraging them from adopting strategies that would lead to lower accuracy. However, it is possible that varying the type of instruction given, such as having the participants make decisions about the category of the object rather than the shape of the object, will likely impact how participants respond to perceptual stimuli. Thus, future research could be carried out to explore how varying the instructions impact how the hemispheres process perceptual matches and mismatches.

One limitation of the current design was that participants were not asked whether they were generating mental images as they completed this task. Future researchers may wish to include questions about mental imagery during their debriefing of participants, as this information might provide valuable insight into how participants approach experimental studies of mental representation during reading. For example, if participants report that they experienced a "mental image" when deciding whether or not the shape of the object in the image matched the shape of the object in the text, this may give researchers more confidence that the shape of the objects described in a text leads to visual processing of information. If on the other hand, participants do not report experiencing these mental images during reading, this may give researchers less confidence that readers are utilizing visual processing of mental images during text comprehension.

In summary, our results suggest that hemispheric processing of the shape of objects during reading is influenced by the level of explicitness with which the text describes the object's shape. Further, the left hemisphere appears to be particularly sensitive to mismatches between the shapes of objects as implicitly described in a text and as depicted in an image. However, both hemispheres seem to be sensitive to mismatches between an object's shape in a text and an object's shape in an image when the text explicitly describes the shape of an object. Thus, the results of these experiments suggests that the sensitivity to mismatches between a description of an object in a text and the depiction of that same object in an image seems to be an important factor in how the cerebral hemispheres contribute to the mental representation of the shapes of objects during text comprehension.

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