Proceedings of the Annual Meeting of the Cognitive Science Society

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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 32(32)

ISSN
1069-7977

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Publication Date
2010

Peer reviewed

Simulation from Schematics:
Dorsal Stream Processing and the Perception of Implied Motion

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Abstract

Schematic language (e.g., prepositions) and depictions (e.g., line drawings) reduce the rich detail of the visual world to a coarser level of description. We investigated how these schematic forms may be represented in the brain. Recent neural evidence suggests that such representations may be computed in the dorsal pathway of the visual system, the same pathway involved in processing motion, including simulated motion in static scenes. Drawing on this association, we examined the stimulus conditions and mental sets that give rise to simulation, and by hypothesis, representations in the dorsal stream. Simulated motion was evident for scenes that were highly schematic, as opposed to highly realistic (Experiment 1), and when realistic scenes were processed schematically (Experiment 2). The results suggest that dorsal stream representations capture the schematic aspects of visual experience, rather than more fine-grained information. In affording simulation, these representations may facilitate certain types of reasoning and inference.

Keywords: schematic representations; mental simulation; dorsal stream; implied motion; word meaning.

Introduction

In physics and engineering textbooks, simple line drawings are often used to illustrate complex physical phenomena. These drawings tend to be highly schematic, representing idealized examples of the processes in question. Schematic depictions of this sort may be useful not only because of their visual simplicity, but also because they have a fundamental cognitive basis. In particular, they may map onto mental representations that are themselves schematic in nature and that may afford certain perceptual and cognitive advantages over representations that more veridically capture the rich detail of the visual world. In this research, we investigate the nature of these hypothesized schematic representations and how they might be realized in the brain.

A distinction between representations that are more detailed or featural and those that are more schematic or configural has been proposed to underlie the meanings of words. Landau and Jackendoff (1993) argued that the representations associated with the meanings of object nouns, which encode detailed featural information, differ from those associated with the meanings of prepositions, which encode coarser configural properties. Moreover, they hypothesized that these different types of representations are computed in different processing pathways in the brain. A highly influential model originally proposed by Ungerleider and Mishkin (1982) points to two separate streams for the processing of visual information: a ventral stream, responsible for the identification of objects on the basis of visual properties such as shape, size, color, and texture (the "what" system), and a dorsal stream, responsible for the localization of objects in space (the "where" system). Landau and Jackendoff proposed that the meanings of object nouns are processed in the "what" system and the meanings of prepositions in the "where" system.

While several of Landau and Jackendoff's (1993) conjectures have been supported by subsequent neural research, recent work suggests that the dichotomy between object nouns and prepositions may not adequately capture processing differences in the two streams. Beyond localizing objects in space, the dorsal stream appears to be responsible for certain aspects of object perception. For example, several areas of the dorsal stream are activated during the passive viewing of objects. The caudal part of the intraparietal sulcus (CIP) shows sensitivity to the shapes of objects even when their location is unspecified (Grefkes & Fink, 2005). Similarly, activity in the V5/MT complex has been linked to differences in the shapes of objects in static images (Chandrasekaran et al., 2006). These findings suggest that the ventral stream is not the only pathway in which objects are processed; the dorsal stream is also sensitive to certain object properties, notably shape.

Nonetheless, the two streams appear to differ in the level of abstraction at which they process objects. Whereas the dorsal pathway is primarily concerned with identifying the principal axes, surfaces, and dimensionality of an object, the ventral pathway fills in featural details such as size, color, and texture (Farivar, 2009). Consistent with this characterization of the two streams, Lehky and Sereno (2006) observed that neurons in the dorsal area LIP were sensitive to shape but less able to differentiate shapes than neurons in the ventral area AIT (see also Chandrasekaran et al., 2006). These findings suggest that the ventral stream makes fine-level distinctions, while dorsal stream processing is at a coarser, more schematic level.

Intriguingly, the dorsal stream is also invoked in the perception of implied motion; that is, the kind of motion suggested by frozen-action photographs or speed lines in cartoons. In an imaging study, Kourtzi and Kanwisher (2000; see also Senior et al., 2000) observed activation in V5/MT in response to still photographs of agents or objects in motion (e.g., an athlete about to throw a discus). These findings suggest a way in which dorsal stream processing might be examined behaviorally. When people perceive implied motion from a static scene, it is highly likely that they are processing the scene in the dorsal stream. Hence, the perception of implied motion can be used as an index of dorsal stream processing, and by hypothesis, of the schematic representations that support such processing.

A necessary condition for taking advantage of this association is to find a way to measure the perception of implied motion. An experimental paradigm developed by Freyd, Pantzer, and Cheng (1988) offers such a measure. In Freyd et al.'s study, participants were presented with a line drawing of a scene depicting a potted plant supported by a pedestal. The scene was then replaced by one in which the pedestal was removed, but the plant was in exactly the same position as it had been previously. This second scene was then replaced with a third scene in which the plant's position was shifted slightly (higher or lower) or remained the same. The participants' task was to indicate whether the plant in the third display was in the same position as in the second. Freyd et al. reasoned that if people viewed the pedestal as exerting a force on the pot, they might (implicitly) expect the plant to move downward due to the influence of gravity. As predicted, participants were more likely to report "same" to a downward shift than an upward one. These results support the hypothesis that motion will sometimes be perceived when a force acting on an object is suddenly removed. This phenomenon of implied motion from disequilibrium is one of several types of *displacement*, in which the mental representation of a target's location is displaced in the direction of (implied) target motion (see Hubbard, 2005, for a review).

Predictions. Based on subsequent neural research, it is highly likely that the implied motion perceived by participants in Freyd et al.'s (1988) study involved processing in the dorsal stream (in particular, area V5/MT). If so, it should be possible to modulate displacement by varying the properties of the visual stimulus. Lobmaier et al. (2008) employed this technique in an fMRI study of face processing, observing greater dorsal (V5/MT) activation to blurred faces (which preserved configural information) than to scrambled faces (which disrupted configural information but preserved detailed featural information) and greater ventral activation to scrambled than to blurred faces. Thus, changing the properties of the visual stimulus changed which pathway was primarily used to process the stimulus.

The findings of Lobmaier et al. (2008) suggest that the perception of implied motion in static scenes will be more pronounced when stimuli are highly schematic, as opposed to highly realistic. Highly schematic stimuli are more likely to be processed in the dorsal stream than in the ventral stream; processing in the dorsal stream should produce larger effects of implied motion, and hence a stronger displacement effect. If this initial prediction is supported, we might find that displacement can be modulated in other ways as well. In particular, it might be possible to influence how a stimulus is processed by varying the observer's mental set. Because relational words like verbs and prepositions encode the world in a relatively schematic fashion, describing a scene by using a high proportion of such words (as opposed to words that encode featural information, such as adjectives) should engage the dorsal stream and result in greater displacement. Drawing a scene might also modulate one's mental set, with more schematic drawings leading to greater displacement. We tested these predictions in the following two experiments.

Experiment 1

In our first experiment, we investigated whether implied motion would be perceived in scenes that varied in realism. We contrasted realistic scenes that resembled photographs with schematic scenes that resembled line drawings, similar to those used by Freyd et al. (1988). Our prediction was that the schematic scenes would engage the dorsal stream more than the realistic scenes, and hence that there would be greater displacement for the schematic scenes than for the realistic ones. Following Freyd et al., we also varied whether the initial picture in the sequence showed a support relation (e.g., a pedestal supporting a plant vs. a plant floating in mid-air), in order to confirm that displacement was due to the perceived removal of a force rather than some perceptual bias to infer that unsupported objects will move downward. Thus, we predicted that displacement would be more likely when the initial picture depicted a support relation than when it did not.

Method

Participants. Fifty-nine Emory University undergraduates received course credit for participating in the experiment.

Materials. We created a set of materials based on the scenes shown in Figure 1. The scenes depicted a room either rich in photorealistic detail (Realistic format) or schematically sketched, as in a line drawing or diagram (Schematic format). The Schematic scene was a contoured rendering of the Realistic scene, with all fine detail removed so that only the basic outline of the objects was visible. All other aspects of the two display formats were identical. Each display was 27.3 cm x 15.7 cm (45.5° x 28.9° visual angle).

Figure 1: The Realistic (top) and Schematic (bottom) support displays used in Experiment 1.

There were four variants of each display format. In the original version shown in Figure 1, a potted plant (height: 2.3 cm / 4.3°) is supported by a marble pedestal at the center of the room (*support* display). In the other three versions, the pedestal was removed and the plant was either in exactly the same position (*no-support* display), slightly raised (*up* display), or slightly lowered (*down* display). In the latter two displays, the plant was 0.15 cm (0.3°) higher or lower, respectively, than its original position. All displays were created using a graphics package called Discreet 3D Studio Max, version 7.

Design and Procedure. Participants were randomly assigned to either the Realistic or Schematic display format and to either the Support or No Support trial type, in a fully crossed between-subjects design with four conditions: Realistic-Support, Realistic-No Support, Schematic-Support, and Schematic-No Support. Figure 2 depicts the trial structure. In the Support conditions, each trial began with the presentation of the support display, which remained on the screen for 250 ms. Following a 250-ms interstimulus interval (ISI), the no-support display appeared for 250 ms. Another 250-ms ISI was followed by one of three test displays: no-support (showing the plant in the same position as it had been previously), up, or down. The test display remained on the screen until participants made a response. The No Support conditions were identical, except that the first stimulus of each trial was the no-support display.

As in Freyd et al. (1988), participants were asked to indicate whether the plant in the test display was in the same position as it had been in the previous (no-support) display. They were instructed to press the 'S' key for *same* and the 'D' key for *different*. The instructions emphasized both speed and accuracy. Participants were also told that they should not expect an equal number of same and different trials, and that they should process the entire display rather than the plant alone. There were a total of 60 randomly ordered trials, 20 with each test display.

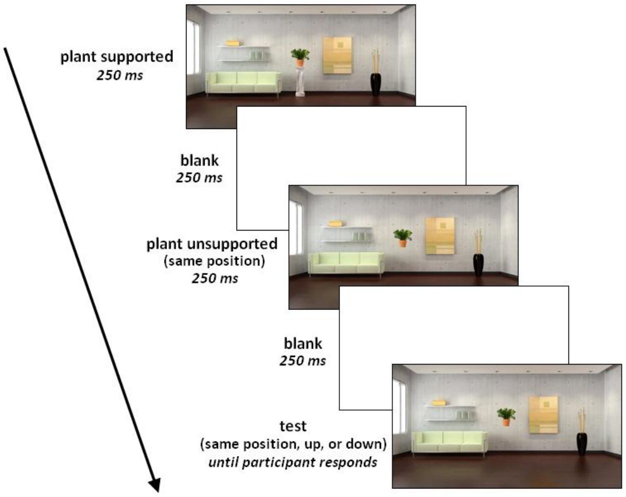

Figure 2: The structure of individual trials, shown with stimuli from the Realistic-Support condition of Experiment 1 and all conditions of Experiment 2.

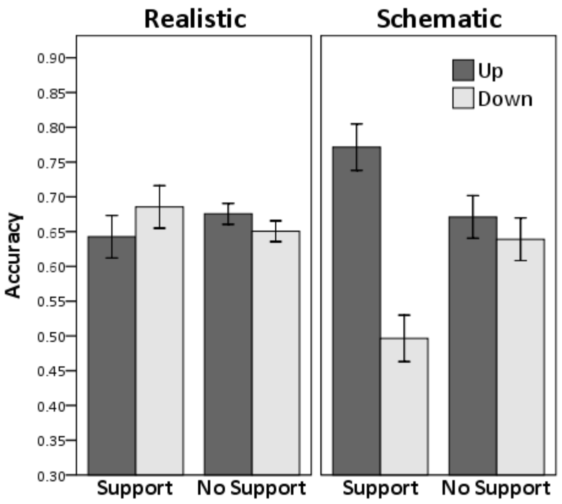

Figure 3: Accuracy on up and down trials across conditions in Experiment 1 (error bars are +/- 1 SEM).

Results

The main finding was that displacement occurred only for schematic scenes that depicted an initial support relation. As shown in Figure 3, participants in the Schematic-Support condition were more likely to indicate "same" when the plant was shifted down than when it was shifted up. No such asymmetry was observed in the other three conditions.

These findings were supported by a mixed ANOVA on participants' accuracy patterns in which format (realistic vs. schematic) and support (initial display showed vs. did not show a support relation) were between-subjects factors and target position (up vs. down) was a within-subjects factor. [The data of 3 participants were excluded from analyses for making *same* responses on greater than 75% of the trials, leaving 14 participants in each condition.] There was a significant main effect of target position [$F(1,52) = 7.01$, $p < .02$], with accuracy lower for down trials ($M = 62\%$) than for up trials ($M = 70\%$). However, this asymmetry between up and down depended on both format and support, as shown by a significant interaction between target position and format [$F(1,52) = 8.78$, $p < .005$] and a significant three-way interaction [$F(1,52) = 7.01$, $p < .02$]. Accuracy was significantly lower for down than for up trials only in the Schematic-Support condition (up: $M = 77\%$, down: $M = 50\%$), $t(13) = 4.11$, $p < .005$. There was no asymmetry in the other three conditions, and no other main effects or interactions were significant (all ps > .2).[1]

Discussion

The results of Experiment 1 replicate the findings of Freyd et al. (1988) in confirming that people simulate

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[1] The RT data showed the same general patterns as the accuracy data across both experiments, though some analyses did not reach statistical significance. In this paradigm, as noted by Freyd et al. (1988), there are often too few correct responses to calculate a reliable RT for some trial types (e.g., down trials in the Schematic-Support condition of Experiment 1).

motion in static scenes only when there is perceived removal of a force. However, the results also highlight an important caveat to this conclusion. The simulation processes associated with the perception of implied motion are engaged more when visual stimuli are schematic, as opposed to realistic. We suggest that displacement varied as a function of realism because the properties of the schematic materials reflected the kinds of representations that are hypothesized to exist in the dorsal stream to a greater extent than did the properties of the realistic materials.

Although there was no evidence of mental simulation in the Realistic conditions, this does not imply that realistic materials cannot lead to the simulation of motion. The materials in the Realistic conditions consisted of certain features (e.g., color, texture) that could be processed only in the ventral stream, but they also included features that could be processed in the dorsal stream (e.g., shape). Because schematic language (e.g., prepositions) and depictions (e.g., line drawings) reflect a relatively coarse level of description, activities that promote the use of such forms might induce a more schematic conceptualization of experience. If sufficiently biased through such activities, people might focus on the schematic aspects of realistic materials, in which case even realistic materials might lead to the perception of implied motion.[2] This possibility was examined in the next experiment.

Experiment 2

Experiment 2 examined whether a prior task prompting people to focus on the schematic properties of a realistic stimulus might induce greater simulated motion. Participants completed the same task as in Experiment 1, but this time they were shown only the realistic stimuli. Prior to this task, participants engaged in activities designed to vary the mental set they used when subsequently processing the realistic scene. Half of the participants were asked to describe the scene in writing, while the other half were asked to draw the scene. Within each of these groups, half of the participants were asked to describe or draw the scene in a realistic manner, while the other half were asked to describe or draw the scene in a schematic manner. The key prediction was that schematic processing, whether induced by describing or drawing, would engage the dorsal stream to a greater extent, and hence lead to greater displacement, than would realistic processing.

Method

Participants. Seventy-nine Emory University undergraduates participated in the experiment as part of a course requirement.

Materials, Design, and Procedure. The materials included the same photorealistic stimuli used in Experiment 1. Participants were randomly assigned to either the Describe or Draw condition and to either the Realistic or Schematic format in a fully crossed between-subjects design with four conditions: Describe-Realistic, Describe-Schematic, Draw-Realistic, and Draw-Schematic.

In all conditions, participants were shown the support display, in which the plant is supported by the pedestal. In the Describe-Realistic condition, participants were asked to describe the room "in rich detail, as if describing the details of a photograph." In the Describe-Schematic condition, participants were asked to describe the room "schematically, as if describing the details of a diagram." Similarly, in the Draw-Realistic condition, participants were asked to depict the room "in rich detail, as if your drawing were a photograph," whereas in the Draw-Schematic condition, they were asked to depict the room "schematically, as if your drawing were a diagram." Participants were given 5 minutes to describe or draw the room. Then they completed the implied motion task using the materials from the Realistic-Support condition of Experiment 1 (see Figure 2).

Results

The results showed that varying the mental set of the observer modulated the perception of implied motion. Displacement was observed for realistic scenes when a prior task induced participants to process the scenes schematically, but not when the task induced them to process the scenes realistically.

These findings were supported by a mixed ANOVA on participants' accuracy patterns. [The data of 7 participants were excluded from analyses for making *same* responses on greater than 75% of the trials, leaving 18 participants in each condition.] There was a significant main effect of target position [$F(1,68) = 7.51$, $p < .01$], with lower accuracy for down trials ($M = 62\%$) than for up trials ($M = 72\%$), just as would be expected if participants were simulating downward motion. A significant interaction between target position and format [$F(1,68) = 5.13$, $p < .03$] showed that the asymmetry between down and up trials was larger in the Schematic conditions than in the Realistic conditions. Within the Schematic conditions (collapsing across Describe and Draw), accuracy on down trials ($M = 61\%$) was significantly lower than on up trials ($M = 78\%$), $t(35) = 3.64$, $p < .001$. Within the Realistic conditions, the difference in accuracy between down ($M = 63\%$) and up ($M = 65\%$) trials was not significant ($p > .7$). No other main effects or interactions were significant (all ps > .09).

The lack of a three-way interaction between target position, format, and medium [$F(1,68) = 1.15$, $p > .2$] suggests that the down-up asymmetry for the Schematic format (relative to the Realistic format) was comparable in both the Describe and Draw conditions. However, the Schematic format showed a greater asymmetry than the Realistic format only for participants who had produced drawings, $F(1,34) = 6.12$, $p < .02$ (see Fig. 4). The difference between the two formats was not significant for participants who had written descriptions ($p > .4$).

Post-hoc analysis indicated that the magnitude of displacement correlated positively with the proportion of relational terms (prepositions and verbs describing spatial relations) in participants' descriptions ($r = .45$, $p < .01$), but

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[2] This prediction is consistent with findings showing that displacement can be influenced by variables such as observers' conceptual knowledge and expectations (see Hubbard, 2005).

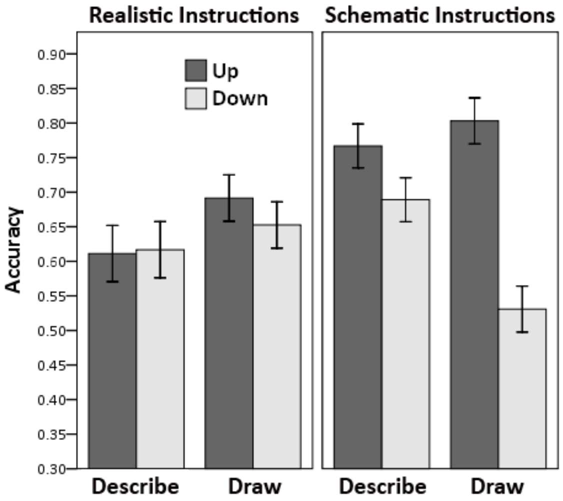

Figure 4: Accuracy on up and down trials across conditions in Experiment 2 (error bars are +/- 1 SEM).

did not correlate with the proportion of adjectives ($r = -.26$, $p > .1$). In addition, descriptions from the Describe-Schematic condition had a significantly higher proportion of relational terms [$t(35) = 3.02$, $p < .005$] and a marginally lower proportion of adjectives [$t(35) = 1.74$, $p = .09$] than descriptions from the Describe-Realistic condition. Ratings of participants' drawings (by a separate group, $N = 15$) on a 1-to-9 Likert scale of "realism," defined as the extent to which a drawing included cues to 3D properties such as depth and texture, were also collected. On average, raters assigned significantly higher realism ratings to drawings from the Draw-Realistic condition ($M = 5.0$) than drawings from the Draw-Schematic condition ($M = 4.7$), $t(14) = 2.32$, $p < .04$. Thus, participants who showed greater displacement were those who had used more schematic language or produced more schematic drawings.

Discussion

The results of Experiment 2 provide further support for the idea that implied motion is more likely to be perceived when a scene is conceptualized in a schematic fashion. When conceptualized schematically, the scene may be processed primarily in the dorsal stream, which is largely responsible for the mental simulation of motion. While we found clear effects of drawing on simulation, the effects of verbal description were less compelling. However, an association between simulation and relatively schematic aspects of language in participants' descriptions suggests that verbal description can in fact modulate processing. In particular, the positive correlation between relational terms and the displacement effect is exactly what would be predicted if relational language leads people to process visual stimuli in a schematic fashion, presumably in the dorsal stream. Further, the lack of correlation with adjectives is not surprising, as adjectives encode information presumably processed in the ventral stream.

In sum, the results suggest that everyday activities such as writing and drawing can direct attention to different aspects of visual stimuli and influence how they are processed. Schematic processing may cause the visual world to be represented more like a line drawing than a photograph, and this format of representation may invoke simulation processes in the dorsal stream.

General Discussion

The results from this research suggest that the mental simulation of motion in static scenes depends on the realism of the scenes and the observer's mental set when processing them. Experiment 1 showed that simulation occurred during the processing of highly schematic scenes resembling line drawings, but not highly realistic scenes resembling photographs. Experiment 2 showed that simulation can occur even for highly realistic scenes when they are processed schematically; that is, when prior activities induce the observer to focus on their schematic properties. Because the simulation of motion is strongly associated with processing in the dorsal visual pathway, the conditions under which implied motion is perceived offer a window into the kinds of representations associated with dorsal stream processing. Consistent with previous evidence indicating that the dorsal stream operates at a relatively coarse level in the perception of objects, our findings are suggestive of a format of representation in which the rough contour of objects and the spatial relations among them are preserved, but detailed featural information is lacking. The sparseness of such representations, much like the line drawings in physics textbooks, may be especially suited for the mental operations at work in the simulation of motion.

This link between schematic representations and simulation highlights the potential utility of such representations for reasoning. In particular, reasoning about physical systems sometimes involves forming a mental image of a system and then "running" it (Hegarty, 2004). For example, when solving problems involving interlocking sequences of gears, people often mentally rotate the gears before discovering the abstract rule that governs how they turn, namely that odd and even gears turn in different directions (Schwartz & Black, 1996). Our findings suggest that more schematically rendered or imagined gears may be easier to mentally rotate, which could influence the tendency to re-represent the problem in terms of a rule. Thus, the use of schematic representations may be beneficial for certain types of problem solving and inference.

One key question concerns exactly what visual properties constitute a "schematic" representation, as opposed to a "realistic" one. In future work, we plan to employ the same behavioral paradigm used in the present experiments to specify which aspects of visual stimuli give rise to simulation, and hence reflect properties of schematic representations in the dorsal stream. If, for example, displacement is minimized or eliminated when visual properties such as depth cues or surface gradients are absent, it would imply that schematic representations include such information. Similarly, if displacement persists even when the stimuli are primitive 3D shapes (e.g., spheres, cylinders), it would imply that schematic representations need not have any shape detail beyond simple geometric forms.

Although we found no evidence of simulated motion with realistic materials under neutral conditions, other studies (e.g., Kourtzi & Kanwisher, 2000; Senior et al., 2000) have used realistic materials specifically to identify the neural correlates of simulated motion. However, these studies used single static stimuli in which motion was strongly implied (e.g., frozen-action photographs), whereas our stimuli invoked more subtle forms of motion (slight changes in spatial position) solely through the sequential nature of their presentation. Our findings suggest that the use of schematic stimuli in the former paradigm might lead to even greater simulated motion. Interestingly, displacement effects in a handful of studies using realistic stimuli have been regarded as validating the widespread use of more impoverished stimuli (Hubbard, 2005), but to our knowledge, the current study is the first to manipulate realism directly. Our findings caution against the assumption that simulation for schematic materials will carry over to more ecologically rich contexts.

Together with recent neural work, our findings have implications for models of the neural bases of word meaning. While Landau and Jackendoff (1993) argued that the dorsal and ventral streams map onto different grammatical categories (preposition vs. noun), it is likely that certain aspects of the meanings of object nouns are represented in the dorsal stream as well. Processing differences in the two streams may be better accounted for by a distinction often made in lexical semantics between structural and idiosyncratic aspects of word meaning (Levin & Rappaport Hovav, 2009). Words for spatial relations, for example, can be divided into a structural component, which specifies the abstract geometry of a spatial relation, and a more idiosyncratic component, which distinguishes spatial terms on the basis of more fine-grained geometric information. We suggest that schematic representations computed in the dorsal stream may reflect structural components of word meaning.

Our findings also suggest a novel perspective on the interface between language and thought (Wolff & Malt, 2010). Recent research has focused on how language might augment thought by putting in place representational systems essential for certain kinds of abstract thinking (e.g., reasoning about exact quantities; Gordon, 2004; see Wolff & Holmes, in press, for a review). In our second experiment, more schematic language was associated with greater simulation, suggesting instead that language may serve as a vehicle to abstraction, promoting the use of schematic representations rather than directly instantiating them. Importantly, however, language may be just one of many vehicles to abstraction. Other types of processing (e.g., drawing) may be just as likely to induce a schematic conceptualization of experience. Thus, it may be the schematic representations themselves, rather than the means by which they are recruited, that offer especially powerful tools for thinking.

Acknowledgments

The authors wish to thank Larry Barsalou, Stella Lourenco, Laura Namy, Marjorie Pak, and Grace Song for helpful discussion, and Tonia Davis, Savina Nikolova, Seho Park, Sam Ritter, and Meredith West for assistance with data collection. This research was supported by a William Orr Dingwall Foundation Neurolinguistics Fellowship to KJH.

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