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The role of the dorsal visual processing stream in tool identification

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Abstract

The dorsal visual processing stream subserves object directed action, while the ventral visual processing stream subserves visual object recognition. Little is known about how information computed by dorsal stream structures influences object recognition. We used Continuous Flash Suppression to functionally isolate the information computed by the dorsal stream from that computed by the ventral stream. We show that the information originating from the dorsal stream influences not only decisions requiring superordinate category knowledge, but also decisions that entail the selection of a basic-level object. We further show that the information computed by the dorsal stream does not carry specific functional information about objects. Our results indicate that the dorsal stream, in isolation from the ventral stream, is agnostic as to the identity of the objects that it processes. Instead, we suggest that structures within the dorsal stream compute motor-relevant information (e.g., graspability) that influences the identification of manipulable objects.

Introduction

Information about an object's shape, surface materials, and how it is grasped, among other information, becomes available soon after that object engages our visual system. Convergent evidence from neuroimaging and neuropsychology indicates that different types of information are differentially relevant to object recognition. For instance, brain-damaged patients may show deficits in reaching, grasping and/or manipulating objects while retaining the ability to identify these objects (e.g., Buxbaum & Saffran, 2002; Buxbaum, Sirigu, Schwartz, & Klatzky, 2003; Hodges, Spatt, & Patterson, 1999; Jeannerod, Decety, & Michel, 1994; Ochipa, Rothi, & Heilman, 1989). In contrast, patients with severe object recognition deficits may exhibit spared object manipulation (e.g., Buxbaum, Schwartz, & Carew, 1997; Goodale & Milner, 1992; Hodges, Bozeat, Lambon-Ralph, Patterson, & Spatt, 2000; Negri, Lunardelli, Reverberi, Gigli, & Rumiati, 2007). Moreover, the processing of these different types of information has been traced to independent anatomical pathways: visuomotor knowledge is extracted by dorsal stream structures, whereas information about object identity necessary for recognition is extracted by ventral stream structures (e.g., Goodale & Milner, 1992; Johnson-Frey, 2004; Shmuelof & Zohary, 2005).

Little is known, however, about how information processed by the dorsal stream might inform object recognition processes, presumably mediated by ventral stream structures. It

has recently been shown that the outputs of the dorsal stream are relevant to the process of semantic categorization (Almeida, Mahon, Nakayama, & Caramazza, 2008). That study made use of an interocular suppression technique - Continuous Flash Suppression (CFS; Tsuchiya & Koch, 2005) – to visually suppress prime pictures.

Stimuli presented under CFS do not reach structures in the ventral stream, but are processed by the dorsal stream (e.g., Fang & He, 2005; Sheinberg & Logothetis, 1997; Tong, Nakayama, Vaughan, & Kanwisher, 1998). Thus, if semantic priming effects could be observed for CFS-suppressed primes, then these effects must be mediated by dorsal stream computations. CFS-suppressed categorically-congruent prime pictures facilitated subsequent categorization responses of manipulable objects, but not of animals or vehicles.

The critical open issue framed by that study concerns the nature of the information originating from the dorsal stream that is able to influence object recognition. The fact that this information can influence superordinate categorization (Almeida et al., 2008) is ambiguous as to whether it can influence narrower categorizations (e.g., categorizing an object as a hammer). Moreover, those previous findings are also not informative about the specificity of the information extracted by dorsal stream structures.

Basic-level picture naming offers a way to study the level(s) of processing at which information computed by dorsal stream structures influences object recognition. Basic-level naming requires precise information in order to isolate a particular target from similar within-category semantic coordinates. If the information originating from the dorsal stream is relevant for the selection of a particular target, then we should see a priming effect specific to tool targets (compared to animals) that are named at the basic-level. Likewise, the use of identical primes and targets can shed light on the specificity of the information that is extracted by dorsal stream structures. If the information originating from the dorsal stream is specific to the presented object, then the more information is shared between prime and target, the stronger the effects should be. ‘Identical’ primes should give rise to an identity effect that exceeds categorical priming.

Here we show that basic-level naming latencies for pictures of manipulable objects (but not for animals) are influenced by information computed by dorsal stream structures. We also find that under CFS, identical primes and targets do not lead to an effect that exceeds categorical priming. In contrast, we show that using masking techniques that allow information to reach the ventral stream (Backward Masking; Dehaene et al., 2001), an identity effect that surpasses categorical priming is obtained. These results show that the information originating from the dorsal stream can influence tasks requiring different degrees of processing – from determining the target's unique name to extracting its superordinate category. It also shows that these effects are not dependent on detailed information about the presented object, but rather suggest that they are based on the extraction of relatively coarse motor-relevant information.

Experiment 1

In Experiment 1 we used CFS-based priming in a picture naming task to understand whether the information originating from the dorsal stream could be used in situations in which a stimulus must be named at the basic level. If this information is relevant to the selection of a particular target object, we should see a priming effect in picture naming.

To ensure reliability of the results we performed two separate experiments (Experiments 1a and 1b). We used different sets of pictures, different participants, and we varied the time between the naming and categorization sessions (from immediately following one another to a few days apart).

Methods

Participants—Forty Harvard undergraduates participated in the experiment (20 per experiment) in exchange for course credit or payment. All participants were right-handed, had normal or corrected-to-normal vision, and gave written informed consent. The project was approved by the appropriate institutional review board.

Materials and Procedure—We used black-and-white pictures of animals and “tools” that have been described elsewhere (Almeida et al., 2008). For each category, we selected four pictures as targets and four different pictures as primes. The primes were made “invisible” using CFS (see Figure 1a). The stimuli were presented centrally, and subtended 7° of visual angle.

We followed the procedures used in Almeida et al. (2008) except that the current experiments consisted of three independent stages: a categorization experiment, a naming experiment, and a prime-discrimination task. The order of the categorization and naming tasks was counterbalanced across participants; the prime-discrimination was always performed at the end of the experiment. In the naming and categorization parts, participants saw a fixation cross (500 ms) followed by the prime and the first random-noise-pattern (100 ms), followed by the prime and a second random-noise-pattern (100 ms) followed by the target picture for 3,000 ms or response, whichever came first (see Fig. 1a). Participants were asked to either name the pictures or categorize them as “animals” or “tools” by pressing buttons.

The prime-discrimination task provided independent data to assess prime awareness. In this task, participants were asked to categorize the prime into the two target categories. The trial structure remained the same as in the previous tasks except that the target was not presented. Only the participants who performed at chance level on the prime-discrimination task are reported here and were included in the main analyses (for detailed analyses see supplemental materials). Stimuli were presented using DMDX (Forster & Forster, 2003).

Analyses—We used planned contrasts to analyze response latencies (Rosenthal, Rosnow, & Rubin, 2000). Two pair-wise contrasts per experiment per category were employed to test the priming effect in the categorization and naming responses.

Results

Significant priming effects were obtained, for both experiments, over naming and categorization responses for tool targets (see Figure 2a). Participants were faster to categorize tools in the context of tool than animal primes (Experiment 1a: $F(1,19) = 10.6$, $MSE = 227.8$, $p = .004$, $d = .73$; mean priming effect = 11 ms, $SEM = 3$; Experiment 1b: $F(1,19) = 5.7$, $MSE = 265.5$, $p = .028$, $d = .53$; mean priming effect = 9 ms, $SEM = 4$). Participants were also faster to name tools in the context of tool than animal primes (Experiment 1a: $F(1,19) = 6.9$, $MSE = 923.7$, $p = .017$, $d = .59$; mean priming effect = 18 ms, $SEM = 7$; Experiment 1b: $F(1,19) = 4.8$, $MSE = 607.2$, $p = .04$, $d = .49$; mean priming effect = 16 ms, $SEM = 6$). The contrasts for animal targets in both tasks did not reach significance (all F s < 1 except for the priming effect for naming in Experiment 1a; $F(1,19) = 2.5$, $MSE = 876.2$, $p = .13$).

Discussion

In Experiment 1 we replicated the previous finding of category-specific priming under CFS in a categorization task, and further showed that the effect is observed in basic-level naming. Participants were faster to categorize or name a target picture in the context of categorically-

congruent CFS-suppressed primes than in the context of incongruent primes. As expected, these results were obtained only for tool targets (and not for animals).

Experiment 2

In Experiment 2 we address the specificity of the information originating from the dorsal stream by including an identity condition (in addition to the categorically congruent and incongruent conditions). If the information originating from the dorsal stream is specific to the prime picture, we should observe an identity effect that surpasses categorical priming.

In Experiment 2, we used two techniques to mask prime pictures. Experiment 2a used CFS, whereas Experiment 2b used Backward Masking (BM). Because under BM information reaches the ventral stream (Dehaene et al., 2001), the identity effect should exceed categorical priming in Experiment 2b.

Methods

Participants—Twenty-four undergraduates, who did not participate in Experiment 1, participated in this experiment (12 per experiment).

Materials and Procedure—We used the same pictures as in Experiment 1a, and we also used the target pictures as primes for the identity condition. Participants were asked to categorize the target pictures by pressing buttons. Experiment 2a used the same procedures as Experiment 1. In Experiment 2b, the prime picture (35 ms) was followed by a black-and-white random-noise mask (100 ms; see Figure 1b). We added 70% additive noise to the prime stimuli (with Photoshop) to facilitate masking. The subsequent target presentation followed the procedures in Experiment 1.

Analyses—We used planned contrasts to analyze response latencies. Three pairwise contrasts per experiment were employed on the responses for tool targets to test the categorical priming effect, the identity priming effect, and to analyze whether the identity effect exceeded categorical priming.

Results

For the CFS experiment (2a), participants were faster to categorize tools in the context of tool than animal primes ($F(1,11) = 6.5$, $MSE = 397.5$, $p = .027$, $d = .74$; mean priming effect = 15 ms, $SEM = 6$). They were also faster to categorize tools in the context of identical than animal primes ($F(1,11) = 8.6$, $MSE = 328$, $p = .014$, $d = .84$; mean identity effect = 15 ms, $SEM = 5$). However, no differences were observed between identical and non-identical tool primes ($F(1,11) < 1$; mean identity effect above the categorical effect = 1 ms, $SEM = 4$; see Figure 2b). The corresponding contrasts for animal targets, under experiment 2a, did not reach significance (all $F_s < 1$).

For the BM experiment (2b), categorical priming for tool targets was significant ($F(1,11) = 5.7$, $MSE = 217.6$, $p = .037$, $d = .68$; mean priming effect = 10 ms, $SEM = 4$), as well as the identity effect ($F(1,11) = 18$, $MSE = 609.4$, $p = .001$, $d = 1.21$; mean identity effect = 30 ms, $SEM = 7$). Moreover, identity primes led to a larger effect than categorically-congruent primes ($F(1,11) = 8.2$, $MSE = 589.4$, $p = .015$, $d = .82$; mean identity effect above the categorical effect = 20 ms, $SEM = 7$). Contrasts for animal targets under BM yielded significant priming effects (categorically-congruent priming: $F(1,11) = 7.6$, $MSE = 154.1$, $p = .019$, $d = .81$; mean priming effect = 10 ms, $SEM = 4$; identity priming: $F(1,11) = 18.9$, $MSE = 319$, $p = .001$, $d = 1.23$; mean identity effect = 22 ms, $SEM = 5$; identity over

congruent priming: $F(1,11) = 6.2$, $MSE = 303.4$, $p = .03$, $d = .69$; mean identity effect above the categorical effect = 20 ms, $SEM = 5$).

Discussion

The identity effect in Experiment 2a did not exceed category-congruent priming. This indicates that the information originating from the dorsal stream, despite being able to influence tasks that require either broad (target categorization) or narrow information processing (target naming), is not specific to the presented object. An enhanced identity effect was, however, observed in a BM paradigm (Experiment 2b), demonstrating that when information reaches ventral stream structures, 'identical' primes lead to the expected enhanced identity effect.

General Discussion

The task of recognizing objects still poses pressing questions to cognitive scientists. One central topic concerns the type of information that is used in object recognition. We have recently suggested that information originating from the dorsal stream can influence object recognition (Almeida et al., 2008; see also Helbig, Graf, & Kiefer, 2006; Mahon et al., 2007; for a similar result in the context of number processing, presumably also performed by dorsal stream structures, see Bahrami et al., in press). Knowing what sort of information this is and how it is used is critical for understanding the role of the dorsal stream in object recognition as well as the interactions between ventral and dorsal visual streams.

We have found that dorsal stream information influences object recognition over broad categorical processing such as superordinate categorization as well as over narrow categorical processing such as basic-level naming. Moreover, our results show that this information is very coarse: When using CFS to render primes invisible, there were no response latency differences between primes that were identical to the targets and primes that were only categorically-congruent.

Our results show that the information computed by dorsal stream structures can be used in recognizing manipulable objects, but not because it specifically identifies functional properties of such objects. In fact, the dorsal stream, in isolation, seems to be agnostic as to the identity of objects. Rather, our findings suggest that this information is not about the object *per se*, but may be about more rudimentary motor-relevant knowledge, presumably related with whether the object is graspable and how it might be grasped, in a strict visuomotor sense.

This conclusion is supported by neuropsychological and neuroimaging evidence suggesting that the processes related to *acting on* an object (e.g., preparing a grasp for moving a hammer) and *using* an object (e.g., preparing a grasp for using a hammer to pound a nail) are dissociable (e.g., Johnson & Grafton, 2003; Rizzolatti & Matelli, 2003). For instance, optic ataxic patients show deficits in reaching and grasping objects but may be able to manipulate familiar objects (Jeannerod et al., 1994). Conversely, apraxic patients are impaired in object use but may perform optimal grasps toward objects (e.g., Buxbaum et al., 2003; Heilman & Rothi, 1997), suggesting the operation of visuomotor transformations over intrinsic physical characteristics (e.g., shape) of the target object.

While the processes involved in grasping an object depend on visuomotor transformations over the intrinsic physical properties of the target objects, using an object requires the integration of stored knowledge about object function, identity, and motor programs associated with it. Studies suggest that dorsal stream regions, such as the inferior parietal lobule are fundamental for these processes (e.g., Buxbaum et al., 2003; Johnson & Grafton,

2003; Rizzolatti & Matelli, 2003). There is also evidence, however, that ventral stream structures are important for object use. Patients with lesions restricted to ventral stream structures may grasp objects in a way that is consistent with their physical structure, but which is not appropriate for subsequent use of the object (Carey, Harvey, & Milner, 1996). Moreover, observation of grasps typically associated with a particular object use, when compared to grasps that are possible but not typical, lead to activations in ventral temporal regions (Valyear & Culham, in press). Our results, taken together with these clinical and neuroimaging observations, indicate that visual dorsal stream information can be interpreted conceptually but that, on its own, is not conceptually defined.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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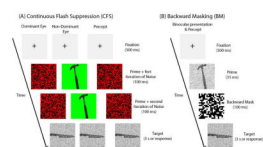


Figure 1. Experimental Design

For experiments 1a, 1b, and 2a, we used CFS to suppress the primes. In CFS a static image competes with a dynamic image, with the latter reliably suppressing the former for a prolonged time. To induce CFS we presented a low-luminance, low-contrast version of the prime stimuli to the participant's non-dominant eye, and a dynamic high-contrast random noise pattern that would change every 100 ms on the dominant eye (the high luminance of images in the figure is for visualization purposes). Red/green anaglyph glasses were worn by the participants to allow for dioptic presentation of the images. For experiment 2b, we used BM to suppress the primes. (A) Procedure employed for CFS in experiments 1a, 1b, and 2a. (B) Procedure employed for BM in experiment 2b.

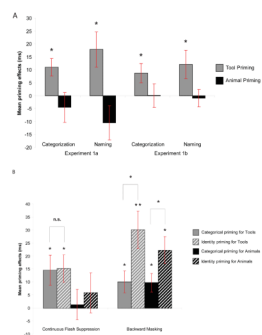


Figure 2. Behavioral priming effects

Average priming effects are plotted as a function of the experimental conditions.* for $p < 0.05$; ** for $p < 0.001$. Error bars represent SEM for priming effects across subjects. (A) Results for experiments 1a and 1b; (B) Results for experiments 2a and 2b.