The visual motion aftereffect from mental imagery depends on speed

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Abstract

When we imagine a train snaking through a desert, does information about the train's speed make it into our visual mental image? In this paper, we make use of the motion aftereffect illusion (MAE) to test whether the speed of imagined visual motion modulates transfer of adaptation to a subsequent visual motion discrimination task. We compared the effects of viewing slow, medium, and fast motion on the magnitude of the MAE (Experiment 1) with the effects of simply imagining the same motion stimuli (Experiment 2). In Experiment 1 we found that increasing the speed of real visual motion from slow to medium produced a corresponding increase in the magnitude of the MAE, but increasing speed from medium to fast did not. Likewise, imagining slow motion produced a smaller MAE than did imagining medium motion, but the effect leveled of between medium and fast motion. These findings suggest that our mental imagery of motion is specific to the speed of the moving objects, and highlight areas of overlap between mental imagery and visual perception.

Keywords: Mental imagery; Motion aftereffect; Embodiment

Background

When we imagine a car racing by, how visual is the process of creating the mental image? Do the representations we generate include information about how fast the car appears to be going? Or are they invariant to this property of visual motion perception? In this paper, we make use of the motion aftereffect illusion (MAE) to test whether the speed of imagined visual motion modulates transfer of adaptation to a subsequent visual motion discrimination task.

Researchers have long debated just how similar imagining a visual scene is to actually witnessing it (Kosslyn, 1981; Pylyshyn, 1973). Previous work examining the metric properties of imagined static scenes has found that information about size (Kosslyn, 1975), distance (Kosslyn, Ball, & Reiser, 1978), and structure (Kosslyn, 1973) is indeed persevered in mental imagery. For example, Kosslyn et al (1978) found that the distance between objects in a mental image is proportional to the physical distance between their real-world counterparts. Participants in their study memorized a fictional map containing several landmarks, and were later asked to "scan" between pairs of landmarks in their mental image of the map. Results showed that the greater the distance between two landmarks on the physical map, the longer it took people to mentally scan between them.

Other work has shown that people are capable of mentally performing metric transformations on images of static objects (Finke, Pinker, & Farah, 1989; Shepard & Metzler, 1971). In a study by Shepard and Metzler (1971), participants judged whether pairs of geometric objects were identical to one another or mirror reversed. The authors reasoned that if people solved this task by mentally rotating one object until it aligned with the other, their reaction time should depend on the physical angular disparity between objects. Indeed, participants took longer to mentally rotate objects that would take longer to physically rotate, and vice versa.

The metric properties of mental imagery for dynamic scenes have not been studied as widely as for static scenes. One feature of visual motion that has been found to make it into mental imagery is motion direction. Winawer, Huk, & Boroditsky (2008) demonstrated that imagining visual motion in a particular direction is sufficient to produce direction-selective adaptation in the visual system (i.e., produce a visual motion aftereffect illusion). After imagining upward motion, participants were more likely to see a subsequent dynamic stimulus as moving *downward*, and vice versa. Transfer of adaptation from mental imagery to perception suggests that a common neural mechanism underlies both processes. However, the degree of adaptation from mental imagery was considerably weaker compared to that from real visual motion perception, which sets a limit on the overlap between these two processes.

The adaptation paradigm used by Winawer and colleagues provides a unique testing ground for discovering other motion properties preserved in dynamic mental images. In this paper, we ask whether the magnitude of the visual motion aftereffect from mental imagery depends on the speed of imagined motion. If so, does motion speed modulate the MAE from imagery in the same way as speed modulates the MAE from real visual motion perception? That is, is speed yet another feature common to both mental imagery and perception, or is it an area in which internally-generated motion representations abstract away from their externally-generated counterparts?

To test these questions, we first measured the effect of speed on the MAE from real visual motion (Experiment 1), and compared that with the MAE from imagining the very same motion stimuli (Experiment 2). In Experiment 1, subjects viewed videos of moving stripes (upward or downward) in three within-subject conditions: slow, medium, and fast. Following each video, participants indicated the direction in which a set of dynamic dots appeared to move. We found that increasing the speed of visual motion from slow to medium produced a corresponding increase in the magnitude of the MAE, but increasing speed from medium to fast did not.

In Experiment 2, participants simply imagined the videos from Experiment 1 prior to completing the dot discrimination task. We found that imagining motion produced a reliable MAE (albeit weaker than from viewing real visual motion). We also found that viewing and imagining motion produced the same relative pattern of results across conditions. As in Experiment 1, imagining slow motion produced a smaller MAE than did medium or fast motion, but there was no difference between the medium and fast conditions.

Experiment 1

How does motion speed modulate the magnitude of the MAE from real visual motion?

Methods

Participants 30 Stanford undergraduate students participated in this study in exchange for payment.

Stimuli & Procedure The task design, procedure, and visual stimuli used were modeled on those used by Winawer and colleagues (2008) and Dils and Boroditsky (2010). On each trial participants judged the direction of dot motion after viewing real visual motion. Trials were presented in 6 blocks: 3(speed: fast, medium, or slow) by 2(adaptation direction: upward or downward). The upward and downward versions of each speed were presented in succession. Block order was otherwise randomized across participants. Participants adapted to 60 seconds of motion in the first trial of each block. The adaptation phase of each subsequent trial lasted 6 seconds. There were 24 total trials per block.

Adapting stimuli. Participants watched videos of drifting black-and-white horizontal stripes. The videos showed a sine grating with a spatial frequency of 3.44 cycles per degree of visual angle drifting either upward or downward. In the medium condition, the grating drifted at 4.77 degrees per second. The slow grating drifted at half the speed of the medium grating (2.39 degrees per second), while the fast grating drifted at twice the speed of the medium grating (9.54 degrees per second). A flickering fixation cross was superimposed at the center of each video. The cross flickered at the same rate that the grating drifted. This feature was included to equate stimuli between Experiments 1 and 2, and it was task-irrelevant in the current study.

Test stimuli. Following the adaptation portion of each trial, participants judged the direction of motion coherence in a field of moving dots, without feedback. One hundred round dots were placed within a round aperture 10 degrees in diameter. The dots were light gray on a dark gray background, and each dot was 0.10 degrees in diameter. The dots moved at 12 degrees per second within the aperture, and any dots whose x-y coordinates exceeded the boundary of the aperture were randomly placed within the aperture on each frame. A light gray static fixation dot 0.15 degrees in diameter was placed at the center of each dot display. Dot motion was always presented for 1 second, at which point the dot display disappeared from the screen. Participants pressed “f” if the dots appeared to move upward, and “j” if the dots appeared to move downward.

Each dot display had net motion coherence either up or down. For each subject, three coherence values were sampled 24 times in each direction. The values were tailored to each participant’s dot motion sensitivity threshold (as assessed in a baseline task described below). They were selected to be 12.5%, 25%, and 50% of the coherence necessary for each individual to detect the direction of motion in a dot display with 99% accuracy. Coherence and direction of motion were fully crossed and balanced across trials and participants.

Baseline Motion Sensitivity Task. During the baseline motion sensitivity measurement, participants viewed 192 dynamic dot displays in succession and on each trial had to indicate the direction of motion coherence, upward or downward. Participants pressed the ‘F’ key on a keyboard to indicate upward motion and the ‘J’ key to indicate downward motion. The percentage of dots that moved coherently varied from trial to trial. In the baseline task, 12 coherence values were tested (99%, 66%, 44%, 29%, 20%, 13%, 9%, 6%, 4%, 3%, 2%, 1%), and each coherence level was sampled 8 times in each direction (upward / downward). A logistic function was fitted to each participant’s data at the end of the baseline task, and the fit was used to compute the participant’s threshold (the percentage of dot coherence required for 75% accuracy). The threshold was then used to compute the coherence values to be used in the main experimental task, namely, values corresponding to 50%, 25%, and 12.5% of the coherence necessary for asymptotic performance. These values were selected to be sufficiently difficult yet discriminable for participants. We refer to these ‘normalized coherence’ values rather than the actual subject-specific values in all references of motion coherence in reporting results.

Analysis. Participants who did not reach asymptotic performance on the baseline motion sensitivity test were excluded from all analyses (5 people). A logistic model was fitted to each participant’s data from the main adaptation task. The regression models used a maximum likelihood algorithm to generate the fits and included a bias term, a term for motion coherence of the test stimulus, and three terms for the direction of the adapting stimulus (slow, medium, and fast motion). We computed the shift in the motion response functions as a function of adaptation direction for each level of motion speed. We used this analysis (1) to ensure that there was a reliable MAE in the full sample, and (2) to subsequently exclude participants who did not show an overall trend in the direction of an MAE after viewing real visual motion (4 participants). Since the aftereffect from real visual motion is typically large and robust, we reasoned that participants who did not at least numerically respond in the direction of adaptation were likely not following task instructions. Even if they were engaged in the task, the absence of an aftereffect would prevent us from being able to assess its dependence on speed in those individuals.

Data from the remaining 21 participants was submitted to a mixed-models logistic regression. The model included fixed-effect parameters for coherence of the test stimulus, direction of adaptation, speed of the adapting stimulus (Helmert coded), and trial number. The model also included terms for the interaction between adaptation direction and motion speed, as well as adaptation direction and trial number. This last interaction term was included to account for longitudinal shifts in the aftereffect due to accumulation of adaptation and fatigue. Finally, the model included random slopes by participant for the full fixed-effects structure.

Results

Figure 1 shows the raw, unfitted means across participants for upward and downward adaptation separately (including participants whose data was not in the direction of an MAE). In this inclusive sample, participants showed a 164.5% shift between the motion response functions in the direction of adaptation. This difference was highly significant, β=-4.63, Z=-7.37, p<0.00001.

Next we tested whether speed modulated the magnitude of the aftereffect in people who responded in the direction of adaptation overall. Indeed, viewing slow motion produced a smaller MAE than did viewing medium or fast motion (β=-2.31, Z=-4.68, p<0.00001). This corresponded with a 12% per deg/s increase in the probability of experiencing an MAE on a given trial. However, the increase in the MAE from viewing fast motion compared to medium motion was much smaller (0.65% per deg/s), and this shift did not reach significance (β=-0.17, Z=-0.38, p>0.5). The predicted means from this analysis are plotted in Figure 2.

Discussion

We asked whether the MAE from real visual motion perception depends on motion speed. We tested for MAEs following slow, medium, and fast visual motion, and we found that increasing speed from slow to medium or fast resulted in a corresponding increase in the magnitude of the MAE. However, we found no additional boost from increasing adaptation speed from medium to fast.

This pattern of results is consistent with previous findings on the relationship between speed of an adapting stimulus and the MAE (Ashida & Osaka, 1995; see Mather, Verstraten, & Anstis, 1998 for a review). For example, Ashida and Osaka found that the magnitude of the MAE for a given subject increases with speed until it peaks between 5-10 degrees per second. It then begins to decrease as speed continues to increase. The slow and medium conditions in the present study fall squarely within the rising phase of this trajectory, but the fast condition falls early in the falling phase for most individuals.

In Experiment 2, we ask whether speed of imagined motion modulates the MAE in the same way as does speed of real visual motion.

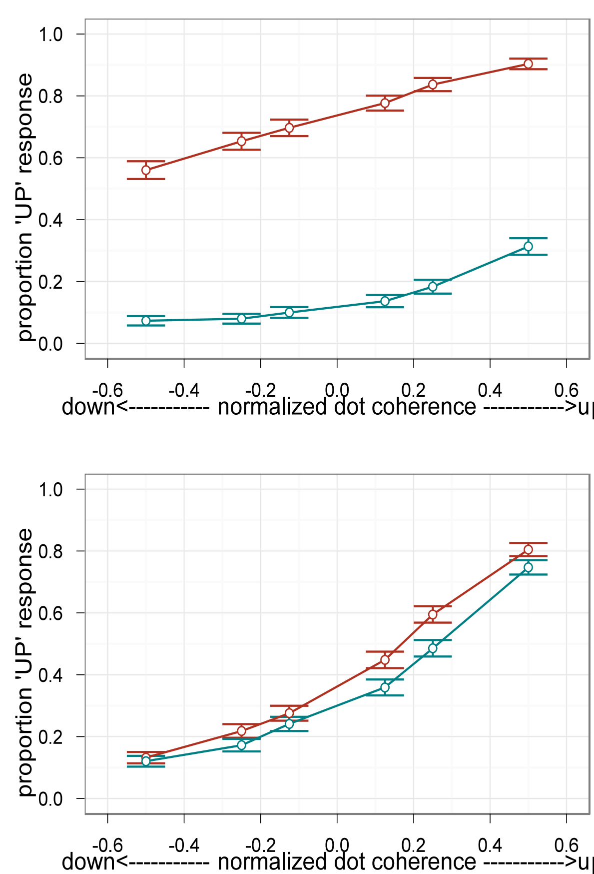

Figure 1. Mean proportion UP responses after viewing real visual motion (upper panel) and after imagining visual motion (lower panel). Upward adaptation is plotted in red, and downward adaptation is plotted in blue. Error bars denote ±1 s.e.m.

Experiment 2

Does speed modulate the magnitude of the MAE from imagined motion? If so, is the pattern of results similar to what we observed from viewing real motion?

Methods

Participants 30 Stanford undergraduate students participated in this study in exchange for payment.

Stimuli & Procedure The stimuli and procedure for this experiment were identical to Experiment 1, except that participants imagined the drifting gratings during the adaptation portion of each trial rather than viewing them.

Before each block, participants were shown upward and downward examples of the grating videos that they would need to imagine during the block. Participants viewed each video twice for 30 seconds before each block in which a new motion speed was being introduced. They viewed each video twice for 6 seconds before all other blocks. We made sure the visual motion presented during this familiarization phase did not interfere with our results during the main experimental task in three ways. 1. Participants were familiarized with both upward and downward motion, creating no net bias in either direction. 2. The familiarization was followed by at least 30 seconds of verbal instructions, a longer delay than necessary for an MAE from this duration of exposure to real visual motion stimuli to dissipate (Hershenson, 1989). 3. The direction of motion adaptation in the first experimental block following familiarization was chosen randomly.

At the beginning of each trial, an upward or downward facing arrow superimposed on a static image of the grating indicated the direction in which participants were to imagine the stripes moving. This cue faded over the course of a second. Once the cue disappeared completely, a flickering fixation cross appeared at the center of the screen. Participants were instructed to fixate on the cross while imagining the stripes and to use the rate of the flicker to help them remember how fast the stripes should move. Participants were also instructed to use the fixation cross as a cue for when to start and stop imagining motion.

Analysis. All analyses described in Experiment 1 were applied in the same way to the data from Experiment 2, including limiting our main analysis to participants who showed a motion aftereffect illusion. We know from previous work that there is considerable variation across individuals in the magnitude and direction of the aftereffect from internally-generated visual motion (Dils & Boroditsky, 2010). Some individuals show a large MAE from mental imagery, others show a small MAE, and a small number shows priming and not adaptation. While the causes of these individual differences are not yet known, the variation itself is systematic. People who show an aftereffect from mental imagery also show an aftereffect from other forms of internally-generated visual motion such as linguistic descriptions of motion. The predictions we drew from Experiment 1 about how participants in Experiment 2 should behave only apply to people who showed an MAE overall, as we did not have enough participants who showed priming from real visual motion to create a set of predictions for this subgroup. Further, we did not have enough individuals who showed priming in Experiment 2 to measure the effect of speed on priming from imagined visual motion. Therefore, after first confirming that there was a reliable aftereffect from visual motion imagery in the entire sample, we limited the primary speed analysis of this paper to those participants whose responses at least numerically trended in the direction of a motion aftereffect.

We excluded 1 participant from all analyses for failing to reach asymptotic performance in the baseline sensitivity task. We excluded 5 participants from the main analysis whose results did not trend in the direction of adaptation. Additionally, we conducted a mixed-models analysis testing for the presence of an interaction between experiments (Nieuwenhuis, Birte, & Wagenmakers, 2011). This analysis included all previously described predictors plus a term for the concreteness of the adapting stimulus (real versus imagined visual motion), as well as the full factorial 3-way interaction between concreteness, adaptation direction, and motion speed.

Results

Figure 1 shows the raw, unfitted means across participants for upward and downward adaptation separately (including participants whose data was not in the direction of an MAE). In this inclusive sample, participants showed a 9.89% shift between the motion response functions in the direction of adaptation. This difference was reliable, $\beta=-0.42$, $Z=-2.13$, $p<0.05$.

Next we tested whether speed modulated the magnitude of the aftereffect from imagined motion in people who responded in the direction of adaptation overall. Indeed, viewing slow motion produced a smaller MAE than did viewing medium or fast motion ($\beta=-0.59$, $Z=-2.08$, $p<0.05$). This corresponded with a 4.97% per deg/s increase in the probability of experiencing an MAE on a given trial. However, the increase in the MAE from viewing fast motion compared to medium motion was much smaller (0.60% per deg/s), and this shift did not reach significance ($\beta=-0.04$, $Z=-0.13$, $p>0.5$). The predicted means from this analysis are plotted in Figure 2.

Finally, we asked whether the magnitude of these effects differed between real and imagined visual motion. The overall magnitude of the motion aftereffect illusion was greater for real visual motion than it was for imagined visual motion ($\beta=-3.30$, $Z=-8.11$, $p<0.00001$). Also, the increase in the MAE from slow to medium and fast motion adaptation was significantly steeper for real visual motion than it was for imagined motion ($\beta=-1.74$, $Z=-3.46$, $p<0.001$).

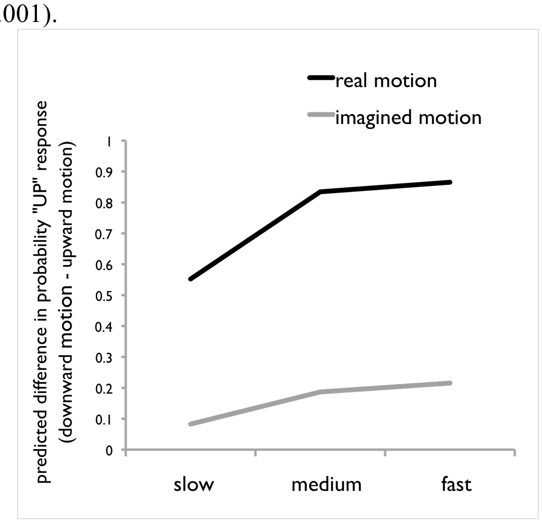

Figure 2. Model estimates of the effect of speed on the degree of adaptation for real and imagined visual motion for average (zero)

coherence and average trial. Positive values are consistent with a motion aftereffect illusion.

Discussion

In this study, we asked whether speed of visual motion is preserved in mental imagery. Specifically, we tested whether imagining slow, medium, and fast motion would differentially affect the magnitude of the motion aftereffect from mental imagery. We found that imagining motion indeed made people more likely to perceive a subsequent dynamic test stimulus as moving in the direction opposite the adapting motion. However, this effect was not constant across all speeds we tested. Increasing the speed of visual motion from slow to either medium or fast produced a corresponding increase in the magnitude of the MAE from imagery. However, increasing the speed of visual motion from medium to fast did not result in any additional increase in the MAE.

We also asked whether the relative effects of speed on the MAE from imagery would pattern like those from perception. Indeed both viewing and imagining motion produced a similar rise and then leveling off of the MAE as a function of speed. However, the initial rise was reliably steeper for real visual motion perception than for mental imagery.

General Discussion

We started this paper by asking just how similar the representations generated in the service of mental imagery are to those generated during actual visual perception. We indeed found evidence of considerable overlap. First we replicated previous work showing that simply imagining motion is sufficient to produce a motion aftereffect illusion. This suggests that perception and mental imagery recruit, at least in part, the same direction-selective neural mechanisms in the visual system (Dils & Boroditksy, 2010; Winawer, Huk, & Boroditsky, 2008). Further, we found that visual motion speed modulates the MAE from both perception and imagery. The relative shape of the effect of speed is similar for internally- and externally-generated visual motion. This pattern suggests that the mechanisms recruited by both perception and mental imagery are in fact speed-specific.

However, we have also identified some key differences between visual motion processing and mental imagery. The effects of imagining motion on subsequent visual perception are considerably smaller overall than those from viewing real motion. Moreover, increasing visual motion speed produces a disproportionately smaller increase in the MAE from imagery relative to perception before it levels off. These findings call for a more nuanced view of how and when the processes that underlie mental imagery and perception interact, and when they diverge.

This work replicates and extends previous findings on the motion aftereffect from mental imagery (Dils & Boroditsky, 2010; Winawer et al., 2008). The present findings help to rule out concerns that the MAE from internally-generated motion results from a high-level cognitive bias and not from direction-selective adaptation of visual mechanisms. Cognitive bias should not depend on metric visual properties such as speed. Even if there were reason to predict such a relationship, it seems unlikely that it would lead to the specific pattern of results we observed. After all, we found that the very fastest imagined motion condition did not produce the largest MAE. Conversely, the real visual motion study provided a useful set of predictions about how speed should modulate the MAE from imagery.

While our findings suggest that speed is a feature of real-world visual motion that is preserved in mental imagery, it may be the case that our participants were particularly likely to create speed-specific mental images simply because it was one of the few differentiating features of our motion stimuli. Had our speed manipulation been subtler, perhaps we would not have seen it modulate the MAE from mental imagery. Future work aims to address whether features of visual motion such as speed, contrast, and spatial frequency creep into mental images automatically and irrespective of context, or whether they are represented in a more context-specific way.

A further set of questions concerns speed represented in linguistic descriptions of motion. If we hear about a train racing versus crawling through the desert, do the resulting mental images contain some of the implied speed information? In previous work, it has been shown that speed implied in linguistic passages can have consequences for cognitive processing. For example, Matlock (2004) demonstrated that people are faster to process sentences describing fictive motion (e.g., *The highway runs through the valley*) after reading a story that describes fast motion compared to a story that describes slow motion. Future work can examine whether differences in the speed of implied motion described in language can also have *visual* consequences (e.g., in the size of the MAE) in addition to the speed of processing effects discovered by Matlock (2004).

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