Visual motion aftereffect from understanding motion language

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Do people spontaneously form visual mental images when understanding language, and if so, how truly visual are these representations? We test whether processing linguistic descriptions of motion produces sufficiently vivid mental images to cause direction-selective motion adaptation in the visual system (i.e., cause a motion aftereffect illusion). We tested for motion aftereffects (MAEs) following explicit motion imagery, and after processing literal or metaphorical motion language (without instructions to imagine). Intentionally imagining motion produced reliable MAEs. The aftereffect from processing motion language gained strength as people heard more and more of a story (participants heard motion stories in four installments, with a test after each). For the last two story installments, motion language produced reliable MAEs across participants. Individuals differed in how early in the story this effect appeared, and this difference was predicted by the strength of an individual's MAE from imagining motion. Strong imagers (participants who showed the largest MAEs from imagining motion) were more likely to show an MAE in the course of understanding motion language than were weak imagers. The results demonstrate that processing language can spontaneously create sufficiently vivid mental images to produce direction-selective adaptation in the visual system. The timecourse of adaptation suggests that individuals may differ in how efficiently they recruit visual mechanisms in the service of language understanding. Further, the results reveal an intriguing link between the vividness of mental imagery and the nature of the processes and representations involved in language understanding.

imagery | language comprehension | embodiment | individual differences | perception

A good story can draw you in, conjure up a rich visual world, give you goose-bumps, or even make you feel like you were really there. To what extent is hearing a story about something similar to really witnessing it? What is the nature of the representations that arise in the course of normal language processing? Do people spontaneously form visual mental images when understanding language, and if so how truly visual are these representations? In this paper, we make use of the motion aftereffect illusion to test whether processing linguistic descriptions of motion produces sufficiently vivid mental images to cause direction-selective adaptation in the visual system (i.e., cause a motion aftereffect).

A number of findings suggest that people do spontaneously engage in imagery during language comprehension, and that processing language affects performance in subsequent perceptual tasks (1–9).

What mechanism might underlie these interactions between linguistic processing and perception? The explanation frequently offered is that the representations generated during the course of language comprehension share processing resources with perception, recruiting some of the very same brain regions (10). As evidence for this possibility, neuroimaging [functional MRI (fMRI)] measures have revealed that classically "perceptual" brain areas are recruited in service of language comprehension (11). Although these findings are consistent with the hypothesis, questions remain. The spatial resolution of current fMRI technology is coarse. A typical voxel (the smallest unit of measurement) may include a few million neurons (12, 13). It is possible, then, that what appear in fMRI to be the same regions activated in linguistic and visual tasks are in fact neighboring (or closely interleaved) but distinct neural populations, potentially with quite different computational properties.

One powerful paradigm for determining whether neural populations involved in particular tasks indeed overlap is that of adaptation. In this paper, we make use of one such adaptation measure, the motion aftereffect (MAE). The MAE arises when direction-selective neurons in the human MT+ complex lower their firing rate as a function of adapting to motion in their preferred direction. The net difference in the firing rate of neurons selective for the direction of the adapting stimulus relative to those selective for the opposite direction of motion produces a motion illusion. For example, after adapting to upward motion, people are more likely to see a stationary stimulus or a field of randomly moving dots as moving downward, and vice versa (14, 15). To quantify the size of the aftereffect, one can parametrically vary the degree of motion coherence in the test display of moving dots (14, 15). The amount of coherence necessary to null the MAE (i.e., to make people equally likely to report the motion as upward or downward) provides a nice measure of the size of the aftereffect produced by the adapting stimulus.

Winawer et al. (16, 17) adapted this technique to test for MAEs after participants either viewed still images implying motion (e.g., a runner in midleap), or simply imagined motion without any visual stimulus. Both implied and purely imagined motion produced reliable MAEs. These studies support fMRI findings suggesting that the hMT+ complex is recruited in the service of mental imagery (18, 19), and further suggest that this activation is driven by direction-selective neurons.

Here we explore whether natural language comprehension can likewise produce MAEs. To the extent that people spontaneously engage in imagery while comprehending language, understanding motion language should yield MAEs (albeit likely weaker than those produced during explicit, effortful imagery). The present study was designed to test this prediction. Participants listened to stories describing motion in a particular direction and then judged the direction of a moving field of dots. The direction in which motion language affects subsequent motion perception speaks to the mechanisms underlying language comprehension. One possibility is that motion language adapts the same direction-selective mechanisms that subserve motion perception; this would cause people to see a real visual stimulus (e.g., moving dots) as moving in a direction *opposite* to that described in the adapting language. Another possibility is that understanding motion language recruits higher-level convergence areas that process visual motion, resulting in a bias to see dot motion in the *same* direction. Previous work has shown such a congruence effect in that hearing the

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words “right” and “left” biased participants to see an apparent motion stimulus as moving in the same direction (20). fMRI data revealed that this audiovisual interaction was driven more by activity in the anterior intraparietal sulcus than in hMT+. A third possibility is, of course, that motion language does not recruit visual motion processing resources of any kind, resulting in no bias in dot motion perception.

The MAE from real visual motion appears after prolonged exposure to motion in a particular direction and builds as the duration of the adapting stimulus increases (21). If language comprehension recruits the direction-selective mechanism in a similar manner, the MAE from linguistic descriptions of motion should build as people hear more of a story. As a result, we present each story as one long initial paragraph followed by three further sections that continue the story, so as to measure the aftereffect at several points throughout each story (we refer to the initial paragraph and these further sections as story “installments”).

Furthermore, the direction and extent of transfer from language to perception may depend on an individual’s ability to use visual motion imagery. People differ from one another in mental imagery ability, and these differences correlate with individual differences in spatial tasks and object perception (22). In previous work by Winawer et al., most but not all participants showed MAEs as a function of imagining motion, and the degree of adaptation differed across participants (17). We reasoned that individuals who show stronger adaptation as a result of imagining should be more likely to show adaptation as they are comprehending motion language. It is reasonable to expect that individuals who do not show an MAE as a result of explicitly imagining motion should also not show one as a result of processing motion language. To test for this possibility, we tested each participant both in an explicitly instructed visual imagery condition (as in ref. 17), and in conditions in which linguistic motion was used as an adapting stimulus (without instructions to imagine). We could then compare the effects of language for each participant with those of explicit imagery.

Finally, the present study is designed to test whether literal and metaphorical descriptions of motion recruit similar perceptual processes. To this end, we contrasted literal motion stories that described the motion of physical objects with metaphorical motion stories that used motion verbs to talk about changes in abstract entities (e.g., rising and falling stock prices).

Results

Results are plotted in Figs. 1, 2, and 3. In the overall sample, participants showed a reliable MAE after imagining motion (mean = 5.7% normalized coherence, SD = 9.8%) [$F(1,53) = 18.26$, $P < 0.001$; $\eta_p^2 = 0.256$] (as in ref. 17), but not after listening to motion stories (mean = 0.8% normalized coherence, SD = 9.2%) [$F(1,53) = 0.40$, $P > 0.5$]. The literal and metaphorical linguistic motion conditions did not significantly differ from one another [$t(53) = 0.219$, $P > 0.5$] and so were combined for analysis. The explicit imagery condition differed reliably from the linguistic motion conditions [$F(1,53) = 10.81$, $P < 0.005$; $\eta_p^2 = 0.169$].

To examine the timecourse of the MAE from imagined and linguistic motion, we subtracted the proportion of “down” responses following upward motion from those following downward motion across adaptation installments (e.g., the four installments of a story, or the analogous four imagery installments). The mean difference by installment across all participants is plotted in Fig. 1. In the explicit imagery trials, the MAE appears after the initial 40-s installment of imagining (as would the MAE from real visual motion), and participants remain adapted for subsequent installments [there is no linear effect of installment; $F(1,53) = 0.076$, $P > 0.5$]. In the two language conditions, however, the MAE does not appear after hearing the initial installment, but emerges over the following three installments [there is a reliable linear effect of installment; $F(1,53) = 6.59$, $P < 0.05$]. After the third and fourth story installments, the motion aftereffect is reliable across all participants [mean = 4.0%, SD = 12.7%; $F(1,53) = 5.42$, $P < 0.05$]. Motion language appears to produce a reliable MAE, but only after sufficient exposure to each story.

Next, we tested for individual differences in the effects of language on visual processing. We reasoned that individuals who do not show MAEs as a result of explicitly imagining motion should also not show MAEs as a result of processing motion language. However, participants who do show strong MAEs from motion imagery should show MAEs from processing motion language as well. Indeed, there was a significant correlation between the effects of motion imagery and motion language [$r(52) = 0.34$, $P < 0.02$], such that stronger adaptation from imagining motion predicted stronger adaptation from understanding motion language (Fig. 2).

To confirm that participants who showed adaptation to imagined motion also showed it in response to linguistic motion (pooling across all story installments), we sorted participants based on the magnitude and sign of the MAE due to explicit motion imagery and divided them into three groups of equal size

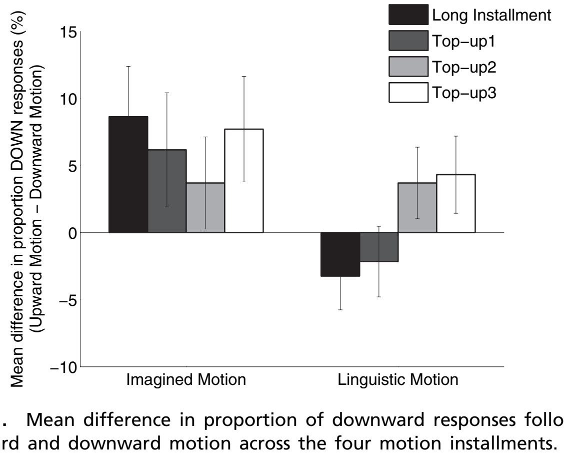

Fig. 1. Mean difference in proportion of downward responses following upward and downward motion across the four motion installments. Data are plotted for the overall sample. Positive values reflect adaptation; error bars denote SEM.

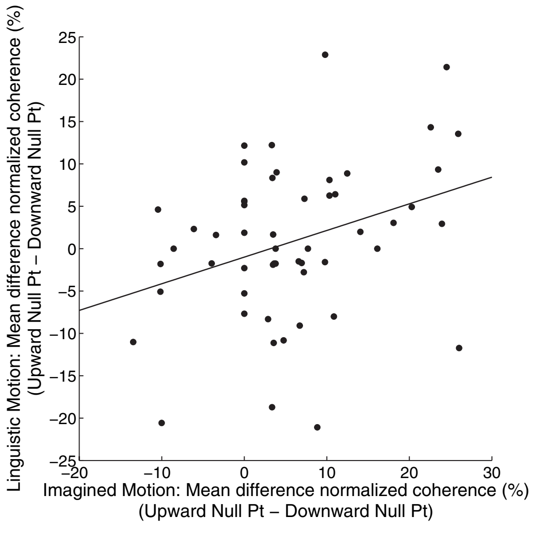

Fig. 2. Correlation across all participants between the separation in motion response functions for imagined and linguistic motion, $r(52) = 0.34$, $P < 0.02$. Positive values reflect adaptation.

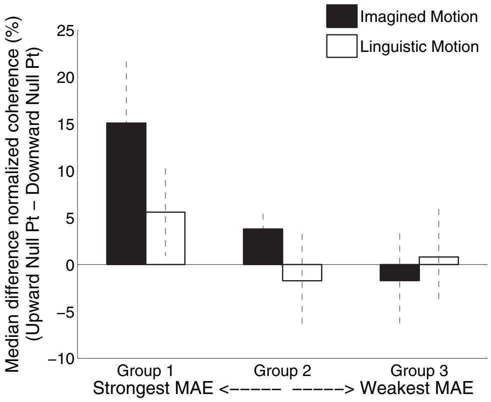

Fig. 3. Participants were divided into three groups of 18 individuals based on the size of the aftereffect in the imagery condition. Plot shows the median separation between motion response functions for each group. Positive values reflect adaptation; error bars denote SIQR.

[Imagery Mdn = 15.1%, 3.8%, −1.7%, and semi-interquartile range (SIQR)* = 6.6%, 1.6%, 5.0% normalized coherence) (Fig. 3). We will refer to these as strong, weak, and no MAE groups, respectively.

Indeed, the group that showed strong MAEs after explicitly imagining motion also showed reliable MAEs after listening to motion language (pooling across all story installments) (Language Mdn = 5.6%, SIQR = 4.7% normalized coherence) (n = 18, $P < 0.031$, sign-test, two-tailed; g = 0.278). There was no difference in the strength of this adaptation effect between the literal and metaphorical language conditions, n = 18, $P > 0.40$. The two groups that showed weak or no MAEs from imagery did not show reliable MAEs from language (when data are pooled across all story installments): (Mdn = −1.7%, SIQR = 5.0% normalized coherence) (n = 18, $P > 0.05$), and (Mdn = 0.8%, SIQR = 5.1%) (n = 18, $P > 0.5$) for groups that showed weak or no MAEs, respectively. The effects of language in the strongest MAE group differed reliably from the other two groups [$\chi^2(1, n = 54) = 7.27$, $P < 0.01$; $\phi = 0.37$].

These findings raise the possibility that individual differences in the MAE from linguistic motion reflect differences in how efficiently people recruit visual direction–selective mechanisms rather than qualitative differences in which mechanisms are recruited. Indeed, the linear effect of story installment does not differ among those who show strong, weak, and no MAEs from motion imagery [$F(2,51) = 0.144$, $P > 0.5$], with everyone showing the same trend toward more adaptation as they get further into the story. Interestingly, the size of the MAE grows within each story but resets when a new story begins, even when the new story is in the same block and therefore describes motion in the same direction as the previous story. That is, although the size of the MAE grows within each story, it does not grow from story to story within a block. The average MAE (pooled across installments within a story) did not differ among the three stories comprising a single block (mean = 0.4%, 1.3%, and 0.3%; SD = 15.2%, 12.2%, and 14.4%) [$F(2,52) = 0.135$, $P > 0.5$]. We return to this observation in the discussion.

Testing for effects of explicit bias. Of the 54 participants included in the analysis, 43 completed an exit questionnaire about their knowledge and predictions about the motion aftereffect (the remaining 11 omitted this portion of the study). Only three reported having heard of the motion aftereffect. Participants' expectations about the direction in which adapting to visual motion in one direction might affect subsequent visual processing did not reliably bias [$F(1,39) = 0.37$, $P > 0.5$] or interact with [$F(1,39) = 0.33$, $P > 0.5$] the effects of imagined and linguistic motion. This finding confirms that the results obtained in this study are not a product of participants' expectations or explicit biases regarding the direction of the effects.

Discussion

We tested whether processing linguistic descriptions of motion produces sufficiently vivid mental images to cause direction-selective motion adaptation in the visual system (i.e., cause a motion aftereffect illusion). We predicted that the perceptual consequences of processing language should depend on an individual's mental imagery ability. Imagery ability was operationalized as the extent to which explicit visual motion imagery produced an MAE in each participant. Put another way, imagery ability or vividness is the extent to which people recruit perceptual resources heavily enough to adapt them during explicit imagery.

We replicated previous work showing that intentionally imagining motion produces a motion aftereffect. We then found that after enough exposure to a story, participants show this aftereffect in the natural course of processing motion language (without instructions to imagine). Specifically, the aftereffect from language gained strength with the number of story installments. For the last two (of four) installments, understanding motion language produced reliable MAEs. Furthermore, we found that participants who show the imagined motion aftereffect most strongly also show this aftereffect for the overall story and not just the last two installments. The same effects held for both literal and metaphorical language. Individuals who did not show a motion aftereffect as a result of imagining motion also did not show an aftereffect from processing motion language overall. This finding suggests the possibility that individuals may differ in how efficiently they recruit visual mechanisms in service of language comprehension. Future work will examine the effects of systematically varying exposure to motion language and the degree of story immersion on the MAE. Participants' knowledge of the MAE and their explicit predictions about the direction of the MAE did not predict their pattern of results. This helps us to ensure that the patterns observed were not simply due to participants' explicit biases or expectations.

One interesting question regarding the linguistic stimuli used in the present study is whether the spatial meanings of individual words themselves produce the MAE, or whether the MAE results from meaning that emerges at the narrative level. Previous research has found evidence for transfer effects to spatial processing both from individual lexical items (2) and from meaning that emerges at the sentence or paragraph level (4, 7). Although the stimuli used in the present study were not designed to distinguish between these possibilities, the data do suggest that the effects emerge as people get more involved in a particular narrative. If the results were driven by individual lexical items, the MAE would have built up over the course of each block as participants heard more and more spatial words. Instead, the MAE built up across installments of a particular story and then reset considerably at the beginning of the next story. This conceptual "resetting" result has precedent in other story understanding work. For example, in a study by Rinck and Bower (4), participants show a similar resetting when there is a large shift in story time; the cognitive availability of previous story-relevant spatial information is erased if the main character is said to have stopped to talk on the phone for 2 hours (as opposed to 2 minutes).

A further question concerns the effects from metaphorical motion language. Some researchers have found that literal and

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*SIQR is a measure of dispersion that is similar numerically to standard deviation but is more robust to outliers. These properties make SIQR a good measure of spread for skewed distributions (in cases where one would use a median rather than a mean). The SIQR is computed as half the difference between the 75th percentile and the 25th percentile.

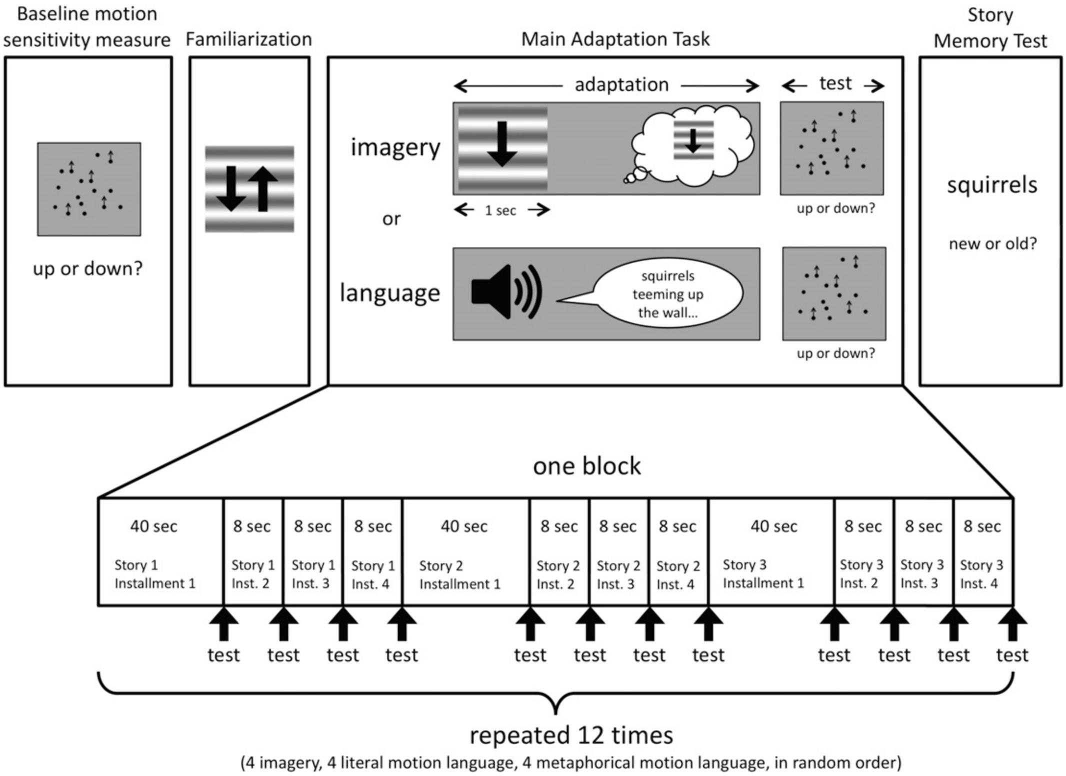

Fig. 4. Schematic of experimental design. Participants first completed a baseline motion sensitivity test, were then familiarized with the moving gratings that they would be instructed to imagine later in the study, and then completed the main adaptation task, followed by a memory test. Block and trial structure of the main adaptation task are depicted. In the imagery blocks, 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 1 s. 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. In language blocks, participants listened to stories using headphones while fixating on a dot centered on the monitor. Participants were told to listen carefully to the stories, as there would be a memory test. They were not instructed to imagine. In each language block, participants heard three stories. Each story came in four installments (one long initial installment, followed by three shorter installments). A moving-dots test followed each installment. Imagery blocks had the same temporal structure, but no stories (only instructions to imagine as described above).

metaphorical language produce similar transfer effects to perceptuo-motor tasks (3, 23, 24), whereas others have found no evidence for transfer from metaphorical language (1). In our study, literal and metaphorical motion language produced the same effects. Our stimuli and methods differ from previous studies in many ways. One potentially important difference is that our stimuli were connected narratives that built over time, whereas the studies just cited used isolated sentences. Our results suggest that for language processing to produce effects on low-level visual processing, a greater amount of exposure to or immersion in a connected narrative may be necessary.

The results of the present study demonstrate that once people are deep enough into a particular story, processing language can spontaneously create sufficiently vivid mental images to produce direction-selective adaptation in the visual system. The findings support a view of cognition in which language comprehension is intimately linked to and dynamically interacts with perception and action. Within this embodied cognition framework, higher-level cognitive processing is grounded in an individual's perceptuo-motor system and their unique interactions with the environment, so variability across individuals becomes an important signal to explain. Future work will examine the source and possible cognitive consequences of the individual differences we observed. Why might some people be better able to recruit or effectively modulate the activity of sensory neurons through top-down processes? Furthermore, are there resulting systematic differences in the content and nature of representations that people form in the service of understanding language?

Methods

Participants. Sixty Stanford University students participated in exchange for payment.

Materials and Design. The experiment consisted of five parts in the following order: (*i*) a baseline task in which we measured participants' motion direction sensitivity; (*ii*) a familiarization task in which participants viewed the stimuli to be imagined later in the study; (*iii*) the main experimental task, in which we tested for MAEs following imagining motion or listening to stories describing motion; (*iv*) a memory task in which we measured participants' recognition memory for the stories; and (*v*) an exit questionnaire in which we ascertained participants knowledge of the motion aftereffect and their explicit predictions about the direction of effects. Details of the stimuli and procedure used in all of the ancillary tasks (baseline, familiarization, memory) are described in *SI Text*.

Main Experimental Task. The task design, procedure, and visual stimuli used were modeled on those used by Winawer et al. (17). On each trial participants judged the direction of dot motion after either listening to stories describing motion or engaging in explicit visual motion imagery. Story and imagery trials were presented in 12 interleaved blocks. There were six block types presented to each participant, 3 (motion type: imagined motion, literal motion, or metaphorical motion) by 2 (motion direction: upward or downward).

Adaptation Stimuli. In the literal motion condition the stories used motion language to describe the movement of physical objects (e.g., squirrels, pingpong balls). In the metaphorical motion condition, the stories used motion language to describe changes in abstract entities (e.g., stock prices, emotions). A total of 12 literal and 12 metaphorical stories were used, with an upward and a downward version for each, yielding a total of 48 stories. Individual participants heard 24 stories (either the upward or the downward version of each story, but not both). Example stories are summarized in Table S1. In the imagery condition, participants were instructed to imagine upward and downward moving gratings (17) (*SI Text*).

Block Structure. In the two language conditions, each block consisted of three stories with four installments each, for a total of 12 trials per block. Each story was broken up into one longer paragraph and three shorter "top-up" installments so that multiple measurements could be collected for each story. The longer installments lasted on average 40.00 s, and the top-up installments 8.29 s. The imagery blocks mirrored this structure. Participants imagined motion for 40 s, and on the three subsequent "top-up" trials, participants imagined motion for 8 s. This pattern was repeated two more times within the block to parallel the three stories used per block in the language conditions. A trial is defined as a single presentation of the adapting stimulus (either language or imagery) followed by a single presentation of moving dots. The trial and block structures for the language and imagery conditions are depicted in a diagram in Fig. 4.

Adaptation Test. Following each story or imagery installment, participants judged the direction of motion coherence in a field of moving dots without feedback. The moving dot stimuli were presented as described for the baseline task in *SI Text*. Each dot display had net motion coherence either up or down. For each subject, two coherence values were sampled 36 times in each direction: 12.5% and 25% of the coherence necessary for asymptotic performance (as assessed individually for participants in the baseline task). Coherence and direction of motion were fully crossed and balanced across trials and participants.

Exit Questionnaire. At the end of the experiment, we ascertained participants' familiarity with the motion aftereffect and also asked them to generate a prediction about which way they thought the effect would go. Participants were asked, "Have you ever heard of the Motion Aftereffect or Waterfall Illusion?" and "After viewing upward motion, which way would you expect a static image to appear to move?"

Data Analysis. The distance between the null points of the logistic fits for upward and downward motion (normalized coherence values at which participants are equally likely to report upward and downward motion) was computed for both the imagined and linguistic motion conditions for each participant. Positive values reflect adaptation. Data from 54 participants were included in subsequent analyses (inclusion criteria in *SI Text*).

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