Research Article

ASSOCIATION FOR PSYCHOLOGICAL SCIENCE

Psychological Science
22(12) 1535–1542

DOI: 10.1177/0956797611417134
http://pss.sagepub.com
SAGE

Evaluating the Mind's Eye: The Metacognition of Visual Imagery

Joel Pearson[1,2,3], Rosanne L. Rademaker[1,2,4], and Frank Tong[1,2]
[1]Psychology Department, Vanderbilt University; [2]Vanderbilt Vision Research Center, Vanderbilt University; [3]School of Psychology, The University of New South Wales; and [4]Cognitive Neuroscience Department, Maastricht University

Abstract

Can people evaluate phenomenal qualities of internally generated experiences, such as whether a mental image is vivid or detailed? This question exemplifies a problem of metacognition: How well do people know their own thoughts? In the study reported here, participants were instructed to imagine a specific visual pattern and rate its vividness, after which they were presented with an ambiguous rivalry display that consisted of the previously imagined pattern plus an orthogonal pattern. On individual trials, higher ratings of vividness predicted a greater likelihood that the imagined pattern would appear dominant when the participant was subsequently presented with the binocular rivalry display. Off-line self-report questionnaires measuring imagery vividness also predicted individual differences in the strength of imagery bias over the entire study. Perceptual bias due to mental imagery could not be attributed to demand characteristics, as no bias was observed on catch-trial presentations of mock rivalry displays. Our findings provide novel evidence that people have a good metacognitive understanding of their own mental imagery and can reliably evaluate the vividness of single episodes of imagination.

Keywords

mental imagery, visual attention, visual memory, visual perception, cognition, individual differences, metacognition, visual attention, introspection, short-term memory, binocular rivalry, bistable perception, consciousness

Received 11/25/10; Revision accepted 6/8/11

Conscious thoughts are fundamentally private and subjective, yet some types of thoughts are easier to compare or evaluate than others. For example, an individual's perceptions of the immediate environment can be readily compared across the sensory modalities. If information from one modality proves somewhat unreliable, perceptual judgments can be dynamically adjusted in favor of sensory information from the more reliable modality (Ernst & Banks, 2002). The immediacy of perception also allows for people to communicate with others to resolve potential ambiguities (Bahrami et al., 2010), such as when two referees must confer before deciding whether a foul might have occurred.

By contrast, it is much more difficult to assess or to compare internally generated experiences, such as those resulting from mental imagery. For example, suppose that a participant is asked to imagine the appearance of the current president. From a third-person perspective, it would be very difficult to determine the precise details of the participant's mental image, or even to tell whether the participant had truly formed a mental image at all. This gap between first- and third-person perspectives has received considerable attention in the domains of psychology, philosophy, and cognitive neuroscience (Crick & Koch, 2003; Dennett, 1991; Tong, 2003). The highly subjective and volitional nature of imagery may help account for the intriguing and controversial aspects of this research area (Kosslyn, Ganis, & Thompson, 2001; Pylyshyn, 2003).

However, there is another core problem that exists from the first-person perspective of the imaginer. How can the individual know whether or not his or her mental image is accurate, vivid, or detailed, given that the mental image cannot be verified against an external stimulus or directly compared with the subjective experiences of anyone else? For that matter, how would a subject ever come to the decision that a mental image was inaccurate, as this would imply some type of access to a more accurate representation, and if such a representation were available, why would a mental image of that more accurate representation not be formed? This problem pertains to human metacognition (Flavell, 1979), that is, how do people know their own thoughts? There has been growing interest in metacognitive judgments of memory and perceptual decision making (Fleming, Weil, Nagy, Dolan, & Rees, 2010; Kiani &

Corresponding Author:
Joel Pearson, The University of New South Wales, Mathews Building, Sydney 2052, Australia
E-mail: joel@pearsonlab.org

Shadlen, 2009; Song et al., 2011), but little is currently known about the metacognition of mental imagery.

Research has provided a growing body of behavioral and neuroimaging evidence indicating that imagery can indeed be successfully studied from a third-person perspective (Kosslyn et al., 2001; Pearson, Clifford, & Tong, 2008; Tartaglia, Bamert, Mast, & Herzog, 2009). For example, behavioral studies have demonstrated systematic effects of imagery manipulations (e.g., mental-rotation time) as well as causal influences of imagery content on subsequent perceptual or cognitive tasks (Ishai & Sagi, 1995; Pearson et al., 2008; Shepard & Metzler, 1971). Recent neuroimaging studies have shown that by analyzing activity in visual cortex, it is possible to decode which of two visual patterns a person is imagining or retaining in working memory (Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh, 2009; Stokes, Thompson, Cusack, & Duncan, 2009). Studies employing transcranial magnetic stimulation further show that disruption of visual cortical activity can impair imagery-based memory performance (Kosslyn et al., 1999).

By contrast, much less is known about whether people can form accurate metacognitive judgments about their own mental images. At a general level, people seem to have some insight into whether they are reasonably good at forming mental images or not. Since the time of Galton (1880), it has been noted that individuals differ in their self-reports of imagery ability, and such differences have been found to predict both behavioral performance (Kosslyn, Brunn, Cave, & Wallach, 1984; Mast & Kosslyn, 2002) and brain-activity levels during mental-imagery tasks (Amedi, Malach, & Pascual-Leone, 2005; Baddeley & Andrade, 2000; Cui, Jeter, Yang, Montague, & Eagleman, 2007). However, it remains to be determined whether people have accurate metacognitive knowledge at a fine-grained scale, regarding specific instances of imagery. For example, can subjects readily determine how vivid their mental images are on a particular occasion? Might repeated attempts to form a particular visual image lead to varying degrees of success with each try?

To address whether people have accurate metacognition of specific instances of imagery, researchers must be able to measure the effects of imagery on a trial-by-trial basis. In a previous study, we demonstrated that sustained imagery can bias the perception of an ambiguous display presented several seconds afterward, with reliable bias effects occurring on a considerable proportion of individual trials (Pearson et al., 2008). This study capitalized on a visual phenomenon called *binocular rivalry*: When two different patterns are presented one to each eye, one pattern reaches awareness while the other is suppressed. We found that longer periods of imagery led to stronger bias effects, and these effects were highly specific to the orientation and location of the imagined pattern. Catch-trial presentations of mock rivalry displays revealed no such bias, ruling out the possibility of demand characteristics (Pylyshyn, 2003). Thus, our previous study provided compelling evidence that imagery can have a pronounced and visually specific impact on subsequent perception and likely depends on processing in early cortical visual areas (Slotnick, 2008).

The goal of the current study was to investigate whether subjects might have accurate metacognitive knowledge of their imagery performance. This was assessed in two ways. First, we obtained subjective ratings of visual-imagery ability using an off-line questionnaire (the revised version of the Vividness of Visual Imagery Questionnaire, or VVIQ2; Marks, 1973, 1995). These off-line ratings allowed us to test whether individual differences in self-reported imagery vividness might predict the extent to which an individual's mental imagery could influence the subsequent perception of rivalry displays. Second, we obtained on-line ratings of imagery vividness during the experiment itself. These data allowed us to test whether these on-line ratings of vividness were predictive of the impact of imagery on a trial-by-trial basis. We further compared the facilitatory effects of imagining an oriented grating on subsequent perception of rivalry displays with the effects of attending to one of two overlapping gratings on subsequent perception of rivalry displays. This comparison allowed us to examine perceptual-bias effects resulting from mental imagery and visual attention. In both the imagery and attention conditions, mock rivalry catch trials were included to control for potential demand characteristics and decisional bias. The results of this study provide compelling new evidence that subjects have a good metacognitive understanding of their mental imagery and can evaluate the vividness of this imagery in a reliable manner from one moment to the next.

Method

Participants

Participants were 20 undergraduate students from Vanderbilt University. All participants had normal or corrected-to-normal vision, and all provided written informed consent. The Vanderbilt University institutional review board approved the study. The students were reimbursed for their time with course credit.

Materials

Participants completed the VVIQ2 (Marks, 1973, 1995) using paper and pencil. The VVIQ2 asks respondents to imagine real-world objects and rate their vividness on a scale from 1 to 5, with higher ratings indicating greater vividness (Marks, 1995). Visual stimuli for the two rivalry conditions were generated using MATLAB (The MathWorks, Natick, MA) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and were presented on a Sony monitor (resolution of 1024 × 768 pixels; 85-Hz refresh rate). The experiment took place in a darkened room, as previous work has shown that light signals can interfere with imagery generation and storage (Pearson et al., 2008; Sherwood & Pearson, 2010).

A mirror stereoscope was used to present a different pattern to each eye. A bull's-eye fixation point (diameter = 0.8°) was placed in the center of each display to aid binocular convergence. The rivalry stimuli consisted of a green vertical grating and a red horizontal grating, both presented inside of an annulus surrounding the central fixation point (see Fig. 1a). The circular gratings had a Gaussian-shaped luminance profile (maximum luminance = 11 cd/m^2) that faded to black at the stimulus edge (Gaussian σ = 5°), and the sine-wave grating pattern (spatial frequency = 1 cycle/°) had an internal contrast of approximately 70% based on local luminance levels. The spatial phase of each grating was randomized on each presentation. Commission Internationale de l'Eclairage color values of the stimuli were as follows—green: x = 0.293, y = 0.572; red: x = 0.602, y = 0.353. In the feature-based attention condition, a plaid stimulus was constructed by physically combining the green vertical grating and red horizontal grating into a single image, which was presented to both eyes simultaneously. The luminance of each color component in the plaid stimulus was set to 40% of the luminance of the original rivalry gratings, as in previous work (Pearson et al., 2008).

On catch trials, observers were presented with mock rivalry displays that consisted of the same image presented to both eyes (to avoid binocular rivalry and interocular competition). This experimental design allowed us to test for demand characteristics and decisional bias. We used two types of mock rivalry stimuli; one stimulus consisted of a physical blend of the two rivalry patterns to form a plaid-like stimulus. The other mock rivalry stimulus consisted of a piecemeal stimulus containing about half of one grating and half of the other, with a jagged border to separate the two halves. The shape of this jagged border was varied randomly from trial to trial within 2° of spatial distance.

To minimize potential effects of eye dominance, we used perceptual methods to match the relative strength of the rivalry gratings before the start of the experiment. This procedure

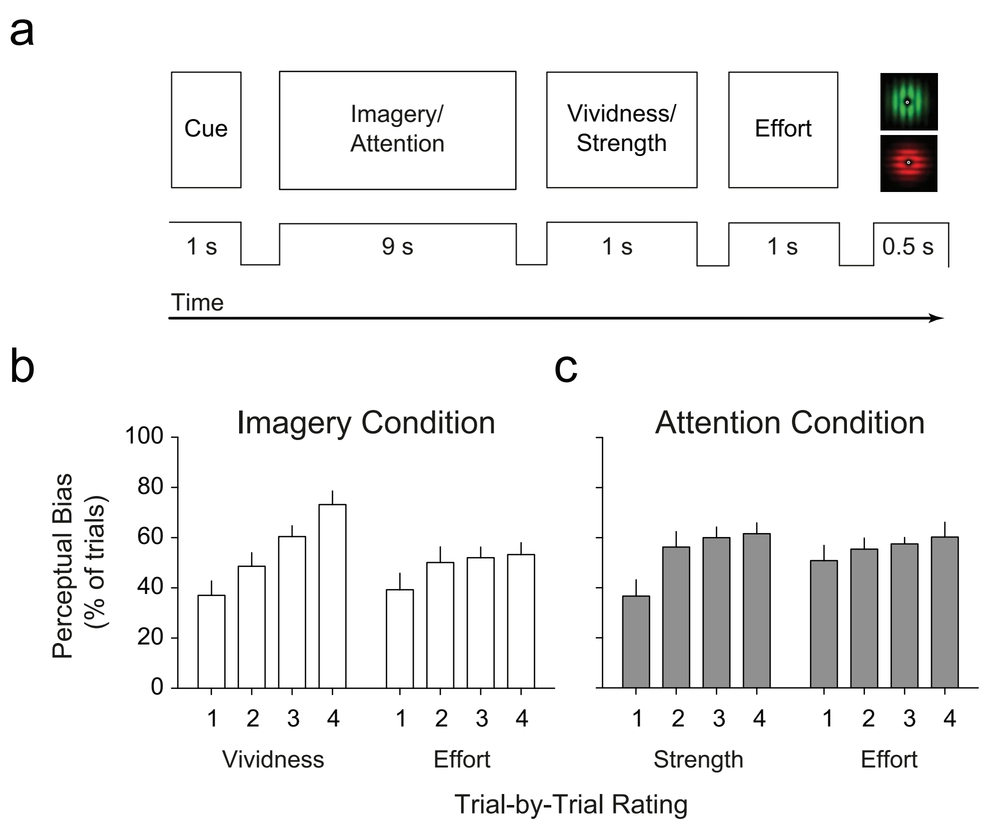

Fig. 1. Sample trial sequence and results from the imagery and attention conditions. In the two conditions (a), participants were presented with a 1-s letter cue ("G" or "R"). In the imagery condition, this cue indicated whether participants should form a mental image of a green vertical grating or a red horizontal grating during the subsequent 9-s period; in the attention condition, this cue indicated whether they should focus their attention on the green vertical component or the red horizontal component of a plaid stimulus shown during the subsequent 9-s period. Participants were then cued either to report the vividness of the imagined item and the degree of effort exerted in imagining it (imagery condition) or to report the perceptual strength of the attended item and the degree of effort exerted to perceive it (attention condition). Next, either a binocular rivalry or a mock rivalry display was presented for 500 ms, and subjects reported whether the red horizontal grating or the green vertical grating was perceptually dominant. For the imagery condition (b), the mean percentage of responses biased in favor of the imagined grating pattern is shown as a function of binned vividness and effort ratings (1= lowest, 4 = highest). For the attention condition (c), the mean percentage of responses biased in favor of the attended grating pattern is shown as a function of binned strength and effort ratings (1= lowest, 4 = highest). Error bars show standard errors of the mean.

involved adjusting the relative contrast of the two gratings to determine the point at which perceptual competition was most balanced and, therefore, most liable to disruption. These methods were the same as those used in our previous research (Pearson et al., 2008).

Procedure

After first completing the VVIQ2 (Marks, 1973, 1995), subjects were seated in a darkened testing room for the behavioral experiment. In the experiment, subjects used a chin rest to view all displays at a distance of 57 cm from a monitor. Observers were instructed to maintain fixation on the central bull's-eye throughout each block of trials while viewing stimuli through the mirror stereoscope.

In the imagery condition, a central cue ("G" or "R") was presented at the beginning of each trial to indicate whether subjects should form a mental image of a green vertical grating or a red horizontal grating, respectively (see Fig. 1a). This was followed by a 9-s imagery period, during which participants were instructed to imagine the appropriate grating. After the completion of the imagery period, participants were first cued to report the vividness of their imagery on that trial by pressing one of four keys (1 = *almost no imagery*, 2 = *some weak imagery*, 3 = *moderate imagery*, 4 = *strong imagery almost like perception*). Following the vividness rating, subjects were cued to report their subjective impression of the effort they expended to form their mental image, again on a scale from 1 to 4 (1 = *almost no effort*, 2 = *some effort*, 3 = *moderate effort*, 4 = *tried very hard to form a mental image*). Subjects were cued with the words "vividness" and "effort," which were presented at the fixation point and accompanied by an audible beep.

Next, observers were presented with either the binocular rivalry display (75% of all trials) or a mock rivalry display (25% of all trials) for 500 ms. On binocular rivalry trials, the green vertical grating was shown to the left eye and the red horizontal grating was shown to the right eye.

Participants pressed one of three assigned buttons on a keyboard to indicate whether they primarily saw the green vertical grating, the red horizontal grating, or an approximately equal mixture of the two as a result of binocular combination or piecemeal rivalry. To minimize potential response conflict, we assigned different sets of keys for mental-imagery ratings and for reports of the rivalry stimuli: Subjects used their left hand to report subjective ratings and their right hand to indicate their dominant perception.

In our previous study, we showed that local feature-based attention can also bias perception of rival stimuli (Pearson et al., 2008). Therefore, in the study reported here, we administered attention trials to assess the impact of feature-based attention on subsequent perception; these trials were administered in separate experimental blocks performed in the same session as the imagery trials. In attention trials, participants were cued to focus their attention on either the green vertical component or the red horizontal component of a compound plaid stimulus, which was presented throughout a 9-s interval (see Fig. 1a). Participants were then required to provide subjective ratings of the vividness or relative strength of the attended grating component, as well as the effort exerted in this task.

Subjects performed two blocks of the imagery condition and two blocks of the attention condition in pseudorandomized order, with 40 trials performed in each block. Ten catch trials occurred at random within each block. Subjects were encouraged to rest between experimental blocks.

Results

On-line ratings of imagery vividness

We hypothesized that if subjects had good metacognitive knowledge of their own mental imagery, then their vividness ratings in the imagery condition (see Procedure) should be highly predictive of the efficacy of that imagery at biasing perception of actual rival stimuli. By contrast, we anticipated that ratings of effort should be a poorer predictor of genuine perceptual bias, because attempts to exert greater effort do not always seem to result in highly effective imagery.

Figure 1b shows the percentage of trials in the imagery condition in which perception of the binocular rivalry display was biased in favor of the imagined grating pattern; results are binned according to the four levels of rated vividness and the four levels of rated effort. A within-subjects analysis of variance yielded a main effect of vividness; on trials in which participants reported greater vividness, they were more likely to see the imagined pattern during the subsequent rivalry display, $F(3, 48) = 10.67$ $p < .001$, $\eta^2 = .4$. For these vividness ratings, there was a clear linear trend, $F(1, 16) = 28.59$ $p < .001$, $\eta^2 = .64$, suggesting that the degree of vividness might be associated with the subsequent perceptual effect. (Note that data from 3 participants were excluded from the trial-by-trial analysis, as they did not use the full spectrum of vividness and effort ratings of 1 to 4. All remaining participants used the entire range of ratings, which was required for performing a within-subjects analysis of the data, sorted by rating level.)

Unlike their ratings of imagery vividness, participants' ratings of effort when performing the imagery task failed to predict their degree of perceptual bias, $F(3, 48) = 0.7$, $p = .5$, $\eta^2 = .04$. We observed a statistically reliable effect of rating type (vividness vs. effort), indicating that vividness ratings were more predictive than effort ratings, $F(1, 16) = 9.97$, $p = .006$, $\eta^2 = .384$. The mean correlation between vividness and effort ratings across all imagery trials for each individual was quite low ($r = .19$, $p = .077$), indicating that these two subjective measures are quite distinct. This pattern of results is interesting because it suggests that the functional effects of mental imagery on actual perception are not well predicted by the self-reports of effort but instead are closely related to subjective impressions of vividness.

In a separate condition, we assessed the impact of feature-based attention on subsequent perception by having participants attend to the green vertical component or red horizontal component of a compound plaid stimulus presented on the screen. Figure 1c shows the extent of perceptual bias in the attention condition; results are binned according to the four rating levels for strength and effort. Higher ratings of the strength of the attended grating were predictive of a greater bias in perception in favor of the attended grating, $F(3, 48) = 5.1$, $p = .004$, $\eta^2 = .241$. However, this result was driven by the significant difference between ratings of 1 and 2 for strength, $t(16) = 3.43$, $p = .003$, as there were no other significant differences between ratings 2, 3, or 4 ($p \geq .65$ for paired t tests). The attention data also showed a significant linear trend, $F(1, 16) = 7.8$, $p = .013$, $\eta^2 = .329$. By comparison, the likelihood of perceptual bias did not vary reliably as a function of the degree of effort in this task, $F(3, 48) = 0.78$, $p = .51$, $\eta^2 = .038$.

Catch trials

We determined whether observers showed response bias in favor of the imagined pattern on catch trials, in which a mock rivalry display was presented. The mock rivalry displays consisted of physical combinations of the two rivalry patterns, with the same image shown to both eyes to preclude binocular rivalry. If demand characteristics or decisional bias were responsible for the bias effects observed during rivalry trials, then one would expect to find the same degree of response bias on catch trials. It is worth noting that the participants were naive to binocular displays, and none reported noticing anything unusual about the way the stimulus looked on some trials relative to other trials. Even if subjects did notice something different about the appearance of the mock displays, this control still provides a valid measure of decisional bias, as the stimuli contained balanced portions of the two grating components.

Figure 2 shows individual data for all 20 subjects, indicating the percentage of catch trials in which the participant's response was biased in favor of the imagined grating. In this analysis, the veridical response "mixed" was coded as 50%, a report that matched the cued imagined grating was coded as 100%, and a report opposite to the imagined pattern was coded as 0%. Averaged across all subjects, the mean percentage of bias was 50.2%, which is negligible. This finding suggests that the introspective data reported here are related to imagery's effect on perception. If demand characteristics or decisional bias were responsible for the bias effects observed during rivalry, one would expect to find the same degree of response bias on catch trials.

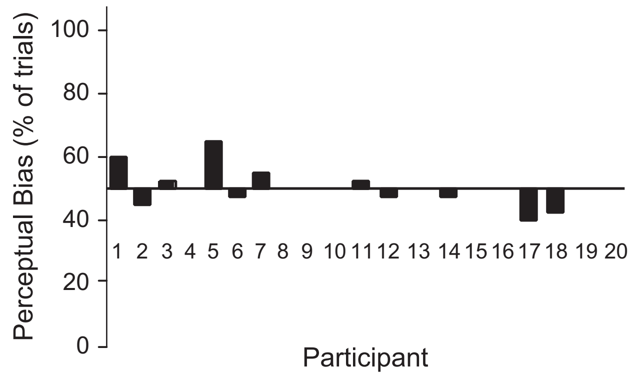

Fig. 2. Mean percentage of catch trials in which the participant's response to the rivalry display was biased in favor of the imagined grating. Each bar shows the results of a single participant. A score of 50% indicates a lack of bias.

Off-line ratings of imagery vividness

We investigated whether a subject's score on the VVIQ2 would relate on average to the degree that imagery biased subsequent perception of rivalry. As Figure 3 shows, there was a statistically significant positive correlation between questionnaire scores and individual measures of imagery bias, $r(18) = .73$, $p < .001$. In other words, individual participants who reported having generally more vivid mental imagery on the questionnaire also showed an overall stronger influence of imagery on the subsequent perception of rivalry stimuli. The reliable relationship found between these two very different measures (one perceptual, one a questionnaire) provides evidence to suggest that both measures could serve as useful indices to assess individual differences in imagery vividness.

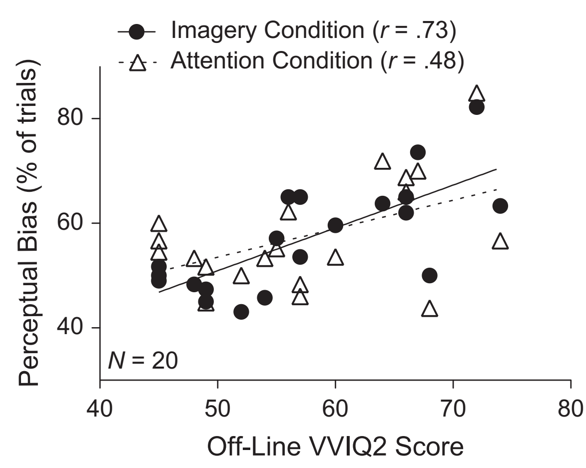

Fig. 3. Relationship between individual questionnaire scores for imagery vividness and overall perceptual bias in the imagery and attention conditions. This scatter plot (with best-fitting regression lines) shows perceptual bias in favor of the imagined or attended grating (i.e., percentage of trials in which that grating was reported as dominant in the rivalry display) as a function of score on the revised version of the Vividness of Visual Imagery Questionnaire (VVIQ2; Marks, 1973, 1995). The correlation between bias and VVIQ2 score is shown for each condition.

Visual attention can strongly influence the perception of briefly presented rivalry displays (Chong & Blake, 2006; Mitchell, Stoner, & Reynolds, 2004; Pearson et al., 2008). Hence, we wondered whether the effect of visual attention on subsequent rivalry perception would also correlate with individual scores on the VVIQ2. As Figure 3 shows, there was some correlation between the bias effects due to visual attention and VVIQ2 scores, $r(18) = .48$, $p = .03$, although it is less than the correlation between the imagery task and VVIQ2 scores, $r(18) = .73$, $p < .001$. It is important to note that these two r values are significantly different from each other, $t(17) = 2.13$; $p < .05$ (Williams t test between nonindependent r values), indicating that VVIQ2 scores provided a better prediction of imagery bias than of attentional bias in this study. Although self-reported vivid imagers may exhibit an advantage in their attentional abilities, the difference in correlation strength found here adds to the evidence that visual attention and imagery rely on somewhat separable mechanisms (Pearson et al., 2008). Despite the fact that individual differences in imagery and attentional bias were highly correlated, $r(18) = .78$, $p < .01$, we found that VVIQ2 scores still provided a better prediction of imagery bias than of attentional bias.

Discussion

In the study reported here, we demonstrated that the vividness of mental imagery can predict the perceptual consequences of that imagery. When an image in the mind's eye was judged as more clear and vivid, it had a reliably greater impact on subsequent perception. Metacognitive judgments not only predicted trial-by-trial variations in the impact of imagery on perception, but offline subjective reports on the VVIQ2 also predicted individual differences in the strength of imagery bias. Together, these results indicate that participants not only had good metacognitive knowledge of their overall imagery ability, but that they could also evaluate the vividness of individual episodes of imagery.

Why might such metacognitive knowledge be important and useful, and how might accurate metacognitive evaluations be achieved? How would an individual determine whether or not a mental image is vivid or detailed, given that the mental image cannot be verified against an external stimulus? One proposal is that mental imagery involves the top-down activation of perceptual representations in visual cortex, based on information stored in short- or long-term memory (Kosslyn, Thompson, & Ganis, 2006). These activated perceptual representations can, in turn, be compared with the representations stored in memory, thereby allowing for on-line adjustments of imagery (cf. Baddeley & Andrade, 2000). Evaluations of the vividness of imagery could reflect the extent to which perceptual representations are activated in visual cortex. Consistent with this notion, recent neuroimaging results have shown that individual differences in subjective ratings of imagery vividness are predictive of individual activation levels in visual cortex during imagery (Amedi et al., 2005; Cui et al., 2007). Though not currently known, it would be interesting for future studies to investigate whether activity levels in visual cortex also predict trial-by-trial variations in imagery vividness.

Unlike judgments of vividness, assessments of the accuracy of a mental image would require a comparison between memory and the generated image. A higher-level memory representation of a visual object could be used to generate top-down activation of perceptual representations, and the resulting activity patterns could, in turn, be compared with the high-level representations of the target object stored in short- or long-term memory (Baddeley & Andrade, 2000). With this feedback loop, discrepancies between the high-level memory representation of an object and the reactivated perceptual representations might be assessed, allowing for on-line adjustments of the imagery representation as needed.

This supposition of the presumed relationship between mental imagery and memory, though tentative, is consistent with reported interactions between memory performance and imagery performance in many studies (Baddeley & Andrade, 2000; Heuer et al., 1986; Reisberg & Leak, 1987), but not in all studies (Lorenz & Neisser, 1985). This relationship also appears to be consistent with recent results demonstrating that activity in primary visual cortex contains item-specific information about objects held in working memory (Harrison & Tong, 2009; Serences et al., 2009). This raises an intriguing question: What would happen if an individual's imagery were highly vivid and lifelike? Might such imagined experiences contribute to the original memory store just like an actual experience? If this interactive system spanning memory and imagery allows for bidirectional influences, then not only would memory affect imagery ability, but also imagery could in turn alter stored memories. Studies of false memory have found that imagined experiences can be confused with real experiences (Gonsalves & Paller, 2000; Loftus, 2003), with repeated acts of imagery leading to increased likelihood of confusion with reality (Goff & Roediger, 1998). Such findings can also be considered examples of impaired metacognitive judgments for source memory, which should be distinguished from the reliable metacognitive knowledge we found for introspective judgments of imagery vividness.

Our study also addresses a controversy regarding whether the subjective experience of imagery is relevant or epiphenomenal to cognitive performance. It has been argued that the phenomenal experience of imagery might be epiphenomenal to a participant's ability to perform tasks such as mental rotation, image scanning, or answering a question, such as whether a German Shepherd's ears are pointed (Pylyshyn, 2003). However, in the study reported here, we found that subjective ratings of imagery vividness were highly predictive of the impact of imagery on conscious perception. Our study ruled out potential concerns of demand characteristics (cf. Pylyshyn, 2003), as the imagery task failed to bias participants' judgments of mock rivalry displays. Our results contradict assertions of epiphenomenality; by considering the participant's phenomenological state during imagery, we can better predict the subsequent impact on perception.

Might introspection into the nature of mental imagery help us to better understand the complex processes that underlie sensory awareness? These processes are typically hidden from introspective understanding. For example, if we look around a room, we may have the impression of becoming immediately aware of the room and its contents, such as the landscape of colors, shapes, and textures formed by many familiar objects. This perceptual analysis seems so effortless and automatic, despite the fact that a multiplicity of hidden brain processes is likely involved. Unlike perception, mental imagery involves more voluntary, effortful processes that seem to allow for greater introspection. Nonetheless, there is growing evidence indicating that imagery and perception involve many common processes and neural circuits. Thus, the study of imagery could provide a back door into the normally hidden introspective realm of sensory perception.

Acknowledgments

We thank Stephen Kosslyn for sharing questionnaires on mental imagery.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

This research was funded by grants from the National Eye Institute of the U.S. National Institutes of Health (NEI R01 EY017082 and NEI R01 EY14202) to F. T. and by National Health and Medical Research Council of Australia CJ Martin Fellowship 457146 to J. P. In addition, this research was facilitated by Grant P30-EY008126 from the National Eye Institute.

References

Amedi, A., Malach, R., & Pascual-Leone, A. (2005). Negative BOLD differentiates visual imagery and perception. *Neuron*, *48*, 859–872.

Baddeley, A., & Andrade, J. (2000). Working memory and the vividness of imagery. *Journal of Experimental Psychology: General*, *129*, 126–145.

Bahrami, B., Olsen, K., Latham, P. E., Roepstorff, A., Rees, G., & Frith, C. D. (2010). Optimally interacting minds. *Science*, *329*, 1081–1085. doi:10.1126/science.1185718

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436.

Chong, S. C., & Blake, R. (2006). Exogenous attention and endogenous attention influence initial dominance in binocular rivalry. *Vision Research*, *46*, 1794–1803.

Crick, F., & Koch, C. (2003). A framework for consciousness. *Nature Neuroscience*, *6*, 119–126.

Cui, X., Jeter, C. B., Yang, D., Montague, P. R., & Eagleman, D. M. (2007). Vividness of mental imagery: Individual variability can be measured objectively. *Vision Research*, *47*, 474–478.

Dennett, D. C. (1991). *Consciousness explained* (1st ed.). Boston, MA: Little, Brown and Co.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*, 429–433. doi:10.1038/415429a

Flavell, J. H. (1979). Metacognition and cognitive monitoring. *American Psychologist*, *34*, 906–911.

Fleming, S. M., Weil, R. S., Nagy, Z., Dolan, R. J., & Rees, G. (2010). Relating introspective accuracy to individual differences in brain structure. *Science*, *329*, 1541–1543. doi:10.1126/science.1191883

Galton, F. (1880). Statistics of mental imagery. *Mind*, *5*, 301–318.

Goff, L. M., & Roediger, H. L., III. (1998). Imagination inflation for action events: Repeated imaginings lead to illusory recollections. *Memory & Cognition*, *26*, 20–33.

Gonsalves, B., & Paller, K. A. (2000). Neural events that underlie remembering something that never happened. *Nature Neuroscience*, *3*, 1316–1321. doi:10.1038/81851

Harrison, S. A., & Tong, F. (2009). Decoding reveals the contents of visual working memory in early visual areas. *Nature*, *458*, 632–635. doi:10.1038/nature07832

Heuer, F., Fischman, D., & Reisberg, D. (1986). Why does vivid imagery hurt colour memory? *Canadian Journal of Psychology*, *40*, 161–175.

Ishai, A., & Sagi, D. (1995). Common mechanisms of visual imagery and perception. *Science*, *268*, 1772–1774.

Kiani, R., & Shadlen, M. N. (2009). Representation of confidence associated with a decision by neurons in the parietal cortex. *Science*, *324*, 759–764. doi:10.1126/science.1169405

Kosslyn, S. M., Brunn, J., Cave, K. R., & Wallach, R. W. (1984). Individual differences in mental imagery ability: A computational analysis. *Cognition*, *18*, 195–243.

Kosslyn, S. M., Ganis, G., & Thompson, W. L. (2001). Neural foundations of imagery. *Nature Reviews Neuroscience*, *2*, 635–642.

Kosslyn, S. M., Pascual-Leone, A., Felician, O., Camposano, S., Keenan, J. P., Thompson, W. L., . . . Alpert, N. M. (1999). The role of area 17 in visual imagery: Convergent evidence from PET and rTMS. *Science*, *284*, 167–170.

Kosslyn, S. M., Thompson, W. L., & Ganis, G. (2006). *The case for mental imagery*. New York, NY: Oxford University Press.

Loftus, E. F. (2003). Make-believe memories. *American Psychologist*, *58*, 867–873. doi:10.1037/0003-066X.58.11.8672003-09329-007

Lorenz, C., & Neisser, U. (1985). Factors of imagery and event recall. *Memory & Cognition*, *13*, 494–500.

Marks, D. F. (1973). Visual imagery differences in the recall of pictures. *British Journal of Psychology*, *64*, 17–24.

Marks, D. F. (1995). New directions for mental imagery research. *Journal of Mental Imagery*, *19*, 153–167.

Mast, F. W., & Kosslyn, S. M. (2002). Visual mental images can be ambiguous: Insights from individual differences in spatial transformation abilities. *Cognition*, *86*, 57–70. doi:S0010027702001373

Mitchell, J. F., Stoner, G. R., & Reynolds, J. H. (2004). Object-based attention determines dominance in binocular rivalry. *Nature*, *429*, 410–413.

Pearson, J., Clifford, C. W., & Tong, F. (2008). The functional impact of mental imagery on conscious perception. *Current Biology*, *18*, 982–986.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.

Pylyshyn, Z. W. (2003). Return of the mental image: Are there really pictures in the brain? *Trends in Cognitive Sciences*, *7*, 113–118.

Reisberg, D., & Leak, S. (1987). Visual imagery and memory for appearance: Does Clark Gable or George C. Scott have bushier eyebrows? *Canadian Journal of Psychology*, *41*, 521–526.

Serences, J. T., Ester, E. F., Vogel, E. K., & Awh, E. (2009). Stimulus-specific delay activity in human primary visual cortex. *Psychological Science*, *20*, 207–214.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*, 701–703.

Sherwood, R., & Pearson, J. (2010). Closing the mind's eye: Incoming luminance signals disrupt visual imagery. *PLoS ONE*, *5*(12), e15217. Retrieved from http://www.plosone.org/article/metrics/info%3Adoi%2F10.1371%2Fjournal.pone.0015217;jsessionid=7AF66CF5F08369D40AE644041C560294.ambra01

Slotnick, S. D. (2008). Imagery: Mental pictures disrupt perceptual rivalry. *Current Biology*, *18*, R603–R605. doi:10.1016/j.cub.2008.06.002

Song, C., Kanai, R., Fleming, S. M., Weil, R. S., Schwarzkopf, D. S., & Rees, G. (2011). Relating inter-individual differences in metacognitive performance on different perceptual tasks. *Consciousness and Cognition*. Advance online publication. doi:10.1016/j.concog.2010.12.011

Stokes, M., Thompson, R., Cusack, R., & Duncan, J. (2009). Top-down activation of shape-specific population codes in visual cortex during mental imagery. *Journal of Neuroscience*, *29*, 1565–1572. doi:10.1523/JNEUROSCI.4657-08.2009

Tartaglia, E. M., Bamert, L., Mast, F. W., & Herzog, M. H. (2009). Human perceptual learning by mental imagery. *Current Biology*, *19*, 2081–2085. doi:10.1016/j.cub.2009.10.060

Tong, F. (2003). Primary visual cortex and visual awareness. *Nature Reviews Neuroscience*, *4*, 219–229.