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Visualizing trumps vision when training attention

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Abstract

Mental imagery can have powerful training effects on behavior, but how this occurs is not well understood. Here we show that even a single instance of mental imagery can improve attentional selection of a target more effectively than actually practicing visual search. By recording subjects' brain activity, we show that these imagery induced training effects were due to perceptual attention being more effectively focused on targets following imagined training. Next, we show the downside of this potent training by changing the target after several trials of training attention with imagery. Finally, we found that proactive interference from task-irrelevant elements in the visual displays appears to underlie the superiority of imagined training compared to actual practice. Our findings demonstrate that visual attention mechanisms can be effectively trained to select target objects in the absence of visual input, and this results in more effective control of attention than practicing the task itself.

Keywords

mental imagery; visual attention; event-related potentials; learning; visual search; perception

Mental imagery has been employed across a wide variety of fields, from psychiatry (Holmes & Mathews, 2010; Simplicio, McInerney, Goodwin, Attenburrow, & Holmes, 2012) and physical therapy (Guillot & Collet, 2005), to music (Zatorre, Chen, & Penhune, 2007; Zatorre & Halpern, 2005) and competitive sports (Morris, Spittle, & Watt, 2005), with the goal of improving performance. It has been hypothesized that imagery has training benefits because it improves motor control (Crammond, 1997), or visuomotor coordination (Binder et al., 2014). However, an untested possibility is that imagery can train perceptual attention early in the course of information processing, resulting in more efficient processing of task-relevant visual input.

Our goal was to determine whether it is possible to improve the focusing of attention early in the stream of visual processing by imagining searching for a certain target object in a scene. Visual search tasks require observers to find and report the identity of target objects embedded in arrays of task-irrelevant distractors, placing particular demands on front-end

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perceptual attention mechanisms (Gilbert & Li, 2013; Wolfe & Horowitz, 2004). We designed a visual search task (Fig. 1a) that allowed us to measure the effects of training visual attention. Subjects searched for the same target object across runs of trials, allowing us to measure the processing of the visual scenes becoming more efficient with practice. We randomly interleaved training in which actual practice trials were replaced with trials in which subjects imagined searching for a particular object. To determine if the effects of imagery were due to changes in perceptual attention, and not late-stage mechanisms like speeding of motor processes, we recorded subjects' event-related potentials (ERPs) elicited during visual search. The N2pc is an early electrophysiological response (see Fig. 1b) that indexes the focusing of attention on target objects in visual search arrays (Woodman & Luck, 2003b). This ERP component measures the selection of attended objects prior to subsequent storage in memory and independent of behavioral responses (Woodman & Luck, 2003a). If imagining searching for a target can improve the focusing of attention on targets in cluttered visual scenes, then we should see these effects with the N2pc hundreds of milliseconds before subjects press a button to report whether the target is present.

Methods

Participants

Different groups of eighteen subjects (18–35 years of age, 62% women) with normal color vision, normal or corrected-to-normal visual acuity, and no reported history of neurological problems volunteered for each experiment. All subjects gave informed consent to procedures approved by the Vanderbilt University Institutional Review Board prior to participation.

The necessary sample size was estimated from a pilot experiment. By conservatively pooling mean differences and standard deviations across the behavioral and electrophysiological responses, we estimated Cohen's d effect size based on paired samples two tailed t -tests (reaction time: $d = 0.54$, N2pc amplitude: $d = 0.65$). We found that a sample size of 18 subjects is sufficient to detect an effect of the same magnitude with 80% power at the $p = 0.05$ significance level.

Stimuli

Stimuli were viewed from 114 cm on a grey background (54.3 cd/m^2). A black fixation cross ($<0.01 \text{ cd/m}^2$, $0.4 \times 0.4^\circ$ of visual angle) was visible throughout each trial. Cue stimuli were presented 2.2° to the left and right of the center of the monitor. The cue array contained one red item ($x = 0.612$, $y = 0.333$, 15.1 cd/m^2) and one green item ($x = 0.281$, $y = 0.593$, 45.3 cd/m^2). Search stimuli were arranged similar to the number locations on a clock face, 4.4° from the center of the monitor. Each search array contained one red, one green, and ten black distractor ($<0.01 \text{ cd/m}^2$) Landolt-C stimuli (0.88° diameter, 0.13° thick, and 0.22° gap width) of eight possible orientations (0° , 22.5° , 45° , 67.5° , 90° , 112.5° , 135° , 157.5°). The task-relevant color (i.e., red or green) of the cue and target Landolt-C was counterbalanced within and across subjects to rule out physical stimulus confounds that would make the lateralized N2pc difficult to measure if the input to the left and right visual field was not balanced (Woodman, 2010).

Procedure

Each trial began with the fixation point presented for 1200–1600 ms, randomly jittered from a rectangular distribution of times. Next, two cue stimuli were presented for 100 ms, followed by a 1000-ms interval. Then, the search array was presented for 2000 ms. The inter-trial interval was 1200–1600 ms, randomly jittered. A target was presented on half of the search arrays (defined as matching the shape and color of the task-relevant cue) and was absent on the other half (the item matching the cue color was of a different shape than the cue). Subjects responded as quickly and accurately as possible to the search array by pressing one button on a handheld gamepad (Logitech Precision) for target present and a different button for target absent, using their right hand.

The cued target shape, target presence (present or absent), and target location when present, were all randomly selected on each trial. Each subject completed 720 trials, except in Experiment 3 where each subject completed 1,080 trials due to the increase in experimental conditions. To examine the impact of imagery on the efficient processing of complex scenes, we capitalized on the phenomenon of attentional tuning becoming more precise across trials as subjects search for the same object (Carlisle, Arita, Pardo, & Woodman, 2011). We repeated the search target for three, five, or seven consecutive trials, with length of run randomized, before changing it to a different object.

Experiment 1 had two types of runs of trials: the stimulus condition and the imagery condition. In the stimulus condition (50% of runs, randomly interleaved with those of the imagery condition), cue and search stimuli were presented on every trial in a run, exactly as described above. This provided a baseline measure of the speed of subjects' attentional tuning. In the mental imagery condition, cue stimuli on the first two trials of a run were accompanied by text instructions to "Visualize Search". Subjects were instructed to generate an array of stimuli in their mind's eye and imagine searching through this array for the cued target object, but the screen remained blank for the same duration as the search array presentation in the stimulus condition. For the remainder of the run (i.e., target repetition 3–7), all stimuli were visually presented, and subjects continued to search for the same object that they imagined searching for during the first two trials.

Experiment 2 was identical to Experiment 1, except that the cued target that subjects imagined searching for during the first two trials of a run was changed to a different shape during the last 5 trials of the run (marked as 1'–5' in Fig. 1c). Similarly, in the stimulus condition, the cued target was changed to a different shape after two trials of each run. This manipulation allowed us to determine if imagining searching for a particular target can create interference when we begin searching for something else and compare the switch costs associated with a change in target identity across stimulus and imagery conditions.

Experiment 3 was identical to Experiment 1 except that there were three imagery conditions in addition to the stimulus condition baseline (each condition comprising 25% of the total runs). The imagery conditions differed by the number of trials of imagining performing a search before actually searching (i.e., either 1, 2, or 3 trials). This manipulation allowed us to parametrically manipulate the number of times subjects imagined performing a search

before performing a search among visual inputs. This allowed us to measure something analogous to the dose-response curve of imagery's effects on attentional deployment.

Experiment 4 was identical to Experiment 1, except that all ten black distractor Landolt-C stimuli in the search array were removed in both the stimulus and imagery conditions. This manipulation allowed us to test the hypothesis that the attentional improvements we observed following visual mental imagery in Experiments 1–3 were due to subjects avoiding the processing of task-irrelevant information while visualizing search.

Experiment 5 was identical to Experiment 1, except that Landolt C cue stimuli were replaced by an arrow, providing a symbolic cue of the direction of the gap in the target Landolt C. This manipulation allowed us to test the hypothesis that the attentional improvements we observed following visual mental imagery were simply due to priming.

Electrophysiology

The electroencephalogram (EEG) was acquired from 21 tin electrodes (250 Hz sampling rate, 0.01–100 Hz band-pass filter, using an SA Instrumentation Amplifier), including 3 midline (Fz, Cz, Pz), 7 lateral pairs (F3/4, C3/4, P3/4, PO3/4, T3/4, T5/6, O1/2), and 2 nonstandard sites (OL, halfway between O1 and T5; and OR, halfway between O2 and T6), arrayed based on the International 10/20 System and embedded in an elastic cap (Electrocap International). The right mastoid electrode served as the online reference, and signals were re-referenced offline to the average of the left and the right mastoids (Nunez & Srinivasan, 2006). The electrooculogram (EOG) was recorded using bipolar electrodes placed 1 cm lateral to the external canthi to measure horizontal eye movements and bipolar electrodes beneath the left eye to measure vertical eye movements and blinks. Trials containing incorrect behavioral responses (see below) or ocular or myogenic artifacts were excluded. A two-step ocular artifact rejection method was implemented (Woodman & Luck, 2003b), resulting in the removal of 2 subjects from Experiments 1 and 3, 1 subject from Experiment 4, and 1 subject from Experiment 5 for excessive eye movements (either > 25% of individual trials rejected or any residual systematic eye movement that resulted in HEOG voltage deflections > 3.2 μ V, corresponding to an ocular deviation of $\pm 0.1^\circ$).

Analysis

The N2pc was measured at lateral occipital electrodes (OL/R) as the mean difference in amplitude between the ipsilateral and contralateral waveforms with respect to the search target during the window 200–300 ms after search array onset, corrected to the baseline –200 to 0 ms prior to search array onset (Woodman & Luck, 1999). The current density of the N2pc was modeled using standard methods previously described (Reinhart et al., 2012). Planned comparisons using two-tailed t-tests were applied to search reaction times (RTs) and N2pc amplitudes between imagery and stimulus conditions. We verified that the same conclusions would be drawn from the RT and N2pc data when analyzed using ANOVAs with the factors of condition (imagery versus stimulus) and target repetitions (3–7) in each experiment. Data were binned by target repetition (i.e., serial position) in each run. However, the last bin consisted of the average of the remaining target repetitions (i.e., trials 5–7 in a run in Experiments 1, 3, 4, and 5, trials 3–5 in Experiment 2). The longest runs

occurred less frequently because each run length was equally likely, insuring that the end of the run was not predictable at the beginning of each run.

Results

Figure 1c shows that in Experiment 1, we found that two trials of imagining performing search (the imagery condition) sped search RTs more than two trials of actually searching for these same targets in visual arrays (the stimulus condition). This imagery effect appeared to drive RTs to floor levels, with subsequent practice performing the search task not resulting in further improvement in the speed of search. These effects resulted in significantly faster RTs at target repetition 3 in the imagery condition, relative to target repetition 1 ($t_{17} = 2.605$, $d = 0.74$, $p = 0.018$), 2 ($t_{17} = 2.318$, $d = 0.61$, $p = 0.033$), and 3 ($t_{17} = 2.326$, $d = 0.61$, $p = 0.033$) in the stimulus condition. We observed no significant differences between conditions thereafter (target repetition 4, $t_{17} = 1.238$, $d = 0.34$, $p = 0.232$; repetitions 5–7, $t_{17} = 1.055$, $d = 0.27$, $p = 0.306$).

These RT effects were not due to a speed-accuracy tradeoff across conditions, as accuracy was universally high (mean 98.3% correct) and did not differ across conditions or target repetitions ($ps > 0.34$). The difference between conditions was also not due to the presence of randomly interleaved target absent trials in the stimulus condition, because when we looked just at target present trials in the stimulus condition (light blue line in Fig. 1c) we observed the same superiority for imagery training. These findings appear to support the conclusion that imagining search does not just improve how rapidly we can focus attention on targets in a future scene, but is more effective at training attention to find these targets than actual practice with visual input. We now turn to the ERPs to provide converging evidence for this counterintuitive conclusion.

If imagery changes how effectively visual attention can be focused on the task-relevant items in the search arrays, then the canonical electrophysiological index of covert visual attention (i.e., the N2pc) should show effects that parallel the improvement in RT. We found that the N2pc component elicited by the objects in the search arrays that matched the cue color showed just this pattern (Fig. 1c, Experiment 1). The amplitude of the N2pc was significantly larger after imagining visual search (i.e., target repetition 3) than following search practice with actual visual stimuli (i.e., target repetition 1, $t_{17} = 2.263$, $d = 0.86$, $p = 0.040$, target repetition 3, $t_{17} = 2.466$, $d = 0.93$, $p = 0.027$). Similar to the pattern of RTs, we observed no significant N2pc differences between conditions after training became strictly visually driven (target repetition 4, $t_{17} = 1.536$, $d = 0.60$, $p = 0.147$; target repetition 5–7, $t_{17} = 0.933$, $d = 0.31$, $p = 0.367$). As expected if the more efficient focusing of perceptual attention propagated to the subsequent behavioral effects of RT, the size of a subject's imagery-induced increase in N2pc amplitude predicted the size of their imagery-induced RT benefit (i.e., measured as the difference between conditions in RT and N2pc to search target repetition 3, $r_{17} = 0.534$, $d = 0.76$, $p = 0.022$). These results demonstrate that mental imagery confers covert visual attention benefits beyond that of perceptual experience performing search. Our measurements of brain activity show that imagery changes how effectively attention can be focused on task-relevant inputs in the visual field when search is later performed.

If imagery can result in such large benefits, then we should be able to observe similarly large costs when subjects imagine searching for one object, but then are required to search for a different object. In Experiment 2, we cued subjects to search for a specific Landolt C (e.g., the gap at 45°) for two trials in both the imagery and stimulus conditions. Then we changed the cued target to a different shape (e.g., the gap at 135°). In the stimulus condition, there was a predictable switch cost associated with searching for a new target (Fig. 1d, blue line, compare target repetition 1 to 1'). Critically, we found that switching the target after the first two trials in the imagery condition led to a significantly larger cost, impairing the ability of subjects to rapidly retune attention to the new target object (Fig. 1d, red line). This was evidenced by slower search RTs in the imagery condition at target repetition 1' ($t_{17} = 2.622$, $d = 0.49$, $p = 0.018$) and 2' ($t_{17} = 3.513$, $d = 0.61$, $p = 0.003$) relative to the stimulus condition. Interestingly, it was not until after two trials of practice searching with visual input that subjects showed recovery from the imagery induced switch cost (i.e., no between condition RT difference in the last target repetition bin 3'–5', $t_{17} = 1.296$, $d = 0.15$, $p = 0.212$). Accuracy was at ceiling across all trials (mean 97.5% correct) with no effects of condition or target repetition ($ps > 0.40$).

We found that the N2pc amplitude again mirrored this pattern of search RTs (Fig. 1d). We found between-condition reductions in N2pc amplitude at target repetition 1' ($t_{17} = 3.302$, $d = 0.73$, $p = 0.004$), but not 2' ($t_{17} = 0.871$, $d = 0.27$, $p = 0.396$) or 3'–5' ($t_{17} = 0.112$, $d = 0.02$, $p = 0.912$). As in Experiment 1, these ERP findings demonstrate that the effects of imagery actually changed how covert visual attention was focused. These results indicate that the potent training with imagery that we observed in Experiment 1 has a downside when the searched-for target changes. The results from Experiment 2 also rule out the explanation that the passage of time itself, not visual imagery, could account for the changes we observed in attentional focus and search efficiency.

In Experiment 3, we sought to determine how far we could push these imagery effects by parametrically manipulating the number of times subjects imagined searching (i.e., 1, 2, or 3 consecutive trials of imagining search) before they actually searched for the target in an array of visual input. We found that when we manipulated the number of times that we instructed subjects to imagine searching, we could systematically speed RTs until they reached apparent floor levels. Figure 1e shows the orderly layering of effects that replicate and extend the findings from Experiment 1. Search RTs were significantly faster after one trial of imagery relative to when the visual stimulus of the array was actually searched (target repetition 2, $t_{17} = 2.588$, $d = 0.35$, $p = 0.019$). Search RTs were even faster after two trials of imagery relative to one (target repetition 3, $t_{17} = 2.161$, $d = 0.29$, $p = 0.045$), but no further improvements were observed after three trials of imagining visual search (target repetition 4, $t_{17} = 0.025$, $d = 0.14$, $p = 0.981$), indicating a lower limit for the imagery-induced attentional benefits in this task as measured with behavior. Accuracy of these responses was at ceiling (mean 97.3% correct across all trials) and did not differ across conditions or target repetitions ($ps > 0.31$).

We found that the changes in N2pc amplitude largely mirrored the changes in RT (Fig. 1e). This observation was evidenced by a comparable dose-response function following imagery measured with subjects' N2pc component (target repetition 2, $t_{17} = 2.536$, $d = 0.55$, $p =$

0.019; target repetition 3, $t_{17} = 2.291$, $d = 0.62$, $p = 0.032$; target repetition 4, $t_{17} = 2.012$, $d = 0.64$, $p = 0.057$). The N2pc measurements suggest that the focusing of covert visual attention may benefit from additional trials of imagery training even after behavioral RT have reached their fastest possible levels (i.e., three trials of imagery practice). These results show that the benefit of training attention with imagery accumulates in strength with each instance of imagery, resulting in responses of sufficient speed that they may no longer be sensitive to the attentional training that continues in the earlier perceptual stage.

It may seem counterintuitive that imagery improved the focusing of visual attention more than actual practice. However, this makes sense if we consider the cognitive demands of processing the search arrays. When practicing the visual search task with visual input, the visual system must process and recognize the distractor objects as nontargets in the array (Woodman & Luck, 1999, 2003b), leaving memory traces that linger in the visual system (Chun, 2000). Processing the task-irrelevant distractors in this way appears to result in proactive interference, in which the representations of the distractors interfere with the guidance of attention to objects with only the target features on subsequent trials. In contrast, when imagining performing the search task, subjects likely minimize or avoid imagining distractors, dedicating virtually all of their mental effort on visualizing the target object. Focusing high-level cognitive processing exclusively on targets should result in a stronger top-down bias toward target objects under theories of attentional control (Desimone & Duncan, 1995), resulting in the N2pc and the behavioral improvements we observed during search following imagery. This idea that performing search with visual input results in proactive interference on subsequent trials can account for why we observed the subjects' RTs and N2pc amplitudes return to the baseline levels of the stimulus condition after a couple of trials of performing search with visual input (i.e., Fig. 1e, target repetitions 5–7).

To directly test this hypothesis, we ran Experiment 4, in which nontarget-distractor items were removed from the search arrays (i.e., the black distractors in Fig. 1a), minimizing the impact of distractor-related proactive interference. If the attentional advantages of imagery training over actual practice were due to less proactive interference from task-irrelevant information during imagery, then removing distractor objects from the search arrays should enhance the training benefits of perceptual experience. In addition, removing this source of proactive interference should eliminate the difference in training benefits between mental imagery and perception. Consistent with the first prediction, we found that RTs were faster in the stimulus condition of Experiment 4 relative to the stimulus condition of Experiment 1 where distractors were included (compare blue lines in Fig. 1c and 1f, target repetitions 1–7, $t_{17} = 3.294$, $d = 0.21$, $p = 0.004$). Consistent with the second prediction of the proactive interference account, the improvement in search efficiency following training with distractor-free visual input was comparable to the search efficiency following training with mental imagery, evidenced by no between-condition RT differences (target repetition 3, $t_{17} = 0.761$, $d = 0.23$, $p = 0.460$; target repetition 4, $t_{17} = 0.441$, $d = 0.15$, $p = 0.666$; target repetition 5–7, $t_{17} = 0.567$, $d = 0.21$, $p = 0.580$). The N2pc was modulated in a similar fashion (Fig. 1f). There were no N2pc amplitude differences between the distractor-free imagery and stimulus conditions from Experiment 4 (target repetition 3, $t_{17} = 0.155$, $d =$

0.05, $p = 0.879$; target repetition 4, $t_{17} = 0.428$, $d = 0.17$, $p = 0.676$; target repetition 5–7, $t_{17} = 0.319$, $d = 0.08$, $p = 0.703$).

The results from Experiment 4 indicate that the superior training effects of mental imagery on the focusing of visual attention arise because subjects minimize processing of task-irrelevant information during mental imagery. This results in stronger top-down control of visual attention because the memory representations that guide attention are relatively uncontaminated by proactive interference from the memory traces of the distractors. This interpretation converges with work from a different research domain. A recent study using a complex motor task showed that imagining performing data entry led to less forgetting and more positive transfer of learning than did physical practice, and argued that imagined practice does not suffer from proactive interference, unlike physical practice (Wohldmann, Healy, & Bourne, 2008). Here we are proposing that the distractors are resulting in interference in the stimulus condition that prevents the learning effects across same-target runs from being even larger, as in the imagery condition. However, it might be more accurate to say that imagery reduces or eliminates concurrent interference between imagined distractors and the imagined target. Reductions in concurrent interference might then lead to a stronger top-down bias toward subsequently processed target objects.

Finally, we determined whether repetition priming, rather than imagery, could explain the effects from the imagery condition on attention that we observed across experiments. In Experiment 5, all Landolt-C cues were replaced by arrows indicating the gap direction on the search targets. If cue-induced priming was the source of the attentional and behavioral improvements following imagery, then removing the visual stimulus of the target prior to search should eliminate these effects. Contrary to this hypothesis, Figure 1g shows that even with symbolic arrow cues, the focusing of attention and behavior were enhanced after two trials of imagining search, compared with two trials of performing search with visual input. Specifically, RTs were faster on target repetition 3 of the imagery condition relative to target repetition 1 ($t_{17} = 2.986$, $d = 0.82$, $p = 0.008$), 2 ($t_{17} = 2.639$, $d = 0.68$, $p = 0.017$), and 3 ($t_{17} = 2.320$, $d = 0.64$, $p = 0.033$) of the stimulus condition, and the N2pc amplitude showed a similar pattern of results (target repetition 1, $t_{17} = 2.201$, $d = 0.80$, $p = 0.042$, target repetition 3, $t_{17} = 2.206$, $d = 0.73$, $p = 0.041$). These findings rule out a priming explanation for the effects we interpreted as due to imagery.

Discussion

Brain training has become a major topic of study and investment. A central question in research focused on using mental imagery to remediate clinical symptoms, speed recovery from physical injuries, and more generally optimize performance and promote learning, has been how mental imagery training changes information processing in the brain (Guillot & Collet, 2005; Holmes & Mathews, 2010; Schack & Bar-Eli, 2007; Schack & Hackfort, 2007; Simplicio et al., 2012). In addition, there is an increasingly intense interest in using computer-based training programs to improve cognitive processing in the general population. These brain-training programs involve having customers practice games, like those used in the present study, with the goal of improving attention and memory. The findings of this study suggest that improvements of attention may be most effectively trained

using imagery, without actually performing the task that one hopes to optimally perform. Imagery-based training appears to result in superior learning because it avoids the interfering effects from the memories for the task-irrelevant information during the actual performance of such tasks.

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Fig. 1.

Basic paradigm and results from Experiments 1–5. a, In Experiment 1, the task-relevant cue (red or green Landolt C) signaled the shape of the target in the upcoming search array. The target was repeated across 3–7 trials (or target repetitions). Central fixation was maintained for the trial duration. In the stimulus condition, all stimuli in the runs of trials were externally presented. In the imagery condition (illustrated here), subjects were instructed to visualize search through an imaginary array of stimuli with the given task-relevant object across the first two target repetitions in a run. After visualization, subjects completed the run of trials with externally presented stimuli. b, The N2pc time locked to the onset of the search array from the third trial in the imagery condition (red waveform from the electrode contralateral to the target and black waveform is from the ipsilateral electrode), the analysis window shaded in grey and the inset shows the current distribution from this window. Mean search reaction times (RTs) and N2pc amplitudes are shown for the stimulus and imagery conditions across target repetitions for Experiment 1, light blue lines show just target present trials in the stimulus condition (c), Experiment 2, 1 prime denotes the presentation of the second new target in the 7-trial run (d), Experiment 3 (e), Experiment 4 (f), and Experiment 5 (g). Error bars are ± 1 standard error of the mean.