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Visualizing Trumps Vision in 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 found that these imagery-induced training effects were due to perceptual attention being more effectively focused on targets following imagined training. Next, we examined the downside of this potent training by changing the target after several trials of training attention with imagery and found that imagined search resulted in more potent interference than actual practice following these target changes. Finally, we found that proactive interference from task-irrelevant elements in the visual displays appears to underlie the superiority of imagined training relative 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, open materials

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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, and consequently lead to more efficient processing of task-relevant visual input.

Our goal in the experiments reported here 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 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, which allowed us to measure the extent to which the processing of the visual scenes became more efficient with practice. We randomly interleaved runs consisting entirely of actual practice with runs in which some of these 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 such as speeding of motor processes, we recorded subjects' event-related potentials

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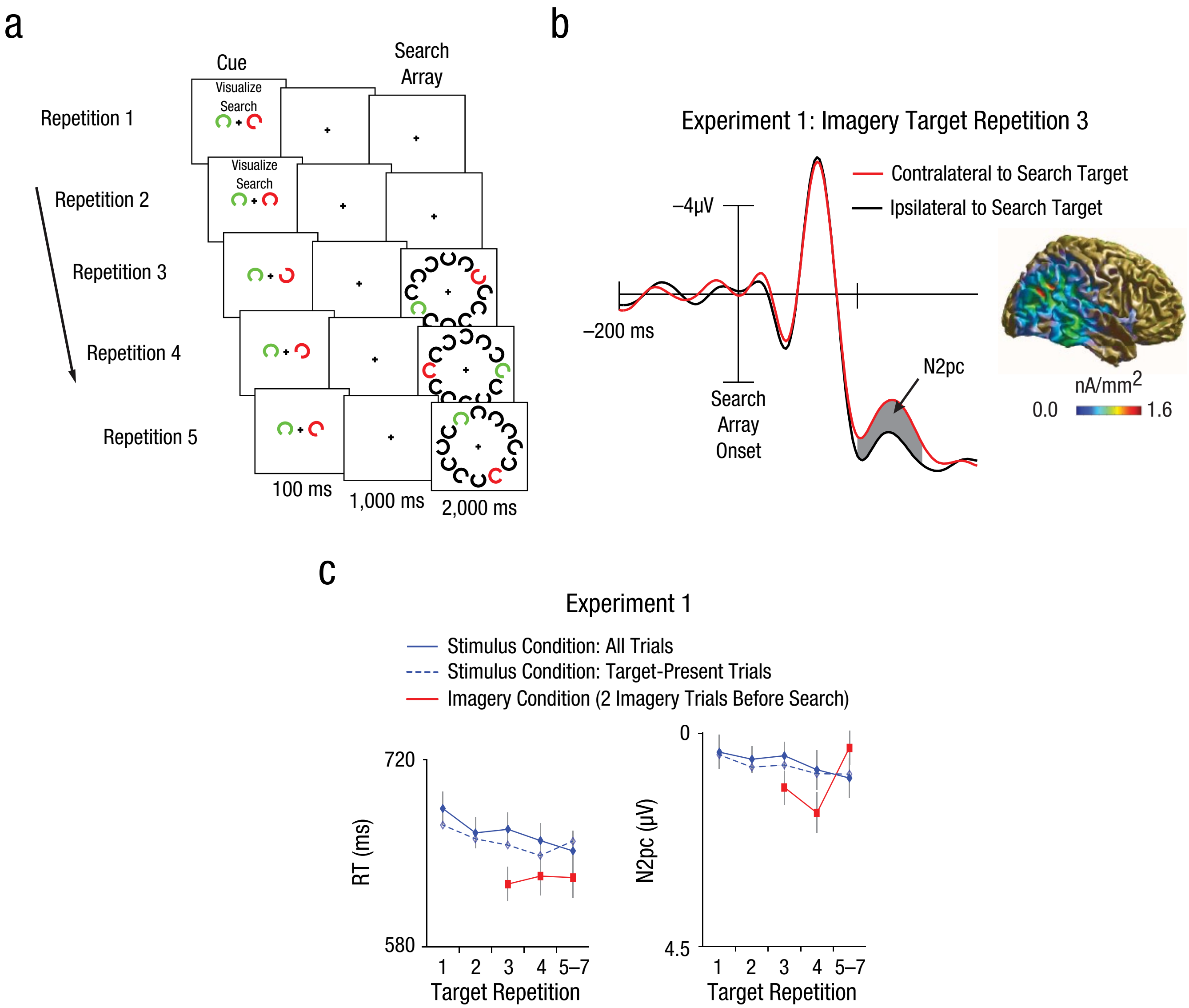

Fig. 1. Basic paradigm (a) and results (b, c) from Experiment 1. The task-relevant cue (a red or green Landolt C) signaled the orientation of the target in the upcoming search array. The target was repeated across three to seven trials (or *target repetitions*). Central fixation was maintained for the trial duration. In the stimulus condition, all stimuli in the runs of trials were presented externally. In the imagery condition (illustrated here), subjects were instructed to visualize search through an imaginary array of stimuli with the given task-relevant object during the first two trials in a run; after this visualization, subjects completed the run of trials with externally presented stimuli. The waveforms in (b) show event-related potentials from electrodes OL and OR over the hot spot of the current-density model shown in the inset. The waveforms are time locked to the onset of the search array and averaged across Target Repetition 3 trials in the imagery condition of Experiment 1. The time window for analysis of the N2pc is shaded in gray. These waveforms illustrate how the N2pc amplitude was measured for all the experiments reported. The graphs in (c) show mean search reaction times (RTs; on the left) and N2pc amplitudes (on the right) as a function of target repetition in Experiment 1. Results are shown separately for the stimulus condition (all trials and target-present trials only) and the imagery condition. Error bars indicate ±1 *SE*.

(ERPs) elicited during visual search. The N2pc is an early electrophysiological response (for an illustration, 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 independently 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 these effects on the N2pc should be apparent hundreds of milliseconds before subjects press a button to report whether the target is present.

Method

Participants

Participants (18–35 years of age; 62% women and 38% men) were volunteers with normal color vision, normal or corrected-to-normal visual acuity, and no reported history of neurological problems. All subjects gave informed consent to procedures approved by the Vanderbilt University Institutional Review Board prior to participation. A different group of 18 subjects participated in each of five experiments.

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 using paired-samples two-tailed t tests on reaction times (RT), $d = 0.54$, and N2pc amplitude, $d = 0.65$. We found that a sample size of 18 subjects would be sufficient to detect an effect of the same magnitude with 80% power at the .05 significance level.

Stimuli

Stimuli were presented on a gray background (54.3 cd/m^2) and were viewed from a distance of 114 cm. A black fixation cross (< 0.01 cd/m^2, 0.4° × 0.4° of visual angle) was visible throughout each trial. All cues and search stimuli were Landolt Cs (diameter = 0.88°, thickness = 0.13°, gap width = 0.22°) of eight possible orientations (0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, and 157.5°). They were colored red ($x = 0.612$, $y = 0.333$, 15.1 cd/m^2), green ($x = 0.281$, $y = 0.593$, 45.3 cd/m^2), or black (< 0.01 cd/m^2; color coordinates are given in CIE 1931 color space).

At the beginning of the experiment, each subject was told whether the red or the green stimuli would be task relevant, that is, which color designated both the task-relevant cue and the target Landolt C. To rule out physical-stimulus confounds that would make the lateralized N2pc difficult to measure if the inputs to the left and right visual fields were not balanced (Woodman, 2010), we had subjects switch between task-relevant colors every 360 trials, and which color was task relevant first was counterbalanced. Thus, when the cue stimuli were presented, subjects knew that the orientation of the Landolt C in the task-relevant color indicated the orientation they should look for in the subsequent search array. For example, a subject told that green was the task-relevant color would search for a green Landolt C with its gap oriented to the bottom in the run illustrated in Figure 1a. Each cue display showed a red Landolt C and a green Landolt C, one 2.2° to the left and the other 2.2° to the right of the center of the monitor.

In the search displays, the Landolt Cs were arranged similarly to the numbers on a clock face, 4.4° from the center of the monitor. Each search array contained one red object, one green object, and 10 black distractors.

Procedure

Each trial began with presentation of the fixation point for between 1,200 and 1,600 ms (randomly jittered from a rectangular distribution of times). Next, two cue stimuli were presented for 100 ms, followed by a 1,000-ms interval. Then, the search array was presented for 2,000 ms. The intertrial interval was 1,200 to 1,600 ms (randomly jittered). A target (i.e., Landolt C matching the orientation and color of the task-relevant cue) was presented in half of the search arrays and was absent in the other half (in this case, the object matching the cue color was of a different orientation than the cue). Subjects indicated as quickly and accurately as possible whether the target was present or absent in each search array by pressing one of two buttons on a handheld game pad (Logitech Precision, Lausanne, Switzerland), using their right hand.

The cued target orientation, target presence (present or absent), and target location (when present) were randomly determined on each trial. Each subject completed 720 trials, with the exception that we increased the number of trials in Experiment 3 to 1,080 because of the increase in the number of experimental conditions. To examine the impact of imagery on the efficiency of processing of complex scenes, we capitalized on the fact that attentional tuning becomes more precise across trials as subjects search for the same object (Carlisle, Arita, Pardo, & Woodman, 2011). Except in Experiment 2, the search target remained the same for a run of three, five, or seven consecutive trials, with length of run randomized, before the target was changed to a different object in the next run; in Experiment 2, runs were also a maximum of seven trials, but the target object changed within each run, after the first two trials of practicing or imagining search.

Experiment 1 included two experimental conditions, the stimulus condition and the imagery condition, runs of which were randomly interleaved. In the stimulus condition (50% of runs), cue and search stimuli were presented on every trial in a run, exactly as just described. This provided a baseline measure of the speed of subjects' attentional tuning. In the imagery condition (Fig. 1a), cue stimuli on the first two trials of a run (i.e., Target Repetitions 1 and 2) 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 following the cue array remained blank for the same duration (2,000 ms) as the presentation of the search array in the stimulus condition. For the remainder of the run (i.e., Target Repetition 3 up to Target Repetition 7, depending on the length of the run), all stimuli were visually presented, and subjects continued to search for the same object that they had imagined searching for during the first two trials.

Experiment 2 was identical to Experiment 1, except that the cued target that subjects practiced or imagined searching for during the first two trials of a run was changed to a different orientation during the remaining trials of the run (referred to as Target Repetitions 1′–5′). This manipulation allowed us to determine if imagining searching for a particular target can create interference when the observer begins searching for something else and to compare the switch costs associated with a change in target identity across the stimulus and imagery conditions.

Experiment 3 was identical to Experiment 1 except that there were three imagery conditions (25% of the runs each) in addition to the stimulus condition (also 25% of the runs). The imagery conditions differed in the number of trials on which subjects imagined performing a search before they actually searched (i.e., one, two, or three trials). 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 no black distractor Landolt C stimuli were included in the search arrays in either the stimulus or the imagery condition. This manipulation allowed us to test the hypothesis that the attentional improvements we observed following visual mental imagery in Experiments 1 through 3 were due to subjects avoiding the processing of task-irrelevant information while visualizing search.

Experiment 5 was identical to Experiment 1 except that the Landolt C cues were replaced by arrows that symbolically cued the direction of the gap in the target Landolt Cs. 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, using an SA Instrumentation (San Diego, CA) amplifier with a 0.01- to 100-Hz band-pass filter, sampled at 250 Hz; 3 electrodes were located at midline sites (Fz, Cz, Pz), 7 were at paired lateral sites (F3/F4, C3/C4, P3/P4, PO3/PO4, T3/T4, T5/T6, O1/O2), and 2 were at nonstandard sites (OL, halfway between O1 and T5; OR, halfway between O2 and T6). The electrodes were positioned according to the International 10-20 System and embedded in an elastic cap (Electrocap International, Eaton, OH). The right mastoid electrode served as the reference, and signals were rereferenced off-line 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 or ocular or myogenic artifacts were excluded. A two-step method of ocular-artifact rejection was implemented (Woodman & Luck, 2003b); subjects were removed from analysis for having an excessively high number of trials with eye movements (> 25% of individual trials) or if residual systematic eye movement resulted in horizontal EOG voltage deflections greater than 3.2 μV (corresponding to an ocular deviation of ±0.1°). This procedure resulted in the removal of 2 subjects each from Experiments 1 and 3, 1 subject from Experiment 4, and 1 subject from Experiment 5.

Analysis

The N2pc was measured at lateral occipital electrodes (OL and OR) during the window 200 through 300 ms after onset of the search array. Specifically, the N2pc was calculated as the mean difference in amplitude between the waveforms ipsilateral and contralateral to the visual hemifield (left vs. right) containing the search target. These potentials were baseline-corrected to the interval 200 to 0 ms prior to the onset of the search array (Woodman & Luck, 1999). The current density of the N2pc was modeled using standard methods previously described (Reinhart et al., 2012). In planned comparisons of the imagery and stimulus conditions, we applied two-tailed *t* tests to search RTs and N2pc amplitudes. Data were binned by target repetition (i.e., serial position) in each run. Because runs were three to seven trials long, there were fewer trials contributing to averages for Target Repetitions 5 through 7 than for Target Repetitions 1 through 3. We therefore averaged across Target Repetitions 5 through 7 (3′–5′ in Experiment 2) to prevent this last bin from being excessively noisy. Although we report the results of the planned-comparison *t* tests here, we verified that the same conclusions would be drawn when we analyzed the RT and N2pc data in each experiment using analyses of variance with the factors of condition (imagery vs. stimulus) and target repetition (3–7).

Results

Figure 1c shows that in Experiment 1, two trials of imagining performing search (the imagery condition) sped search RTs more than two trials of actually searching for the same targets in visual arrays (the stimulus condition). This imagery effect appeared to drive RTs to floor levels, so that subsequent practice performing the search task did not result in further improvement in the speed of search. RTs were significantly faster for

Target Repetition 3 in the imagery condition relative to Target Repetitions 1, 2, and 3 in the stimulus condition, $t(17) = 2.605$, $d = 0.74$, $p = .018$; $t(17) = 2.318$, $d = 0.61$, $p = .033$; and $t(17) = 2.326$, $d = 0.61$, $p = .033$, respectively. We observed no significant differences between conditions thereafter—Target Repetition 4: $t(17) = 1.238$, $d = 0.34$, $p = .232$; Target Repetitions 5–7: $t(17) = 1.055$, $d = 0.27$, $p = .306$.

These RT effects were not due to a speed-accuracy trade-off across conditions, as accuracy was universally high ($M = 98.3\%$ correct) and did not differ across conditions or target repetitions (ps > .34). The difference between conditions was also not due to the presence of randomly interleaved target-absent trials in the stimulus condition (assuming that subjects typically imagined finding their search target in the imagery condition), because when we looked just at target-present trials in the stimulus condition, we observed the same superiority for imagery training (Fig. 1c). These findings appear to support the conclusion that imagining search not only improves how rapidly one can focus attention on targets in a future scene, but also is more effective at producing such improvement than is actual practice with visual input. We now turn to the ERP results for this experiment.

If imagery changes how effectively visual attention can be focused on the task-relevant items in 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 possible target objects in the search arrays showed just this pattern (Fig. 1c). The amplitude of the N2pc was significantly larger for Target Repetition 3 in the imagery condition (i.e., after participants imagined visual search) than for Target Repetition 1 in the stimulus condition, $t(17) = 2.263$, $d = 0.86$, $p = 0.040$, or for Target Repetition 3 in the stimulus condition, after participants had practiced search with actual visual stimuli, $t(17) = 2.466$, $d = 0.93$, $p = .027$. As in the case of the RTs, we observed no significant N2pc differences between conditions after training became strictly visually driven—Target Repetition 4: $t(17) = 1.536$, $d = 0.60$, $p = .147$; Target Repetitions 5–7: $t(17) = 0.933$, $d = 0.31$, $p = .367$. As expected if the more efficient focusing of perceptual attention induced by imagining search propagated to subsequent behavior, the size of subjects' imagery-induced increase in N2pc amplitude for Target Repetition 3 predicted the size of their imagery-induced RT benefit for Target Repetition 3, $r(17) = .534$, $d = 0.76$, $p = .022$. These results demonstrate that mental imagery confers covert visual attention benefits beyond those 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 both conditions of Experiment 2, we cued subjects to search for a specific Landolt C (e.g., with the gap at 45°) for two trials at the beginning of each run. Then we changed the cued target to a different orientation (e.g., with the gap at 135°). In the stimulus condition, there was a predictable switch cost associated with searching for a new target (compare results for Target Repetitions 1 and 1′ in Fig. 2a). 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. 2a). Search RTs were slower in the imagery condition than in the stimulus condition for Target Repetition 1′, $t(17) = 2.622$, $d = 0.49$, $p = .018$, and Target Repetition 2′, $t(17) = 3.513$, $d = 0.61$, $p = .003$. It was not until after two trials of practice searching with visual input that subjects showed recovery from the imagery-induced switch cost; that is, there was no between-conditions RT difference in the last target-repetition bin (3′–5′), $t(17) = 1.296$, $d = 0.15$, $p = .212$. Accuracy was at ceiling across all trials ($M = 97.5\%$ correct) and showed no effects of condition or target repetition (ps > .40).

The data for N2pc amplitude again mirrored the pattern of search RTs (Fig. 2a). N2pc amplitude was reduced in the imagery condition relative to the stimulus condition for Target Repetition 1′, $t(17) = 3.302$, $d = 0.73$, $p = .004$, but not Target Repetition 2′, $t(17) = 0.871$, $d = 0.27$, $p = .396$, or Target Repetitions 3′–5′, $t(17) = 0.112$, $d = 0.02$, $p = .912$. 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 effect of imagery training that we observed in Experiment 1 has a downside when the searched-for target changes. The results from Experiment 2 also rule out the possibility 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., one, two, or three consecutive trials) 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 2b shows the orderly layering of the effects, which replicate and extend the findings from Experiment 1. Search RTs were significantly faster at the beginning of visual search after one trial of imagery (Target Repetition 2) than at the

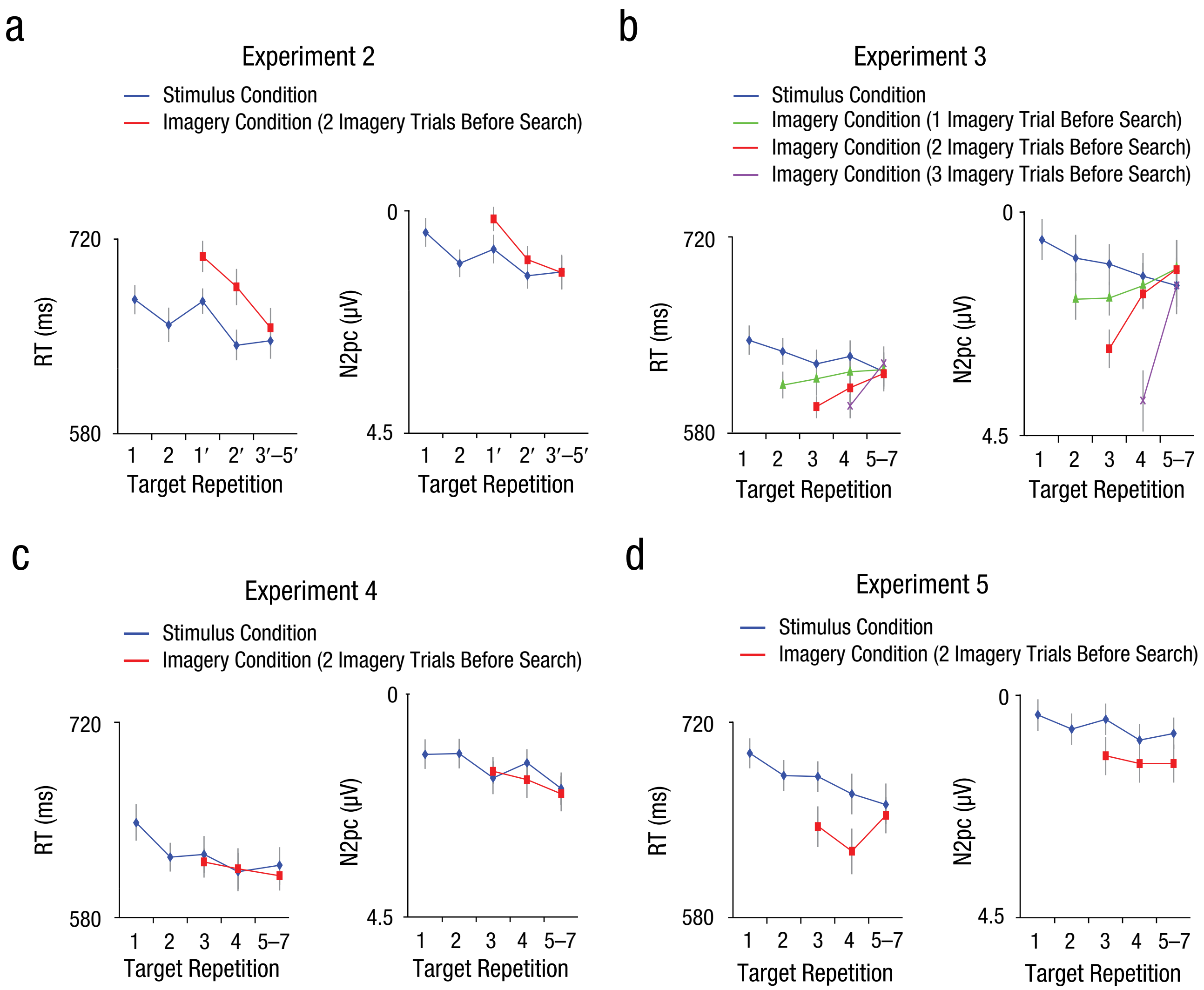

Fig. 2. Results from (a) Experiment 2, (b) Experiment 3, (c) Experiment 4, and (d) Experiment 5: mean search reaction times (RTs; on the left) and mean N2pc amplitudes (on the right) as a function of target repetition. Results are shown separately for the stimulus condition and imagery conditions. In (a), the primes denote trials following a switch in the target during the run. Error bars indicate ±1 *SE*.

beginning of visual search in the stimulus condition (Target Repetition 1), $t(17) = 2.588$, $d = 0.35$, $p = .019$. Search RTs became faster with additional trials of imagining search (compare the RTs across the different imagery conditions in Fig. 2b). RTs were faster when imagery for two trials preceded actual search (Target Repetition 3) than when imagery for just one trial preceded actual search (Target Repetition 2), $t(17) = 2.161$, $d = 0.29$, $p = .045$. However, these benefits appear to have reached asymptote, because there was no significant difference between RTs following imagery for two trials (Target Repetition 3) and RTs following imagery for three trials (Target Repetition 4) before beginning actual search, $t(17) = 0.025$, $d = 0.14$, $p = .981$. These results indicate a lower limit for the imagery-induced attentional benefits in this task as measured with behavior. Accuracy in Experiment 3 was at ceiling ($M = 97.3\%$ correct across all trials) and did not differ across conditions or target repetitions ($ps > .31$).

We found that the changes in N2pc amplitude largely mirrored the changes in RT (Fig. 2b); that is, the dose-response functions following imagery were comparable for N2pc amplitude and RT. Specifically, the N2pc component increased in amplitude across the imagery conditions that parametrically manipulated the amount of imagined practice. The N2pc amplitude differed between the first trial of actual search in the stimulus condition (Target Repetition 1) and the first trial of actual search following one trial of imagery (Target Repetition 2), $t(17) = 2.536$, $d = 0.55$, $p = 0.019$, and also differed between the first trial of actual search following one trial of imagery (Target Repetition 2) and the first trial of actual search following two trials of imagery (Target Repetition 3), *t*(17) = 2.291, *d* = 0.62, *p* = .032. However, N2pc amplitude did not differ between the first trial of actual search following two trials of imagery (Target Repetition 3) and the first trial of actual search following three trials of imagery (Target Repetition 4), *t*(17) = 2.012, *d* = 0.64, *p* = .057. The N2pc measurements suggest that the focusing of covert visual attention may benefit from additional trials of imagery training even after RTs have reached their fastest possible levels (i.e., after two trials of imagery practice). These results show that the benefit of training attention with imagery increases with each instance of imagery, even though RT may reach floor levels, such that it no longer reflects 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 did. However, this makes sense if one considers the cognitive demands of processing the search arrays. When practicing the visual search task with visual input, the visual system must process the distractor objects and recognize them as nontargets (Woodman & Luck, 1999, 2003b), which leaves memory traces that linger in the visual system (Chun, 2000). We hypothesize that processing the task-irrelevant distractors results 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 to visualizing the target object. Focusing high-level cognitive processing exclusively on targets should result in a stronger top-down bias toward target objects, according to theories of attentional control (Desimone & Duncan, 1995), and such a bias could result 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 that subjects' RTs and N2pc amplitudes returned to the baseline levels of the stimulus condition after a couple of trials of performing search with visual input following imagery trials (see Fig. 2b, Target Repetitions 5–7).

To directly test this hypothesis, we ran Experiment 4, in which we removed the black distractor items (see Fig. 1a) from the search arrays, minimizing the impact of distractor-related proactive interference. If the attentional advantages of imagery training over actual practice are due to proactive interference from task-irrelevant information being reduced 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 actual practice. Results were consistent with these two predictions. We found that across Target Repetitions 1 through 7, RTs were faster in the stimulus condition of Experiment 4 than in the stimulus condition of Experiment 1, in which distractors were included (compare Figs. 1c and 2c), *t*(17) = 3.294, *d* = 0.21, *p* = .004. We also found that search efficiency following training with distractor-free visual input was comparable to search efficiency following training with mental imagery (Fig. 2c); that is, there were no between-condition RT differences for Target Repetition 3, *t*(17) = 0.761, *d* = 0.23, *p* = .460; Target Repetition 4, *t*(17) = 0.441, *d* = 0.15, *p* = .666; or Target Repetitions 5–7, *t*(17) = 0.567, *d* = 0.21, *p* = .580. The N2pc was modulated in a similar fashion (Fig. 2c). There were no N2pc amplitude differences between the stimulus and distractor-free imagery conditions for Target Repetition 3, *t*(17) = 0.155, *d* = 0.05, *p* = .879; Target Repetition 4, *t*(17) = 0.428, *d* = 0.17, *p* = .676; or Target Repetitions 5–7, *t*(17) = 0.319, *d* = 0.08, *p* = .703.

The results from Experiment 4 indicate that mental imagery has superior training effects on the focusing of visual attention 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 memory traces of distractors. This interpretation converges with work from a different research domain. In a recent study using a complex motor task, Wohldmann, Healy, and Bourne (2008) showed that imagining performing data entry led to less forgetting and more positive transfer of learning than did physical practice, and the authors interpreted their results as indicating that imagined practice, unlike physical practice, does not result in proactive interference. Here, we are proposing that the distractors in our visual search task caused interference in the stimulus condition that prevented the learning effects across same-target runs from being as large as those 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 that we observed in the imagery condition across the experiments. In Experiment 5, all Landolt C cues were replaced by arrows indicating the direction of the gaps in the search targets. If cue-induced priming was the source of the attentional and behavioral improvements in the imagery condition, then not displaying the target visual stimulus prior to search should eliminate these effects. Contrary to this hypothesis, Figure 2d shows that even when the cues were symbolic arrows, two trials of imagining search, compared with two trials of performing search with visual input, reduced RTs and enhanced the focusing of attention. Specifically, RTs were faster for Target Repetition 3 of the imagery condition than for Target Repetitions 1, 2, and 3 of the stimulus condition, $t(17) = 2.986$, $d = 0.82$, $p = .008$; $t(17) = 2.639$, $d = 0.68$, $p = .017$; and $t(17) = 2.320$, $d = 0.64$, $p = .033$, respectively. N2pc amplitudes showed a similar pattern of results; N2pc amplitude for Target Repetition 3 of the imagery condition was significantly larger than N2pc amplitude for Target Repetition 1 of the stimulus condition, $t(17) = 2.201$, $d = 0.80$, $p = .042$, and Target Repetition 3 of the stimulus condition, $t(17) = 2.206$, $d = 0.73$, $p = .041$. These findings rule out a priming explanation for the observed effects.

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 practice games, like those used in the present study, and are aimed at improving attention and memory. The findings of this study suggest that improvements of attention may be most effectively trained using imagery, without actual performance of the task that is the ultimate focus of training. Imagery-based training appears to result in superior learning because it avoids interference from memories of task-irrelevant information during the actual performance of the task.

Author Contributions

G. F. Woodman conceived of the initial research question. R. M. G. Reinhart and G. F. Woodman designed the experiments. R. M. G. Reinhart programmed the experiments. L. J. McClenahan collected the data and provided initial analyses. R. M. G. Reinhart performed all the final data analyses, wrote the initial version of the manuscript, and created the figures. G. F. Woodman edited the manuscript and provided feedback during the project.

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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.

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Open Practices

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