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From eyes to hands: Transfer of learning in the Simon task across motor effectors

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Abstract Inhibition of irrelevant and conflicting information and responses is crucial for goal-directed behaviour and adaptive functioning. In the Simon task, for example, responses are slowed if their mappings are spatially incongruent with stimuli that must be discriminated on a nonspatial dimension. Previous work has shown that practice with incongruent spatial mappings can reduce or even reverse the Simon effect. We asked whether such practice transfers between the manual and oculomotor systems and if so to what extent this occurs across a range of behavioural tasks. In two experiments, one cohort of participants underwent anti-saccade training, during which they repeatedly inhibited the reflexive impulse to look toward a briefly presented target. Additionally, two active-control training groups were included, in which participants either trained on Pro-saccade or Fixation training regimens. In Experiment 1, we probed whether the Simon effect and another inhibitory paradigm, the Stroop task, showed differential effects after training. In Experiment 2, we included a larger battery of inhibitory tasks (Simon, Stroop, flanker and stop-signal) and noninhibitory control measures (multitasking and visual search) to assess the limits of transfer. All three training regimens led to behavioural improvements in the trained-upon task, but only the anti-saccade training group displayed benefits that transferred to the manual response modality. This transfer of training benefit replicated across the two experiments but was restricted to the Simon effect. Evidence for transfer of inhibition training across motor systems offers important insights into the nature of stimulus-response representations and their malleability.

Keywords Attention · Eye Movements · Cognitive · inhibition

Introduction

The influence of behavioural training on cognitive processes is a topic that has generated much interest and controversy in recent years (Schubert, Strobach, & Karbach, 2014; Simons et al., 2016). While it is accepted that behavioural training on a task can improve later performance for that same task, the extent to which such training generalises or transfers to improve performance on distinct tasks, or for different stimuli or response mappings, remains to be established.

A key executive function that has been the target of training interventions is inhibition, perhaps because deficits of inhibition form the basis for a number of debilitating health conditions, including attention-deficit hyperactivity-disorder (Nigg, 2001) and addiction (Noel, Brevers, & Bechara, 2013). Inhibitory control enables suppression of irrelevant or distracting stimuli, pre-potent responses or impulses, and any prior interpretations or memories that are irrelevant for performing goal-directed behaviour (Aron, Robbins, & Poldrack, 2004). Mechanisms of inhibitory control allow us to function effectively in a complex, ever-changing environment by allowing us to focus on, and respond to, information that is currently relevant for behaviour. Several paradigms have been used to study inhibitory control, some of which require inhibition of a pre-potent or ongoing motor response, such as stop-signal, Go/No-Go, and anti-saccade tasks (reviewed in Aron, 2011; Spierer, Chavan, & Manuel, 2013), whereas others require resolution of some form of

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interference, such as flanker, Stroop, and Simon tasks (Aron, 2011; Diamond, 2013; Spierer et al., 2013).

It has been shown that training each of these inhibitory-control tasks over various durations, ranging from 80–6,000 trials (reviewed in Spierer et al., 2013), can result in behavioural and electrophysiological changes in the *trained on* task. The majority of studies that documented improvements in the trained-upon task (Simons et al., 2016; Spierer et al., 2013) have focused mainly on paradigms in which participants are required to respond as quickly as possible to one set of stimuli but withhold their responses to the same set when a signal is presented following a variable delay (Berkman, Kahn, & Merchant, 2014; Logan & Burkell, 1986; Manuel, Bernasconi, & Spierer, 2013). Similarly, improved performance has been shown in Go/No-Go paradigms in which participants have to withhold their pre-potent response whenever a specific stimulus appears (Manuel, Grivel, Bernasconi, Murray, & Spierer, 2010; Schapkin, Falkenstein, Marks, & Griefahn, 2007; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009; Verbruggen & Logan, 2008). For example, Verbruggen and Logan (2008) demonstrated that repetitive learning of stimulus-response mappings during the training phase of a Go/No-go task improved inhibitory performance on the same task in the test phase. Moreover, in this study a reversal in the stimulus-response mappings following training led to slower responses in the Go trials than when stimulus-response mappings remained consistent with training. These findings have been interpreted as reflecting automatization of inhibition to specific stimuli through reduced reliance on top-down input (Manuel et al., 2013; Manuel et al., 2010). Finally, training-induced improvements also have been reported for response-inhibition tasks, such as the anti-saccade paradigm, in which participants are instructed to inhibit the reflexive response of making a saccade toward a stimulus and instead to saccade away from the stimulus (Dyckman & McDowell, 2005). Dyckman (2007) demonstrated that practice effects on the anti-saccade task manifest as decreased latencies and errors following training.

Benefits of training also have been shown for tasks that measure interference control, such as the Simon task (Simon, Craft, & Webster, 1973) and the Stroop task (Stroop, 1935). Importantly for the present work, transfer of training effects has been observed for both these tasks. In a typical Simon task, participants are instructed to press a left-sided key for one stimulus and a right-sided key for another. The task requires the participant to resolve stimulus-response conflict arising from trials in which the stimulus and the response are spatially incompatible (e.g., a target in the left visual field that requires a right-sided response). In contrast, successful performance of a Spatial Stroop task requires resolution of stimulus-stimulus conflict, in which the stimulus location and its features are incongruent (e.g., an arrow pointing left but appearing in the right visual field). For both

Simon and Stroop paradigms, pretraining on spatially incompatible response mappings can reduce interference effects. This appears to transfer across stimuli and, to some extent, different modalities of presentation and response (Marini, Iani, Nicoletti, & Rubichi, 2011; Yamaguchi, Chen & Proctor, 2015). Specifically, Procter, Yamaguchi, Zhang, and Vu (2009) found that practicing with incongruent spatial locations and responses abolished the Simon effect. This also was found when central arrow stimuli were employed to denote spatial location but took longer to establish when spatial word stimuli were used, and under these conditions transfer only occurred for arrow stimuli. This suggests that physical locations and arrows access the same spatial representations, whereas arrow and word stimuli tap overlapping semantic codes. In addition, Yamaguchi, Chen, and Proctor (2015) found similar transfer when a verbal response was used after training on manual incongruent spatial location responses.

Despite the obvious differences between the wide range of inhibitory control tasks, there is evidence that they rely upon activity within a common neural network, which includes the dorsolateral prefrontal cortex (DLPFC), inferior frontal cortex, and anterior cingulate cortex (ACC) (Liu, Banich, Jacobson, & Tanabe, 2004; Nobre, Gitelman, Dias, & Mesulam, 2000; Peterson, Kane, Alexander, & Lacadie, 2002). Importantly, these regions are implicated in studies that have examined practice-related changes (Milham, Banich, Claus, & Cohen, 2003; Wang & Weekes, 2014).

The studies reviewed above present a complex picture of training transfer of inhibitory control across cognitive operations, stimuli and responses. For example, response inhibition training has been reported as showing no evidence of transfer to untrained tasks in a laboratory setting (Enge et al., 2014; Thorell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009). Conversely, transfer effects have been observed in daily-life contexts, such as the control of food and alcohol consumption via training on a Go/No-Go paradigm that incorporated alcohol-related stimuli (Houben, 2011; Houben, Nederkoorn, Wiers, & Jansen, 2011; but see Jones & Field, 2013, where only stop-signal and not anti-saccade training elicited reductions in alcohol consumption) as well as minimising risk-taking in gambling by using a monetary motor training paradigm (Verbruggen, Adams, & Chambers, 2012). Finally, for the Simon task at least, it appears that transfer only occurs for stimuli and responses that access the same representations, but not universally.

To summarise, to elicit training-based transfer of inhibitory control, the training and test tasks must share some common stimulus-response inhibitory goal associations, location-stimulus mappings, or stimulus-response mappings (Spierer et al., 2013). It remains unclear whether training gains elicited for a task that is structurally similar to a trained task (e.g., both visual tasks requiring spatially lateralised responses) can

transfer across motor effectors. Specifically, can inhibition training in the oculomotor system transfer to manual responses, and how generalised is any such transfer? We hypothesised that if the role of inhibition training is to modulate top-down control mechanisms generally, transfer may be elicited, even with broader stimulus-goal associations across motor systems and inhibition paradigms. Conversely, if inhibition training serves merely to strengthen stimulus-response/location pairings, transfer effects should be observed for the Simon task. We report results from two experiments.

Experiment 1 tested whether repeatedly inhibiting a pre-potent response via an anti-saccade task can elicit training-induced benefits in an integrated, manual response-selection task that combines key elements for eliciting both Stroop and Simon effects (Liu et al., 2004). Experiment 2 was designed to replicate Experiment 1 and to extend our protocol to a wider battery of response-selection test tasks. Briefly, we found that only participants who undertook anti-saccade training showed reliable training benefits, specifically for the Simon task, but not for any of the other inhibition tasks.

Experiment 1

To test whether ocular inhibitory training can induce improvements in an untrained motor inhibition task, we tested three groups of participants (two active control groups and one inhibitory training group). The first group practised inhibiting a pre-potent oculomotor response by making saccades away from a peripheral visual cue (anti-saccade training). A second group, which acted as a control, trained on a task that required them to execute saccades toward the same peripheral visual cue (pro-saccade training). A third group, trained on a simple response selection task (judgements of Gabor orientation) performed at fixation (fixation training). All three groups were tested on the Simon and Stroop tasks (see below) before and after training. The inclusion of the two active-control groups with matched training performance feedback served to control for potential placebo effects (Shipstead et al., 2012).

Methods

Experimental overview

Participants were required to attend the laboratory on 3 consecutive days (Day 1, Day 2, and Day 3). On Day 1, participants underwent a *pretraining test session,* where their performance on the Simon and Stroop tasks was assessed. Immediately following this was the training session, in which participants completed 8 blocks of *training* trials. On Day 2, they continued with an additional 10 blocks of training. Finally, on Day 3, participants were tested on the original Simon and Stroop tasks in a *posttraining session.*

Participants

We calculated the sample size required to achieve 80% power to detect a significant 3 group (Fixation training, Prosaccade Training, Antisaccade Training) × 2 session (pre, post) × 2congruency (Congruent, Incongruent) interaction effect using G*power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) software. Sensorimotor training effects in these interference resolution tasks are typically medium to large in terms of effect size (Millner, Jaroszewski, & Chamarthi, 2012). Using an $f = 0.3$ (Cohen, 1988), the power calculation yielded a recommended sample size of 10 participants per group. Given the somewhat imprecise nature of effect-size estimation and in light of the limited published work on the type of training protocols adopted here, we also replicated our results in a second experiment with a fresh group of participants in each saccade-training group, and with a wider set of behavioural outcome measures (see Experiment 2).

To be included in the experiment, participants had to be older than age 18 years, report normal or corrected-to-normal vision, and demonstrate both a Simon and a Stroop effect (i.e., Incongruent response time (RT) > Congruent response time (RT)) in the pretraining session. If these criteria were met, participants were allocated to groups (Fixation Training, Pro-saccade Training, and Anti-saccade Training) using a customised Matlab script. This script compared each individual's overall response time (RT averaged over both Simon and Stroop tasks) in the pretraining session to the current group means (fixation training, pro-saccade training and anti-saccade training) and then assigned the participant to the group with the lowest mean. This systematic matching of performance across groups in the pretraining session accounted for any baseline differences that might otherwise mask the influence of training. The procedure was successful in balancing pretraining performance. Specifically, for the Simon task, a one-way ANOVA comparing pretraining performance for the fixation, pro-saccade and anti-saccade groups revealed no significant differences in performance [Incongruent – Congruent RT] for all three groups [$F_{(2, 27)} = 0.09$, MSE = 739.8, $p = 0.91$], with group means as follows: fixation (mean = 38.9 ms, standard error of the mean [SEM] = 6.6), pro-saccade (mean = 39.6 ms, SEM = 7.2), Anti-saccade (mean = 43.6 ms, SEM = 11.2). For the Stroop task, a one-way ANOVA revealed no significant differences between pretraining performance [Incongruent – Congruent RT] for all three groups [$F_{(2, 27)} = 1.2$, MSE = 602.9, $p = 0.30$], with group means as follows: fixation (mean = 43.8ms, SEM = 8.9), pro-saccade (mean = 45.5 ms, SEM = 7.8), anti-saccade (mean = 29.7 ms, SEM = 6.5).

We tested 35 participants in total. Data from five had to be excluded, because these individuals did not show either a Simon or a Stroop effect in the pretraining session (i.e., Incongruent RT – Congruent RT < 0). Participant

demographics were as follows: fixation training group [n = 10, average age = 20.6 years (standard deviation [SD] = 1.7), females = 9, right-handed = 9, years of education = 14.8 years (SD = 2.1)], pro-saccade training group [n = 10, average age = 26.3 years (7.35), females = 6, right-handed = 8, years of education = 17.2 (3.1)], anti-saccade training group [n = 10, average age = 20.2 years (0.78), females = 8, right-handed = 10, years of education = 14 (0.8)]. Participants were paid $30 for their time. All procedures were approved by Ethical Review Committee at The University of Queensland.

Materials

All stimuli were presented on an LCD screen with a resolution of 1,024 × 768. Participants were seated at a viewing distance of 62 cm with their head supported via a chin rest. Stimulus presentation, eye movement recording, and response collection were implemented using the Psychophysics Toolbox (Version 3; (Brainard, 1997; Pelli, 1997) and EyeLink Toolbox extensions (Cornelissen, Peters, & Palmer, 2002) for Matlab (MathWorks). Eye movements were recorded at 500 Hz with an EyeLink 1000 (SR Research) infrared eye tracker, calibrated using a 9-point calibration procedure.

Test session stimuli and procedures

We used an integrated Simon-Stroop task to measure inhibitory control (Liu et al., 2004). This paradigm is useful for the simultaneous assessment of Stroop and Simon effects. Importantly, it allowed us to examine whether training has a differential effect on resolving conflict arising from stimulus-stimulus incongruency (Stroop) and stimulus-response incongruency (Simon), while equating all other factors across tasks relating to stimuli and responses (Pratte, Rouder, Morey, & Feng, 2010).

Participants' task was to determine whether a target (a black arrowhead, subtending ~2° visual angle) presented against a white background—pointed upward or downward. Trials began with a black fixation cross that was presented for 1 s. This was followed by the arrow, which appeared for 500 ms. Participants had a 3-s blank response window within which to respond before the commencement of the next trial. In the first 40 trials, the arrow appeared only in the centre of the screen. This allowed participants to become familiar with the response mappings, which were as follows: "up" corresponded with a press of the "F" key on a standard QWERTY keyboard using the left index finger, and "down" was mapped to the "J" key pressed using the right index finger. Participants were required to score a minimum of 38 of 40 trials correct in this familiarization phase to proceed to the test session.

As shown in Fig. 1, for the test session, the trial sequence was the same as that used for the familiarisation trials, except that the arrowhead now appeared at one of four locations (above, below, left, or right) at 2° eccentricity from the centre. Participants were asked to indicate the direction of the arrowhead (up or down) as quickly and accurately as possible, irrespective of where on the display it appeared. There were four stimulus conditions (8 possible display configurations; Fig. 1a-d): (1) Simon Congruent: No stimulus-response conflict between the location of the arrow and the response hand/side (e.g., the "up" arrow appears on the left and requires a left hand response; Fig. 1a); (2) Simon Incongruent: Response and arrow location were on opposite sides (e.g., the "up" arrow appears on the right and requires a left hand response; Fig. 1b); (3) Stroop Congruent: No stimulus-stimulus conflict between the location of the arrowhead and the direction in which it points (e.g., the "up" arrow appears in the top/up position; Fig. 1c); (4) Stroop Incongruent: Arrowhead location and the direction in which it points are incompatible (e.g., the "up" arrow appears in the bottom/down position; Fig. 1d). There were 192 trials in the test session with 48 trials for each condition. The dependent measure was the average response time (RT) for each condition.

Training session stimuli and procedures

Participants were allocated to one of three training groups: fixation training, pro-saccade training, or anti-saccade training, using the procedure outlined above (Fig. 2). They all completed 720 trials spread over 18 blocks (each block had 40 trials), split across 2 days. The goal of the training phase was to improve individual saccade latencies (delay between cue onset and saccade initiation) for the pro-saccade and the anti-saccade training groups and to reduce response times for the fixation-training group. To encourage maximal training gains, while also addressing placebo effects (Shipstead et al., 2012), a feedback-based point system was incorporated for the training sessions. Each participant was set an initial RT (fixation training)/saccade-latency (pro-saccade training and anti-saccade training) target-time of 2s. To earn a point, participants had to be quicker than or match this target-time on at least 70% of the trials while maintaining accuracy at 90%. If a point was earned, a new RT/saccade latency target-time was calculated based on the 75th percentile from the previous block. If the participant failed to earn a point, the RT/saccade latency target remained unchanged. A feedback screen appeared at the end of every 2 blocks informing participants of their average RT/saccade-latency over the two blocks, their average response/saccade direction accuracy, whether or not they scored a point, their total points accumulated, and their new target-time.
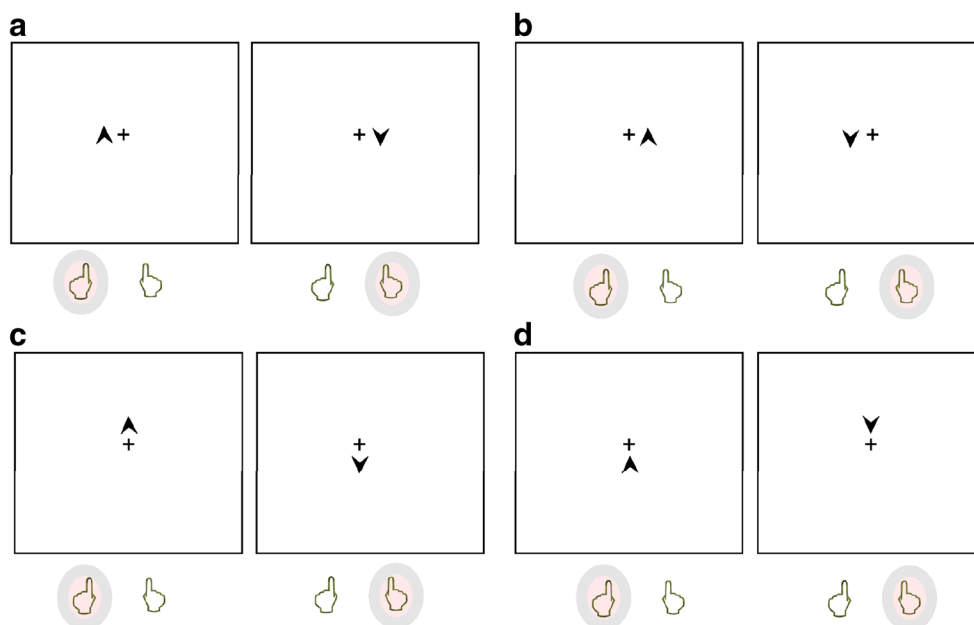
Fig. 1 Different configurations of test stimuli. Participants were required to respond to the direction of the arrowhead (up or down) using a left hand press for "up" and a right hand press for "down," regardless of arrowhead location. The upper row is representative of the Simon task, where the stimulus location and the response location were compatible (**a**) or incompatible (**b**). The bottom row reflects a typical spatial Stroop task, where stimulus location and stimulus feature (arrowhead direction) were either compatible (**c**) or incompatible (**d**)

Fixation training

Participants in the fixation training group reported the direction of tilt of a briefly flashed central Gabor patch (2° size, 2 cycles per degree, 50% contrast) presented against a grey background. The Gabor was either oriented vertically, horizontally, 45° rightward or 45° leftward from vertical. The vertical and horizontal tilts were mapped to the left-hand middle and index finger presses of the A and Z keys, respectively, and the leftward and rightward tilts were mapped to the right-hand middle and index finger presses of the L and "," keys. Overall trial duration was 5 s. As shown in Fig. 2a, trials began with a fixation period (0.5° black spot for 200-1,000 ms) followed by a blank period (800-1200 ms) and then the central target Gabor (20 ms). A response screen containing just the fixation spot was then presented until the participant responded or 5 s had elapsed. Participants were instructed to respond as quickly and accurately as possible, and a tone was
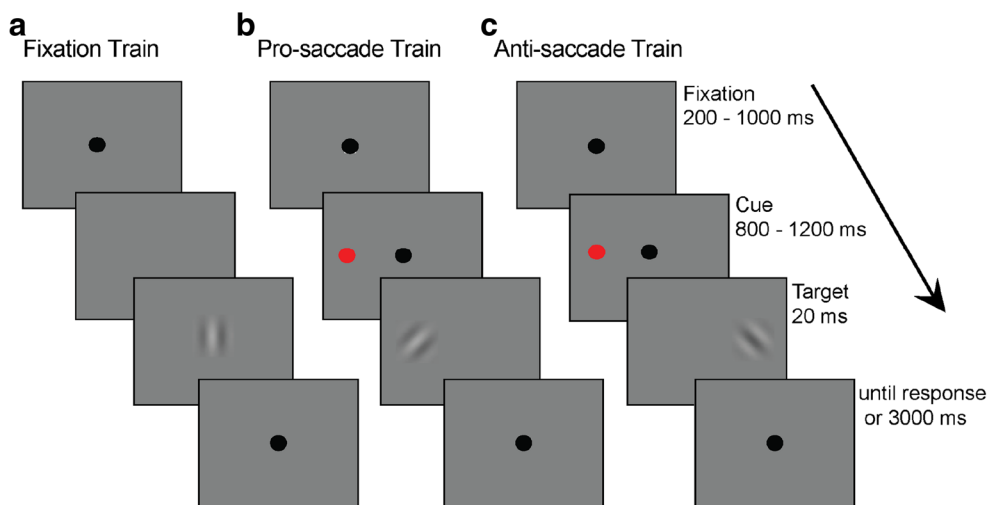

Fig. 2 Training paradigms for the three groups. (**a**) *Fixation Training group*: Participants trained on a task that required tilt identification of a centrally presented Gabor patch (vertical, horizontal, left or right). (**b**) *Pro-saccade Training group*: Participants practised moving their eyes toward a cue and then reported the orientation of the Gabor at the cued location. (**c**) *Anti-saccade Training group:* Participants in this group were required to execute eye-movements to a location directly *opposite* to that indicated by the cue and to report the orientation of the Gabor at this (uncued) location. Participants completed 720 training trials over 2 consecutive days

played in case of an error. Target response times and accuracies were recorded.

Pro-saccade training

Participants assigned to the pro-saccade training group responded to a Gabor that was oriented vertically, horizontally, 45° rightward, or 45° leftward from the vertical with the same response mappings as in the fixation training task, thereby matching task demands. Crucially, in this task the Gabor was flashed at a precued location either 10° to the left or right of centre. The cue comprised a red spot (0.5°) that appeared at the to-be-presented Gabor location alongside the fixation spot (Fig. 2b). The trial sequence was as follows: fixation period (200-1000 ms), a cue either to the left or the right of fixation (800-1,200 ms), target Gabor (20 ms) *at the cued location*, and finally the response period (until response or 3,000 ms). Participants were instructed to move their eyes toward the cue as quickly and accurately as possible and to report the orientation of the target Gabor. An error tone was played in case of a response error. Although response times and response accuracies for the target Gabor were recorded, the measure of interest was saccade latency, measured as the delay between cue onset and eye-movement onset (calculated as movements >2° from fixation).

Anti-saccade training

The training task for the anti-saccade group was identical to that of the pro-saccade group, except that participants were required to move their eyes to a location directly *opposite* that at which the cue appeared (Fig. 2c). The target Gabor was later briefly flashed at this opposite (uncued) location. The trial sequence consisted of a fixation period (200-1,000 ms), a cue either to the left or to the right of fixation (800-1,200 ms), a target Gabor (20 ms) presented *opposite to the cue's location*, and finally the response period (until response or 3,000 ms). To minimise the presence of express saccades (Hamm, Dyckman, Ethridge, McDowell, & Clementz, 2010), the fixation spot and the cue spot overlapped without any temporal gap. Additionally, for this group short blocks of fixation-only trials were included at the beginning of every block to encourage active inhibition of the reflexive pro-saccade response. These intermingled fixation trials were identical to the trials used for the fixation training group. Hence, each block comprised 10 trials that required central fixation, whereas the remaining 30 trials necessitated anti-saccade eye movements.

Data analyses

RT data that were either <200 ms (suggesting anticipatory responses) or >3 standard deviations from the participant's

mean RT for each condition were removed. Identical criteria were used for each block in the training session, except that the minimum cutoff for saccade latency was 100 ms. Excluded trials accounted for <1.5% of the data. Trimmed data were then entered into an omnibus, repeated measures ANOVA with session (pre or post), task (Simon or Stroop) and congruency (congruent or incongruent) as within-subject factors and group (fixation training, pro-saccade training or anti-saccade training) as the between-subjects factor. Where appropriate, p-values were adjusted for the Geisser – Greenhouse sphericity correction. Because our measures of interest were the Simon and the Stroop effects (Incongruent – Congruent RT for each task) in the pre- and posttraining sessions, we tested whether a significant group effect could be elicited for each task separately when controlling for pretraining performance in an ANCOVA design.

Results

Training session

Figure 3 shows the mean latency to initiate saccades for the two saccade-training groups and RTs to report the orientation of the Gabor target for each block in all three training groups. The pattern reflects a trend of declining target RTs and saccade latencies with training (i.e., all groups showed strong training benefits). To confirm that training improved performance across blocks, we subjected all three training groups to repeated measures ANOVA. As shown in Table 1, a significant main effect of block was revealed for both saccade latency and for target RT. We also ran post-hoc LSD comparisons to confirm that both the saccade-training groups showed a significant reduction in saccade latency from the first to the last block and similarly that all three groups showed a significant reduction in RT from the first to the last block (Table 1, right-most column). Finally, we compared latencies across blocks for the two saccade-training groups to ensure that they performed similarly. There was a significant main effect of block (F (17, 306) = 6.9 MSE = 0.004, p < 0.001), reflecting the effects of saccade training for both groups, but crucially there was no significant group x block interaction (F (17, 306) = 0.79, MSE = 0.004, p = 0.7). Hence, training was equally effective in improving performance for all three groups.

Test sessions

The main objective of our study was to assess training-induced benefits on the Simon and Stroop tasks. Specifically, we examined whether, following inhibition training (Anti-saccade Group), Simon and Stroop effects were reduced. The mean RTs depicted in the left panel of Fig. 4 reveal that anti-saccade training did reduce interference in the Simon task (Fig. 4c). We subjected the RT data to a 3 group (fixation
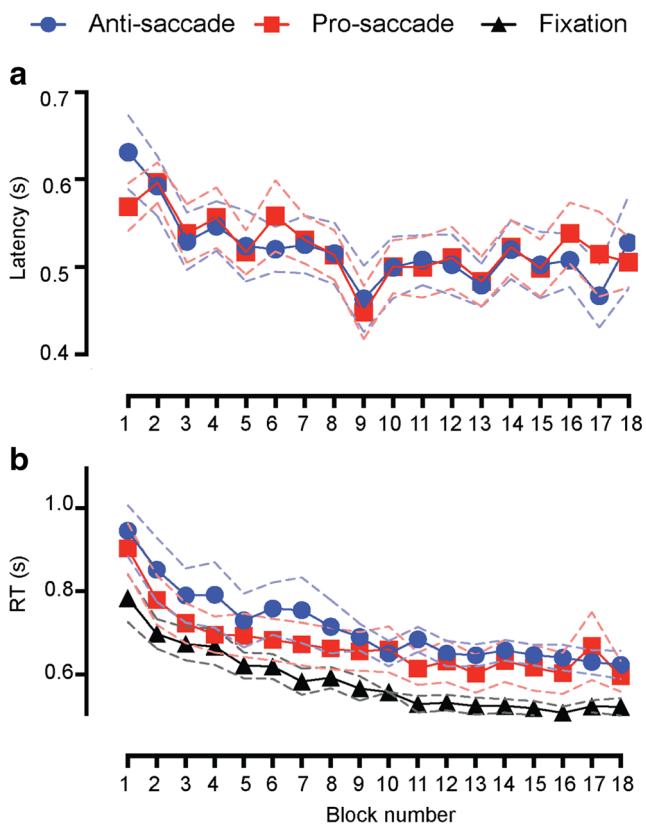
Fig. 3 Saccade latency and target reaction times as a function of training. (a) Reduction in saccade latencies across 18 blocks of training for the pro-saccade training group (red squares) and the anti-saccade training group (blue circles). (b) Reduction in RT over the course of training is depicted for all three training groups. Dotted lines represent 1 SEM

pair of groups was entered into a group x session x task x congruency ANOVA. A 4-way interaction effect was revealed for the anti-saccade training group versus the pro-saccade training group F (1,18) = 6.98, MSE = 167.9, η_p^2 = 0.28, p = 0.017] and similarly for the anti-saccade training group versus the fixation training group [F (1,18) = 7.21, MSE = 181.76, η_p^2 = 0.29, p = 0.015]. Crucially, the interaction effect was non-significant for the pro-saccade training group versus the fixation training group [F (1,18) = 0.028, MSE = 138.3, η_p^2 = 0029, p = 0.87]. This suggests that the performance for the two active-control groups did not differ and that the higher-order interaction effects were driven by the anti-saccade training group.

In light of our *a priori* expectation that only the anti-saccade training group would demonstrate training-related benefits in the transfer tasks, particularly for the incongruent RTs, we conducted independent ANOVAs for each group and focussed on each task separately. As shown in Fig. 4c (left), for the Simon task, the anti-saccade training group showed not only a significant main effect of session (F (1,18) = 53.5, MSE = 455.1, p < 0.0001) but also a session (pre, post) x congruency (congruent, incongruent) interaction effect (F (1,18) = 5.5, MSE = 455.1, p < 0.03)). Post-hoc tests further qualified this main effect of session by verifying that while the congruent RTs were reduced from pretraining to posttraining session (mean difference = 33.5 ms, 95% CI = 10.17 to 56.83, Bonferroni adjusted p = 0.005), the mean incongruent RTs were faster by almost twice as much (mean difference = 65.20 ms, 95% CI = 41.87 to 88.53, Bonferroni adjusted p < 0.0001). In contrast, analyses of the Stroop task revealed that the anti-saccade training group showed only a main effect of session (F (1,18) = 32.81, MSE = 1213, p < 0.0001) without any interaction (F (1,18) = 0.54, MSE = 1213, p = 0.47), suggesting that performance improved to the same extent for congruent and incongruent RTs.

We also examined group-wise performance in each task for the two active-control groups. Neither of the groups showed a significant session x congruency interaction for either the Simon task [fixation training group: Fig. 4a, (F (1,18) = 0.21, MSE =

training, pro-saccade training and anti-saccade training) × 2 session (pre- and posttraining) × 2 tasks (Simon and Stroop) × 2 congruencies (Congruent and Incongruent) ANOVA. A significant 4-way interaction was found (F (2,27) = 5.09, MSE = 162.7, p = 0.013, η_p^2 = 0.27,), indicating that the RTs were differentially affected in each group depending on the transfer task, the testing session and whether the trial was incongruent (requiring inhibitory control) or congruent. To further examine which group was driving the four-way interaction, each

Table 1   ANOVA results for effect of training on saccade latency and target reaction times

| Group	Measure	RM-ANOVA main effect of block	Post-hoc LSD comparison of first vs last block
Pro-saccade	RT	F (17, 153) = 8.21, MSE = 0.01, p = 0.0002	mean difference = 0.31s, 95% CI = 0.16 to 0.46, p = 0.0012
	Latency	F (17, 153) = 3.23, MSE = 0.007, p = 0.015	mean difference = 0.063s, 95% CI = 0.0098 to 0.12, p = 0.021
Anti-saccade	RT	F (17,153) = 7.61, MSE = 0.01, p = 0.0096	mean difference = 0.32s, 95% CI = 0.21 to 0.44, p = 0.0001
	Latency	F (17,153) = 4.50, MSE = 0.003, p = 0.0046	mean difference = 0.1034s, 95% CI = 0.019 to 0.19, p = 0.022
Fixation	RT	F (17,153) = 24.30, MSE = 0.002, p < 0.0001	mean difference = 0.26s, 95% CI = 0.17 to 0.35, p = 0.0001
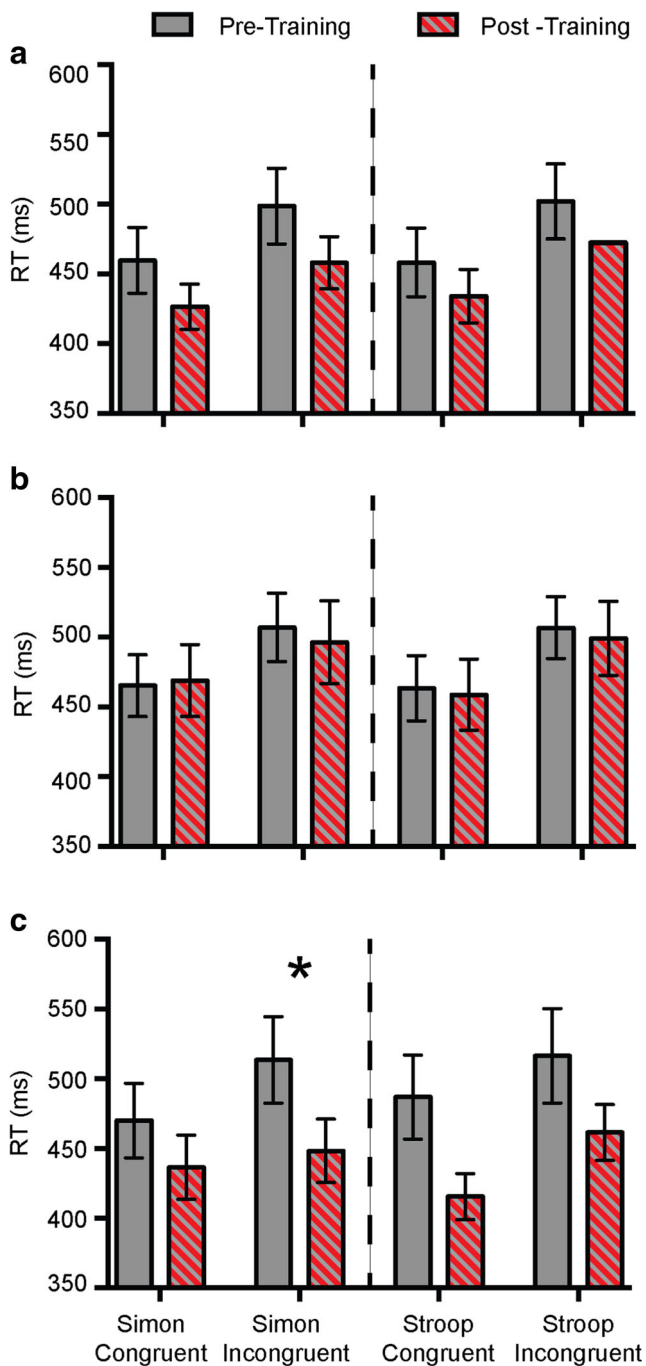
Fig. 4 Mean RT for Simon and Stroop tasks. (**a**) Fixation training did not lead to significant changes in mean RT from pre- (solid gray) to posttraining (patterned red) either for the Simon (left) or the Stroop (right) tasks. (**b**) Pro-saccade training group showed no significant changes in either task after training. (**c**) Anti-saccade training group showed a marked reduction in incongruent RTs between sessions in the Simon Task but not the Stroop task. Error bars indicate 1 SEM. Asterisk indicates $p <$ 0.05

0.15, MSE = 437.8, p = 0.70)]. Hence, training-benefits were specific to the anti-saccade training group.

To determine whether a speed–accuracy trade-off might have accounted for the training-induced changes in performance, accuracy data also were submitted to a group x session x task x congruency omnibus ANOVA. None of the higher-order interactions that included the group factor approached significance (all ps > 0.05). The mean accuracies for all conditions and groups exceeded 90%, indicating reliable accuracies.

Having established that the type of training differentially influenced gains in the Simon task, particularly for incongruent RTs, we examined whether these group differences were evident for effect sizes, i.e., the magnitude of the Simon and Stroop effects (Incongruent RT – Congruent RT), which is the primary index used to quantify inhibitory control. To rule out any residual pretraining differences between group pairs, we subjected the Simon (Fig. 5a) and Stroop (Fig. 5b) effects to an ANCOVA design, with the pretraining effect magnitudes as the controlled covariate.

Our analyses revealed that the group factor again differentially influenced the Simon effect in the posttraining session (F (1,17) = 11.7, MSE = 170.9, p = 0.003, η_p^2 = 0.4), such that the anti-saccade training group showed a significantly greater reduction of the Simon effect compared with the fixation training group [mean difference = 20.1 ms, 95% CI = 1.7 to 39.9, p = 0.003]. Comparing the post-training Simon effects between the Anti-saccade Training group and the Pro-saccade Training group also revealed a similar effect [Mean difference = 19.0 ms, 95% CI = −0.05 to 38.1, p = 0.05]. In contrast, comparing Simon effects for the two control groups in the posttraining session, after controlling for pretraining differences, did not reveal any significant group effects [mean difference = 1.96 ms, 95% CI = −19.9 to 23.9, p = 0.85]. ANCOVAs on data for the Stroop task did not yield significant group effects for any of the group pairs, indicating that unlike the Simon task, the Stroop task was not susceptible to training influences.

Discussion

We asked whether training people to execute anti-saccades can influence performance on inhibitory operations, such as those tapped by the Simon and Stroop effects. Our results reveal that anti-saccade training led to improvements in the Simon task (i.e., a reduction in the magnitude of the Simon effect) but did not extend to the Stroop task. The two control groups—those who underwent fixation training and pro-saccade training—did not show performance benefits following training, further strengthening our conclusions. It would appear that incongruent stimulus-location pairings gained through one motor modality (the eyes) can transfer to another modality (the hands), but the improvements in performance do not generalise to all tasks and consequently do not appear to reflect generalised benefits in inhibitory control.
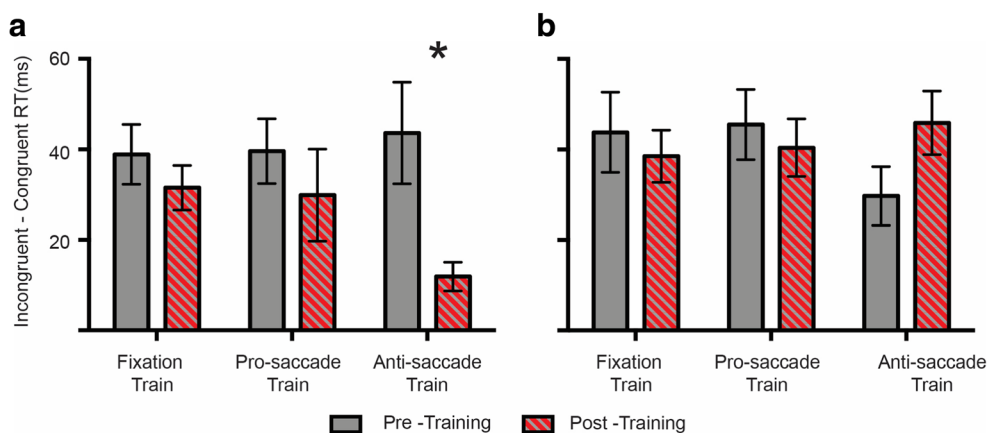
649.2, p = 0.65); pro-saccade training group: Fig. 4b, (F (1,18) = 0.59, MSE = 397.8, p = 0.45)]; or the Stroop task [fixation training group: Fig. 4a, (F (1,18) = 0.11, MSE = 656.5, p = 0.75) and pro-saccade training group: Fig. 4b, (F (1,18) =

Fig. 5 Simon and Stroop effect magnitude. (**a**) Simon effect and (**b**) Stroop effect for all three groups. Solid gray bars indicate pretraining and patterned red bars depict posttraining performance. Error bars indicate SEM

A possible explanation underlying this type of specific transfer can be found in the notion of dimension overlap of the stimulus-response ensemble (Kornblum, Hasbroucq, & Osman, 1990). According to this hypothesis, the extent to which stimulus and response sets share dimensions or attributes, both physical attributes (such as directionality or colour) and mental representations (such as different sensory modalities for the same stimulus or response set), can be used to categorise and account for stimulus-response compatibility effects. It is conceivable that such dimensional overlap may be pivotal even for inducing training-related changes across inhibitory control tasks. In our anti-saccade training task, repeatedly resolving the stimulus-response conflict arising from the cue appearing on one side but requiring an oculomotor response to the other side could have strengthened inhibitory goal-motor associations in the lateralised spatial dimension. Because the Simon task also required resolution of stimulus-response conflicts in a similar spatial dimension (i.e., arrow on one side but manual response on the other), training benefits transferred across the overlapping motor systems—from eye to hand, within this dimension. By contrast, the Stroop task required resolution of conflict in the featural dimension (stimulus-stimulus conflict) in top-bottom locations. Consequently, there was no dimensional overlap between the training and the test tasks and therefore no evidence of transfer. If such dimensional overlap is a prerequisite for observing transfer among inhibitory control tasks, other response inhibition tasks, such as the stop-signal and flanker tasks, the latter of which is reportedly similar to the Stroop (Kornblum et al., 1990), should fail to show transfer following anti-saccade training.

Alternatively, if the Stroop task taps a cognitive-control process, that is perhaps mediated by a distinct cognitive–control system (Bender, Filmer, Garner, Naughtin, & Dux, 2016), anti-saccade training would be expected to speed-up general inhibitory processes. This should translate to improved performance for the other inhibitory control tasks: stop-signal and flanker. To test these predictions, we ran a second experiment

using a battery of test tasks chosen to tap inhibitory control and unrelated cognitive processes. The broad goal was to replicate the results of Experiment 1 to ensure our findings did not merely reflect a type-1 error and to examine the boundary conditions of any transfer effects.

Experiment 2

The results of Experiment 1 showed that improving anti-saccade performance resulted in gains for the Simon task but not for the Stroop task. We speculated that such task specificity might indicate transfer depending on the degree of overlap in the spatial response dimension (Kornblum et al., 1990). To examine this possibility, we trained a fresh set of participants using either pro-saccade or anti-saccade training regimens. A key element of this experiment was the inclusion of an extended set of test tasks, which included the integrated Simon and Stroop task from Experiment 1, as well as a stop-signal task and a flanker task, both of which tap a different set of inhibitory mechanisms (Bender et al., 2016) while also sharing some common neural substrates in the anterior cingulate and left prefrontal cortex (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003). We also included two nonassociated test measures: the *Psychological Refractory Period* (PRP), a multitasking phenomenon in which there is a delay in responding to a second stimulus if it occurs closely in time after the first stimulus; and a *visual search* task, which measures the efficiency of searching for a target shape amongst a varying number of similarly shaped distracter items.

Experimental overview

Just as in Experiment 1, participants underwent a pretraining test session and a posttraining test session, this time separated by three as opposed to 2 consecutive days of training (Day 1, Day 2, and Day 3). In Experiment 2, we included just two groups of participants—an anti-saccade training group and a

pro-saccade training group, because in Experiment 1 participants in the fixation training group performed similarly to those in the pro-saccade training group (Fig. 5). On each training day, participants completed 10 blocks of *training* trials, with 40 trials per block, resulting in 1,200 training trials in all. During the pre- and posttraining test sessions, participants completed the following five tasks in counterbalanced order: 1) integrated Simon and Stroop, 2) flanker, 3) stop-signal, 4) PRP, and 5) visual search. The additional tasks have all been tested previously in our laboratory and showed high test–retest reliability (Bender et al., 2016; Garner et al., 2014).

Participants

We tested 35 new participants, 7 of whom had to be excluded (1 due to drop-out, 1 because of missing pretraining data for one task, and 5 because they failed to show either a significant Simon or a Stroop effect [Incongruent – Congruent RT < 0] in the pretraining session). The remaining 28 participants were assigned to either the anti-saccade training group [n = 14, average age = 19.5 years (SD = 1.6), females = 8, right-handed = 14, years of education = 13.8 years (SD = 1.1) or the pro-saccade training group [n = 14, average age = 22.1 years (4.9), females = 10, right-handed = 13, years of education = 15.3 (2.1)] using the same balancing procedure as employed in Experiment 1. Again, this procedure was successful at minimising baseline differences. An independent samples *t* test was conducted to compare pretraining Simon effects in the pro-saccade and anti-saccade training groups. There were no significant differences in performance (pro-saccade, mean = 52.9 ms, SEM = 4.7; anti-saccade, mean = 47.1 ms, SEM = 7.0, [t (26) = 0.68, *p* = 0.5]. All participants were awarded credits (1 credit per hour) for their time in accordance with institutional ethics.

Materials

The materials, stimuli, and procedures for the training tasks were identical to those used in Experiment 1. However, the test tasks were presented on a 21-inch CRT monitor (100 Hz) using Apple mini computers in combination with Psychophysics Toolbox (Version 3; (Brainard, 1997; Pelli, 1997) for Matlab (R2015b, MathWorks).

Test tasks

Five test tasks were administered to each participant in the pre- and posttraining sessions. The structure of the integrated Simon and Stroop task was identical to that described in Experiment 1, where participants indicated whether a briefly presented arrow pointed upwards or downwards by depressing either the F (right index finger) or the J key (left index finger) as quickly and accurately as possible (Fig. 1).

Flanker task

As shown in Fig. 6a, participants were briefly (200 ms) presented with a central arrow (> or <) and were required to press the corresponding > key or < key, regardless of the direction in which the two flanking arrows pointed. Specifically, on incongruent trials, the flanking arrows were designed to face in the opposite direction from the central arrow (Fig. 6a), whereas on congruent trials all the arrows pointed in the same direction (e.g., >>>>>). Neutral trials were included, such that the flankers were two dashes instead of arrows (e.g., - - < - -). Each trial was preceded by a variable fixation period (200-600 ms) and terminated at the end of an 1,800-ms response window. Each participant completed 24 practice trials followed by 4 blocks of 36 trials with equal representations of all trial types (congruent, incongruent, and neutral). The key measure in this task was the "flanker effect" calculated as the difference in RTs between congruent and incongruent trials. A smaller difference in RT indicated less susceptibility to flanker induced conflict and hence better performance.

Stop-signal task

For this task, participants had to perform a two-alternative forced choice task in which they differentiated between two abstract target shapes (Fig. 6b), which were mapped to the F and J keys, respectively. Participants were required to respond as quickly and accurately as possible, except when the target shape was followed by an auditory tone (750-Hz sine-wave tone, 200-ms duration), which required participants to withhold their response. These stop trials occurred 25% of the time and the stop-signal delay (SSD), referring to the time interval between the shape onset and the auditory stop-signal onset, was continuously manipulated through an adaptive staircase procedure such that participants successfully inhibited their response on 50% of the stop-signal trials (Logan, Schachar, & Tannock, 1997). Similar to previous work (Bender et al., 2016), the initial SSD was set at 250 ms, and then depending on participants' accuracy in inhibiting their response, the SSD was adjusted by 50 ms (increments if correct and decrements otherwise). Participants were provided 24 practice trials and again four blocks of 36 test trials. The dependent variable was the stop-signal RT (SSRT), calculated as mean go RT minus mean SSD (Logan et al., 1997). Lower SSRTs represent better inhibitory performance.

PRP task and visual search task

To ensure that any potential training benefits in the inhibitory control tasks could be attributed solely to changes in inhibitory processes and not more general operations (Redick et al., 2013), a PRP task and a visual search task were included in our test battery. In the PRP paradigm,
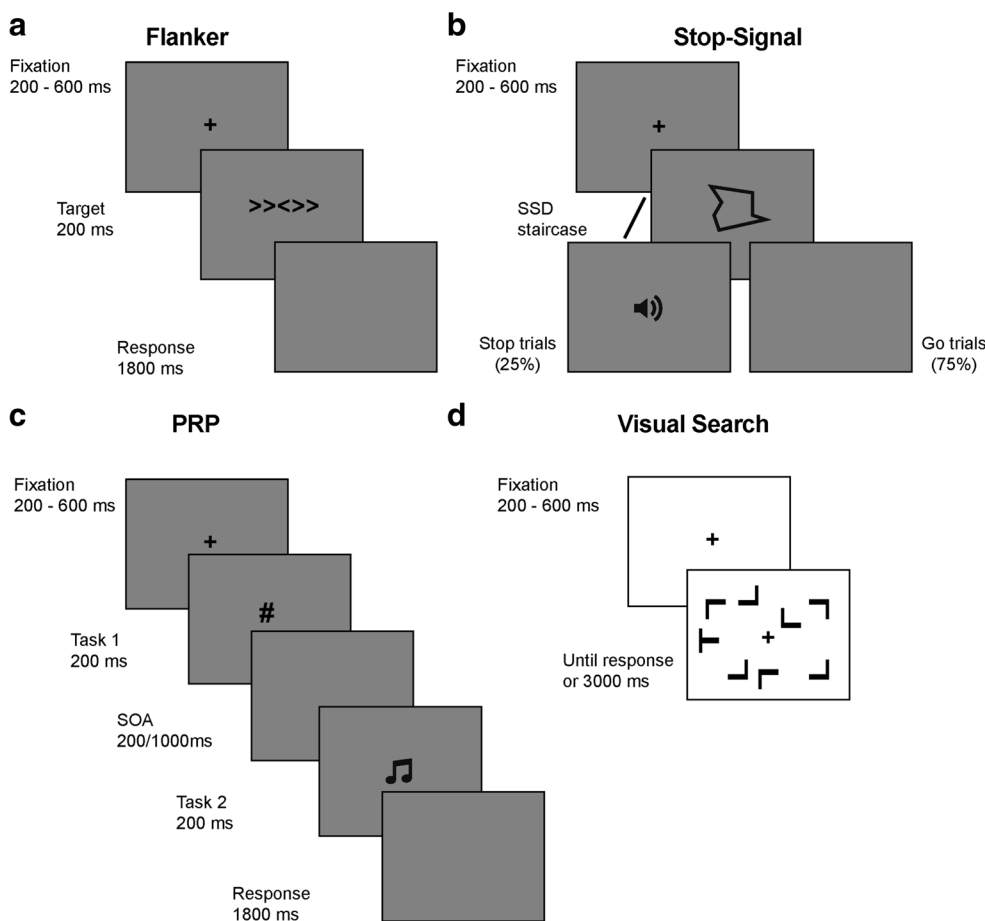
Fig. 6 Experiment 2 test battery. (**a**) *Flanker task*: Participants had to report the direction of the central arrow that was flanked by arrows that were either pointing in the opposite direction (incongruent), the same direction (congruent), or were neutral (dashes) symbols. (**b**) *Stop-signal task*: Participants performed a shape discrimination task on go-trials and withheld their response on stop trials. Stop trials were characterized by an auditory tone, presented after a variable delay following shape onset. (**c**)

Psychological refractory period (PRP) task: This paradigm comprised two tasks—a visual symbol identification task and an auditory tone discrimination task. Participants had to perform both tasks as quickly and accurately as possible, regardless of the short/long delay between the two tasks. (**d**) *Visual search task:* Participants searched for an oriented T (90° or 270°) among 7, 11, or 15 Ls, as quickly and accurately as possible

the participants' first task (T1) was to identify one of four briefly presented symbols (%, &, @, or #) as quickly and accurately as possible using individually predetermined and counter-balanced mappings to their left hand (A, S, D, or F keys) or right hand (J, K, L, or semi-colon keys). The second task (T2) was to identify one of four complex tones (same as those used in Bender et al., 2016), again mapped to one of the two hand responses (opposite hand to that used for T1). Participants were familiarised with the mappings through a practice phase with 3 blocks of 20 trials. The first block was allocated to just the T1 stimuli, the second block to only T2 stimuli, and in the third block participants were required to respond as quickly and accurately as possible to both tasks. This third practice block resembled the experimental phase, for which participants completed 4 blocks of 40 trials. Each trial began with a variable fixation period (200-600 ms), after which T1 and then T2 stimuli were presented (200 ms each),

separated by a stimulus onset asynchrony (SOA) of either 200 ms (short SOA) or 1,000 ms (long SOA). The dependent measure was the PRP effect (Pashler, 1994), defined as the difference between mean RT for T2 following a long SOA versus a short SOA. Typically, a smaller PRP magnitude indicates better dual-task performance.

Finally, the visual search task (Fig. 6d) was a classic inefficient search paradigm (Kwak, Dagenbach, & Egeth, 1991) involving the presentation of a target (the letter T rotated by 90° or 270°) among 7, 11, or 15 randomly placed and rotated distractors (Ls). Participants identified the target orientation by pressing the A or Z keys on a standard keyboard using the index and middle fingers of their dominant hand as quickly and accurately as possible. The search array was displayed for 3 s or until response. Participants were given 12 practice trials and then completed 6 blocks of 24 trials with equal representation of each set size.

Data analyses

As in Experiment 1, RTs that were either <200 ms or >3 standard deviations from the participant's mean RT for each condition were removed. Having established that training in-duced changes are observed both in the RT data and the *dif-ference scores* (Incongruent minus Congruent RT), we re-stricted our analyses to difference measures across all tasks while assessing for baseline differences. Hence, the critical performance measures in this experiment were the Simon and Stroop effect, flanker effect, SSRT, and PRP. Data from each of these tasks were subjected to an omnibus ANOVA analysis to determine if any group-based differences were seen between pre- and posttraining sessions. Relevant differences were followed up with planned pairwise comparisons to elucidate the direction of these training-evoked changes.

Results

Training session

Our first objective was to examine whether training effects were comparable for participants in the two training groups: pro-saccade and anti-saccade training. As depicted in Fig. 7a, the latency data showed group differences. There was a sig-nificant 2 group × 30 block interaction [$F_{(29,754)} = 1.77$, MSE = 0.003, $\eta_p^2 = 0.06$, $p = 0.008$, RM-ANOVA], as well as a significant main effect of block [$F_{(29,754)} = 7.2$, MSE = 0.003, $\eta_p^2 = 0.22$, $p < 0.0001$]. The significant interaction can be interpreted as the anti-saccade training group showing sig-nificantly greater latency improvement as a result of training than the pro-saccade training group. Closer examination of pairwise comparisons between the means from first and last training blocks for the two groups confirmed this conclusion [pro-saccade training: mean difference = 0.02 s, 95% CI = −0.02 to 0.061, $p = 0.24$; anti-saccade training: mean differ-ence = 0.17 s, 95% CI = 0.13 to 0.21, $p < 0.0001$].

This is not surprising, because the generation of pro-saccades is a reflexive and automatic process (Fischer, Gezeck, & Hartnegg, 2000) and is therefore already at ceiling. Importantly, the two groups showed no significant group x block interactions for the RT data [$F_{(29,754)} = 0.59$, MSE = 0.004, $\eta_p^2 = 0.02$, $p = 0.9$, RM-ANOVA] and instead only a steady improvement across blocks [Fig. 7b; $F_{(29,754)} = 48$, MSE = 0.004, $\eta_p^2 = 0.65$, $p < 0.0001$]. Therefore, both pro-saccade training and anti-saccade training beneficially influ-enced performance on the trained task.

Test sessions

We analysed data from each of the five test tasks—integrated Simon and Stroop, flanker, stop-signal, PRP, and visual search—separately to determine whether enhancing inhibition
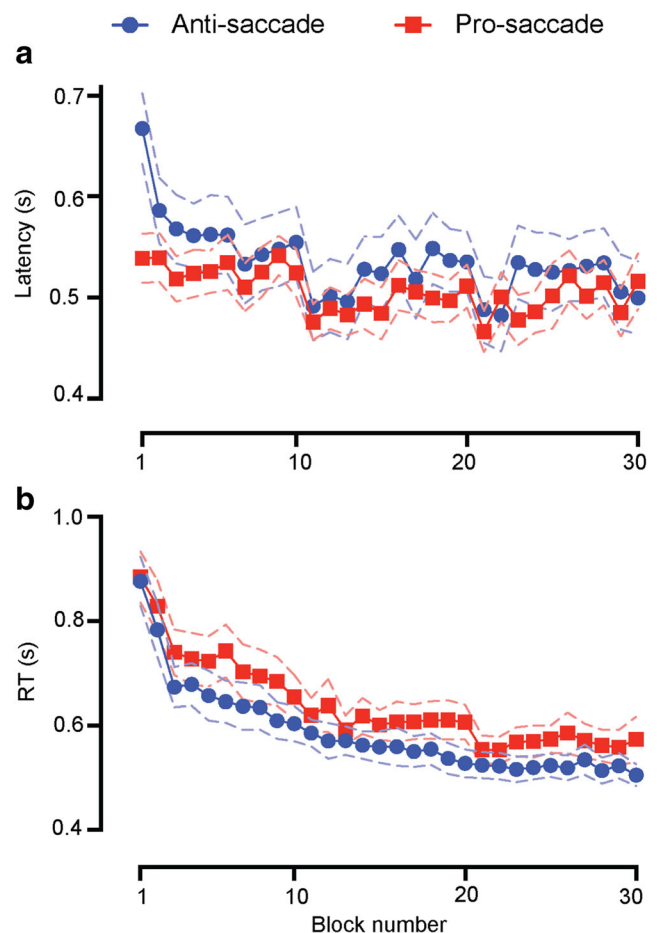

Fig. 7 Experiment 2: effect of training on saccade latency and target reaction time. (**a**) Top panel shows a significant reduction in saccade latencies across 30 blocks of training for the anti-saccade training group (blue circles) but a more subdued modulation of latencies for the pro-saccade training group (red squares). (**b**) The reduction in RT over the course of training is similar for all three training groups. Error bars denote SEM

via anti-saccade training impacted performance on any of the other these measures. To verify that there were no baseline differences between groups at the pretraining session, we ran one-way ANOVAs to compare group means of the effect sizes for each task. No pretraining differences between groups were observed for any of the five tasks [nonsignificant main effects of group, Simon: $F_{(1,26)} = 0.47$, MSE = 500.3, $\eta_p^2 = 0.18$, $p = 0.5$; Stroop: $F_{(1,26)} = 0.002$, MSE = 773.2, $\eta_p^2 < 0.0001$, $p = 0.97$; flanker: $F_{(1,26)} = 0.65$, MSE = 4262.4, $\eta_p^2 = 0.02$, $p = 0.43$; stop-signal: $F_{(1,26)} = 0.34$, MSE = 5074.5, $\eta_p^2 = 0.01$, $p = 0.57$; PRP: $F_{(1,26)} = 2.1$, MSE = 55584.1, $\eta_p^2 = 0.08$, $p = 0.16$; Search: $F_{(1,26)} = 0.37$, MSE = 545.6, $\eta_p^2 = 0.01$, $p = 0.55$].

Integrated Simon-Stroop task

Before using difference measures or effect sizes (incongruent minus congruent) as the key measure in our analyses, we

subjected the pretraining RT data to a 2 task (Simon, Stroop) × 2 congruency (incongruent, congruent) × 2 group (pro-saccade, anti-saccade) ANOVA and found no evidence of group x congruency [F (1,26) = 0.17, MSE = 405.3, η_p^2 = 0.006, p = 0.69] or group x task x congruency [F (1,26) = 0.22, MSE = 231.4, η_p^2 = 0.008, p = 0.65] interactions, thus confirming that there were no pretraining differences between groups. We then used difference scores to test whether the findings from Experiment 1 were replicated. Again a significant 3-way interaction was observed [2 groups (pro-saccade, anti-saccade) × 2 tasks (Simon, Stroop) × 2 sessions (pre, post); F (1,26) = 4.3, MSE = 700.9, η_p^2 = 0.14, p = 0.049], indicating group-based differences in relation to task, from the pretraining to the posttraining session. We followed up this interaction by examining each group and each task separately. As expected, for the Simon task, the anti-saccade training group showed a significant main effect of session [F (1,13) = 8.3, MSE = 530.2, η_p^2 = 0.39, p = 0.01] such that mean performance in the posttraining session [Fig. 8a, mean = 21.9 ms, SEM = 5.3] was significantly better than that in the pretraining session [Fig. 8a, mean = 47.1 ms, SEM = 7.0]. In contrast, comparing pre- [mean = 52.9 ms, SEM = 4.7] and posttraining [mean = 43.4 ms, SEM = 8.4] performance for participants in the pro-saccade training group failed to show significant differences between sessions [Fig. 8a, F (1,13) = 1.4, MSE = 434.4, η_p^2 = 0.1, p = 0.25]. This is consistent with our conclusion from Experiment 1 that training gains arose only for the anti-saccade training group in the Simon task.

Similar mixed-model ANOVA comparisons were run for the Stroop task, but no significant main effect of session was found for the anti-saccade training group [Fig. 8b, F (1,13) = 0.179, MSE = 137.3, η_p^2 = 0.01, p = 0.68] or the pro-saccade training group [F (1,13) = 3.9, MSE = 799.1, η_p^2 = 0.23, p = 0.07]. Hence, unlike the Simon effect, the Stroop effect was not significantly influenced by anti-saccade training.

Flanker task

For the flanker task, there was no significant group x session interaction [F (1,26) = 0.01, MSE = 4058.8, η_p^2 < 0.0001, p = 0.91], suggesting no evidence for an effect of training on this measure. In addition, there was no significant main effect of session [F (1,26) = 0.42, MSE = 4058.8, η_p^2 = 0.02, p = 0.52; Fig. 9a] or group [F (1,26) = 0.52, MSE = 8656.5, η_p^2 = 0.02, p = 0.48], suggesting that the flanker effect was unaffected by either type of training.

Stop-signal task

If anti-saccade training influenced the stop-signal task, we would have expected a 2 session × 2 group interaction. Analyses of the mean stop-signal RT (SSRT) data failed to show any significant interaction effects [Fig. 9b; F (1,26) = 2.5, MSE = 8682.1, η_p^2 = 0.09, p = 0.13], however, and there were no significant main effects of session [F (1,26) = 0.26, MSE = 8682.1, η_p^2 = 0.01, p = 0.62] or group [F (1,26) = 3.4, MSE = 12402.4, η_p^2 = 0.12, p = 0.08].

PRP and Visual search task

For both the PRP and visual search tasks, there was no session x group interaction for either the Task 2 PRP [Fig. 9c, F (1,26) = 0.61, MSE = 25728, η_p^2 = 0.02, p = 0.44] or search efficiency [Fig. 9d, F (1,26) = 0.96, MSE = 247.9, η_p^2 = 0.12, p = 0.08]. Thus, it is clear that the control-tasks were not differentially influenced by pro-saccade or anti-saccade training.

Discussion

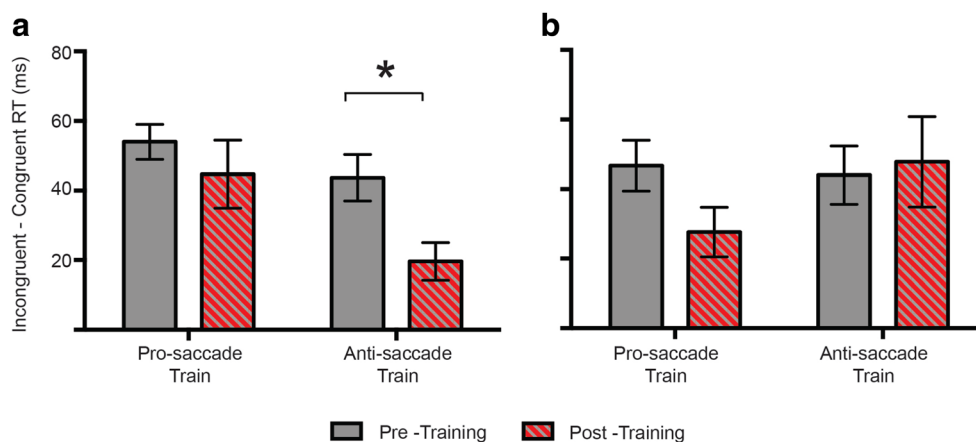In Experiment 2, we showed that training was effective for both the anti-saccade and pro-saccade groups.

Fig. 8 Comparison of performance before and after training for the integrated Simon-Stroop task. (**a**) For the Simon task, there is a marked reduction of the Simon effect following anti-saccade training (significance denoted by asterisk). (**b**) The Stroop task, however, shows no significant effect of training for either the pro-saccade or the anti-saccade training groups. Solid graybars represent pretraining data, and patterned red bars correspond with posttraining data. Error bars denote SEM
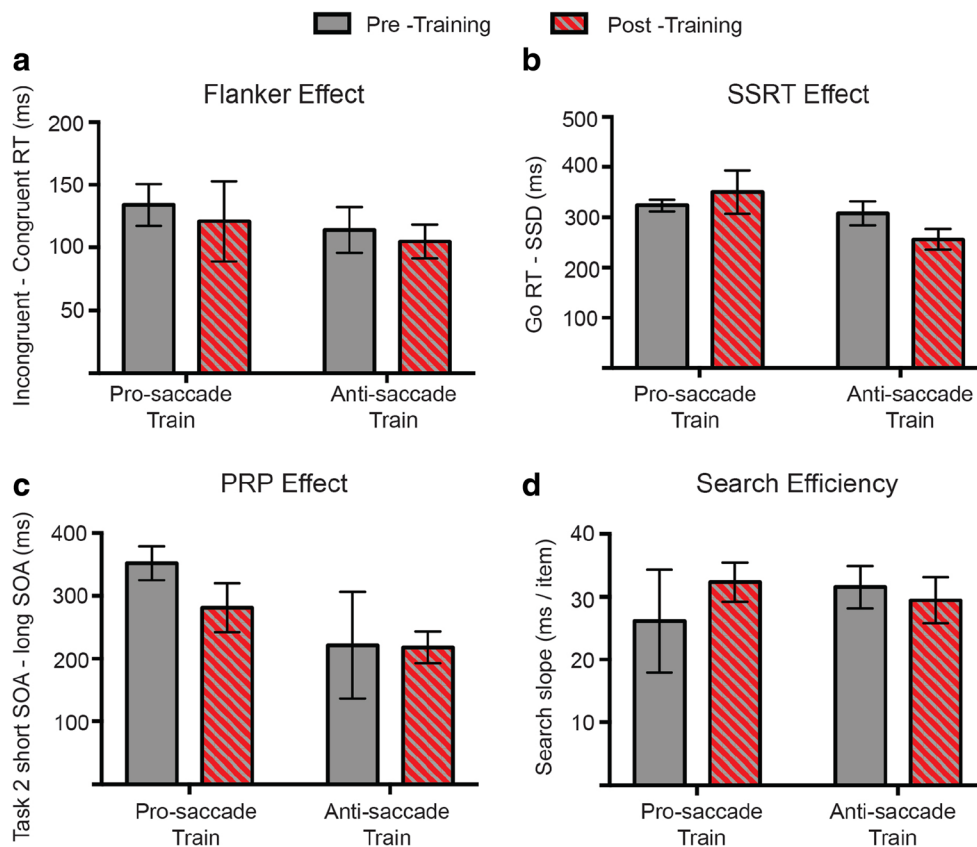
Fig. 9 Effect of training across tasks in Experiment 2. The two inhibitory tasks, (**a**) flanker and (**b**) SSRT, showed no significant modulation before or after training for either group. Similarly, the two control tasks, (**c**) the PRP effect and (**d**) search efficiency measures, showed no training-induced changes. Solid gray bars show pretraining and patterned red bars show posttraining results. Error bars denote SEM

Importantly, we replicated the findings from Experiment 1 by showing that training gains garnered through anti-saccade training transferred across motor response modalities and successfully reduced the Simon effect. Conversely, participants in the pro-saccade training group did not show similar training-related improvements for the Simon task. Interestingly, we found no evidence for differential transfer between groups for any of the other response inhibition tasks—Stroop, flanker, and stop-signal tasks—indicating high task specificity for anti-saccade training.

We hypothesized that if the role of anti-saccade training was to enhance general inhibitory processes, performance in the Stroop, flanker, and stop-signal tasks would show improvements following training. Contrary to this prediction, we found that anti-saccade training benefits generalized only to the Simon task, just as in Experiment 1. This supports our proposition that while transfer of inhibition benefits from one motor modality to another is possible, it requires some form of dimensional overlap (Kornblum et al., 1990). In this case, similar stimulus-location mappings for both the training and test tasks appear to be the prerequisite.

General discussion

Inhibitory control is widely considered to be an important factor in cognitive and behavioural regulation (Diamond, 2013). Training inhibitory control and establishing transfer to other tasks is important, because it could potentially impact performance on executive tasks, such as planning and decision making, which are tightly coupled with inhibitory processes (Bechara, 2005). We tested the hypothesis that inhibitory control in one motor modality (hands) can be modulated via training of inhibitory control in a different modality (eyes). Our results indicated that training anti-saccades leads to generalization of training benefits to a different context. Specifically, the Simon effect did not change following fixation training (Experiment 1) or pro-saccade training (Experiments 1 and 2) but did show a significant reduction after anti-saccade training. A second important finding was that none of the other inhibitory measures—the Stroop, flanker and stop-signal tasks—were differentially modulated by Anti-saccade training. We speculate that the Stroop task and the flanker task required resolution of conflict in the same dimension (stimulus-stimulus conflict), and because no stimulus-location associations were made, this may have prevented any transfer.

Similarly, the stop-signal task taps a distinct inhibitory mechanism from flanker and Stroop (Bender et al., 2016), which likely explains the lack of transfer. Indeed, Manuel and colleagues (Spierer et al., 2013) have suggested that if active inhibition is trained through varied nonpredictive mappings, top-down inhibitory control will constantly need to be engaged and, as a result, will be strengthened. This strengthening of inhibitory control could potentially carry over to enhance inhibitory control in other tasks. It may be the case that our anti-saccade training approach, which required repeatedly resolving the stimulus-location conflict arising from the cue appearing on one side but an oculo-motor response being required on the other, strengthened inhibitory goal-motor associations, such as acquiring a "respond opposite" strategy (Vu, 2007). This associative learning may have influenced the Simon task, because it generates stimulus-response conflict, albeit in a different modality (i.e., an arrow on one side and a manual response on the other).

Our finding that the Simon effect can be reduced through training is in agreement with previous work documenting decreases in the Simon effect following training with spatially incongruent stimuli (Iani, Rubichi, Gherri, & Nicoletti, 2009; Soetens, Maetens, & Zeischka, 2010). Along similar lines, Welch and Seitz (2013) demonstrated that practicing the Simon task with infrequent breaks resulted in learned inhibition briefly generalizing to other contexts. These authors suggested that their results were in line with models that emphasize a gating or suppression of automated responses following training with incongruent trials (Hommel, Proctor, & Vu, 2004; Valle-Inclan & Redondo, 1998) as opposed to models that suggest an attentional shift (Notebaert, Soetens, & Melis, 2001). According to the latter, training strengthens attentional processes and specific spatial stimulus codes, which results in reduced Simon effects (Welch & Seitz, 2013). While the results from our study do not specifically disentangle the two models, they do show that even learning broad associations, such as a "respond opposite" rule (Vu, 2007) in the anti-saccade training task, can be applied to different contexts provided they share a common dimension (lateralized stimulus attributes for both tasks), as per the dimension overlap model (Kornblum et al., 1990). This dimension overlap model also could explain the lack of transfer to the other inhibitory tasks—namely Stroop, flanker and stop-signal tasks—none of which share a common dimension in terms of stimulus response/location sets. According to this model, even the flanker task, which incorporates arrows, has been categorised in the same subtype as the Stroop task (Kornblum & Lee, 1995) and requires featural conflict resolution.

The dissociation between conflict resolution in the Simon and the Stroop tasks in Experiment 1 (and replicated in Experiment 2) has been consistently reported in previous studies (Liu, Park, Gu, & Fan, 2010; Pratte et al., 2010). Despite latent variable analyses indicating that the Stroop task

(specifically Stroop-colour) and the anti-saccade task load on a single factor (Friedman & Miyake, 2004), other inhibition training studies have found no evidence of transfer to the Stroop task (Enge et al., 2014; Millner et al., 2012; Zhao, Chen, Fu, & Maes, 2015). For example, in Enge et al.' (2014) large scale (N = 122) training study, in which participants trained on an adaptive go/no-go task and a stop-signal task intermittently over 3 weeks, significant improvements were observed in the trained task, but there was no transfer to the Stroop task. Likewise, Millner et al. (2012) found transfer from inhibition training on a combined Simon task and an emotional go/no-go task to a flanker task but not to an emotional Stroop task (although the lack of control groups in this study is problematic).

Because all three training groups—fixation, pro-saccade and anti-saccade—showed similar performance improvements in the training phase and received similar performance feedback, the differential effects of training on test outcomes cannot be attributed to test-retest or placebo effects (Shipstead et al., 2012). Moreover, during the training phase all the groups performed the same motor task of responding to an oriented Gabor using stimulus-response mappings that were distinct from the mappings used in the test task, thereby ensuring that any associative learning was not tied to specific stimulus features. Hence, the most parsimonious explanation for group based-differences in the Simon task following training seems to be strengthened associative learning across spatial motor dimensions. Whether the gains in inhibitory control are a by-product of improved attentional shifts (Notebaert et al., 2001) to lateralised locations or better suppression of automated responses (Valle-Inclan & Redondo, 1998) to lateralised stimuli remains an open question. Along the same lines, if anti-saccade training were conducted in the vertical dimension, the extent of dimensional overlap between this task and the spatial Stroop task used here would have been greater (because responses for both tasks would have a vertical reference). Whether this would hinder or help posttraining performance is also a question for future research. Regardless, our results demonstrate reliable transfer of gains in inhibitory control across motor modalities and tasks.

The idea of such transfer across motor systems is empirically supported by studies examining whether priming effects transfer across motor effectors (Moher & Song, 2014, 2016). In these studies, participants had to report if a uniquely coloured target was present, either by making an eye-movement or a reaching movement depending on a pretrial cue. Priming effects (faster responses for consecutive trials with the same colour) were found regardless of the response mode, suggesting that target selection effects transferred across motor systems. The present results suggest that this is true even for inhibition, where training effects transfer across response modes, albeit only in the Simon task.

Another question raised by our study is whether increasing the "dosage" of training could elicit more long-term transfer (Soetens et al., 2010). While previous studies have successfully modulated the Simon effect using short-term associations ranging between 84-600 spatially incompatible practice trials (Proctor, Marble, & Vu, 2000; Proctor, Yamaguchi, Zhang, & Vu, 2009; Tagliabue, Zorzi, Umilta, & Bassignani, 2000), it would be worthwhile to examine if more prolonged training (Dyckman & McDowell, 2005) might elicit lasting changes. It also will be important to examine whether using other spatially lateralized tasks, such as a go/no-go Simon task (Lugli, Iani, Nicoletti, & Rubichi, 2013), would show corresponding gains in performance as a result of anti-saccade training. In a similar vein, it will be important to assess whether transfer to even broader tasks involving planning and decision-making, which rely on effective inhibitory control (Verbruggen et al., 2012), can be achieved.

Understanding how humans resolve conflicting sensory information may aid in the development of techniques for training people to be better at everyday tasks, such as driving or playing sports, where effective inhibitory control is essential. Enhancing impaired inhibition might be usefully applied in clinical settings. The present results demonstrate that transfer of inhibition training gains is possible and highlight the boundary as well as necessary conditions under which such transfer can be observed.

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