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Persistent modification of cognitive control through attention training

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Abstract

An important aspect of cognitive control is to direct attention towards relevant information and away from distracting information. This attentional modulation is at the core of several influential frameworks, but its trainability and generalisability remain unclear. To address this issue, two groups of subjects were invited to the lab on three consecutive days. On Day 2, they performed an arrow priming task which trained them to adopt an attentional bias towards (prime-attended group) or away from (prime-diverted group) a potentially conflicting prime. Direct generalisation of the attention training was measured by assessing task performance on the same task without the attentional manipulation directly after training (Day 2) and the next day (Day 3), and comparing it to baseline (Day 1). Performance on this direct transfer task showed a difference in attentional modulation between groups directly after training that persisted the next day. No cross-task generalisation was found to two other tasks that were closely or more remotely related to the trained task. Together, these results are in accordance with cognitive control frameworks that limit attentional modulation to the specific features of the trained task.

Keywords

Attention; cognitive control; training; generalisation; conflict

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Introduction

Focusing on relevant and ignoring irrelevant information is crucial for efficient goal-directed behaviour. This adaptive behaviour is needed whenever we are in conflict about what to do. For example, when an outdated global positioning system (GPS) points us in a different direction than the road signs, conflict emerges that needs to be resolved by ignoring the GPS and following the signs. This requires cognitive control, or a flexible adjustment of behaviour to overcome dominant response tendencies in favour of more appropriate behaviour.

Given its importance, a question of interest is whether cognitive control can be trained. Most studies that have addressed this issue implemented training by having subjects perform a specific task repetitively on multiple days. Training effects are then inferred from increased performance on the task. For example, studies on response inhibition using stop-signal and go/no go tasks have shown significant improvement in task performance over the course of training (Berkman, Kahn, & Merchant, 2014; Ditye, Jacobson, Walsh, & Lavidor, 2012; Oelhafen et al., 2013). Other training programmes have incorporated multiple tasks, targeting different domains of cognitive control such as response inhibition as well as conflict resolution. These programmes have generally yielded mixed results. Improvement was found on some of the trained tasks but not on others, and transfer to non-trained tasks often showed ambiguous patterns (e.g., Maraver, Bajo, & Gomez-Ariza, 2016; Thorell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009). Other studies that have shown changes in cognitive control through training should be interpreted with caution because active control

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groups were missing or showed improvements similar to the trained groups (Enge et al., 2014; Millner, Jaroszewski, Chamarthi, & Pizzagalli, 2012; see also Boot, Simons, Stothart, & Stutts, 2013).

The approach to combine different aspects of cognitive control in one training programme may be justifiable from a practical and clinical point of view (i.e., in order to design a programme that can improve cognitive functioning more generally). However, it may hinder theoretical inferences on the trainability of cognitive control. For example, when a training programme consists of several tasks targeting different subdomains of cognitive control, it is hard to ascertain which (combination of) trained processes contribute to the obtained training effects. If a diverse range of transfer tasks is further added to the programme, it becomes nearly impossible to isolate the specific mechanisms underlying changes in cognitive performance. In this study, we therefore focused on just one specific aspect of cognitive control, namely, modulation of attention towards relevant information and away from distracting, irrelevant information. This is an important cognitive control process according to several influential frameworks (Abrahamse, Braem, Notebaert, & Verguts, 2016; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver, 2012; Egner, 2008). Yet, the exact boundaries of this attentional modulation, for example, with regard to its generalisation over tasks, are unclear.

Associative learning accounts of cognitive control predict clear limitations to such generalisation. According to these accounts, generalisation is specific to currently active stimulus, response, and goal features (Abrahamse et al., 2016). For example, Verguts and Notebaert (2008, 2009) proposed that conflict elicits arousal which in turn stimulates a Hebbian learning mechanism that binds all representations that are active at that moment. Since the task goal to attend to the relevant stimulus dimension is one of these active representations, the result is an increased top-down attention to this dimension. In a Stroop task, this would mean that on a conflicting trial (e.g., the word RED printed in blue), the association between the current colour (blue) and the active task goal to respond to the colour is strengthened. This leads to some generalisation within the same task, namely, enhanced attention, not only to the current colour (blue) but also to the other colours of the task that are also slightly active. This in turn increases attention to the relevant dimension (i.e., colour) on subsequent trials.

Whereas generalisation of control across tasks sharing stimulus and response features has been demonstrated (e.g., Braem, Verguts, & Notebaert, 2011), it is still an open question to what degree generalisation exceeds concrete task features and extends to tasks sharing more abstract features. It has been suggested that overlap between contextual cues such as stimulus category, task difficulty, task requirement, or temporal context is sufficient to elicit generalisation. These contextual cues may trigger the retrieval of goal representations, such as "attend to colour." Generalisation to novel tasks that share any of these attentional settings may then occur (Abrahamse et al., 2016; Egner, 2014).

Generalisation of attention can be studied in several ways. Most studies on generalisation of attention have not used training, but rather cross-task paradigms where trials of two different tasks alternate. Although there is some evidence for cross-task generalisation of attentional modulation on a list-level (e.g., Torres-Quesada, Funes, & Lupiáñez, 2013; Wühr, Duthoo, & Notebaert, 2015), most paradigms do not support generalisation (for reviews, see Braem, Abrahamse, Duthoo, & Notebaert, 2014; Egner, 2008). For the current purpose, these paradigms have the disadvantage that they require task-switching. Since task-switching itself also requires cognitive control, it may mask or interact with attentional adjustments in control (Egner, 2008). Contrarily, in training paradigms, trial-by-trial task-switching is not required. However, so far, evidence for cross-task attentional modulation after training is also ambiguous (e.g., Enge et al., 2014; Millner et al., 2012; Thorell et al., 2009).

In short, it has been claimed that cross-task attentional modulation is more likely if tasks overlap, but it is not entirely clear which (combinations of) features need to be shared between tasks (see also Yeung, 2013). One reason why generalisation is difficult to obtain may be because subjects are inclined to utilise lower level associations (e.g., at the stimulus or response level), if available. Binding of attentional settings to specific stimuli or responses (Abrahamse et al., 2016; Verguts & Notebaert, 2009) may hinder transfer to tasks with different stimuli or responses. It has been suggested that only when lower level associations are not apparent or rendered impractical, more abstract associations may be exploited to improve task performance (Bugg, 2014). In that case, similar task structure or temporal vicinity might be sufficient for attentional settings to generalise (Egner, 2014).

The goals of this study were to train subjects in attention modulation in the context of a conflict task and to test the trainability and generalisability of this modulation. The trained task consisted of a sequential presentation of a prime and target arrow. Subjects were taught to direct attention either towards or away from the prime. The overlap between trained and transfer tasks was varied across tasks from concrete features, such as stimuli, to more abstract features, such as task goal. Crucially, all tasks had a similar task structure and allowed for the same attentional settings. This way, the scope of the induced attentional manipulation could be assessed. For example, if the attentional setting induced by the training is bound to specific task stimuli, then transfer to tasks with different stimuli would not be expected. On the other hand, if the attentional settings are associated to more general task features such as the task structure (i.e., prime followed by

Table 1. Task administration.

Task type	Task	Day 1	Day 2	Day 3
Training	Arrow priming with attentional manipulation: *Prime-attended* *Prime-diverted*		X	
Direct transfer	Arrow priming	X	X	X
Close transfer	Number priming	X		X
Far transfer	AX-CPT	X		X

X signals which tasks were administered on that day.
AX-CPT: AX-Continuous Performance Task.

target), then a more widespread generalisation may be observed, for example, to tasks with different stimuli.

Two groups of subjects received 1 hr of training on a task consisting of a potentially conflicting prime arrow followed by a target arrow. During the task, subjects received main trials and inducing trials. On main trials, subjects had to respond to the target arrow which could be congruent (i.e., pointing in the same direction as the prime) or incongruent (i.e., pointing in a different direction as the prime). On inducing trials, subjects in the prime-focused group had to adhere to specific instructions that were aimed to increase attention to the prime, thereby increasing the congruency effect (CE, that is, difference in performance between incongruent and congruent trials). For the prime-diverted group, the instructions were aimed at decreasing attention to the prime, thereby decreasing the CE. We argued that subjects might apply this implicitly acquired attentional strategy to the main trials too, thereby creating a task-wide or even cross-task bias towards or away from the prime.

Subjects came to the lab on three consecutive days. On Day 2, they performed a 1-hr training. The first goal of the study, as it is a premise for examining direct and cross-task training effects, was to assess whether an effective attentional modulation on the trained task could be achieved, as evidenced by a larger CE on the main trials for the prime-focused group than for the prime-diverted group.

The second goal was to measure the direct generalisation of this CE. For this reason, a direct transfer task was administered before training (pre-test, Day 1), immediately after training on the same day (post-test, Day 2), and the day after training (post-test, Day 3; Table 1). The direct transfer task consisted of a priming task similar to the trained task, without the attentional manipulation but using the same stimuli (arrows). This allowed assessment of the survival of the induced attentional strategy (i.e., focus on prime or not) directly after training and after 24 hr.

In addition to the direct transfer task, we also administered close and far transfer tasks on Days 1 and 3. The close transfer task had a similar task structure as the trained and direct transfer task, but used different stimuli (numbers instead of arrows). If similarity of stimuli is required for generalisation, then transfer from the training to the close transfer task should not occur. If similarity of task structure is sufficient for generalisation, then training should also impact the close transfer task since it involved the same sequence of primes followed by targets and hence allowed for the same attentional settings as the training task (e.g., "attend to target and ignore prime"). The far transfer task consisted of an AX-Continuous Performance Task (AX-CPT; Servan-Schreiber, Cohen, Jonathan, & Steingard, 1996). Trials on this task also consist of a sequential presentation of stimuli (cue and probe). This far transfer task was included to assess whether the induced attentional settings were robust enough to generalise to a task that differed in procedure and task goal, but still allowed for the same attentional strategy as the trained task (e.g., "ignore cue, attend to probe"). Together, these transfer tasks allowed examination of cross-task generalisation of the training, as a function of task similarity.

Method

Subjects

Fifty subjects were recruited from the subject pool of the Vrije Universiteit Brussel. All subjects gave written informed consent and received course credits for participation. Subjects were randomly assigned to one of two groups: the prime-attended or the prime-diverted group (see details below). Five subjects in the prime-attended group who did not adhere to the attentional manipulation (i.e., showed error rates higher than 50% on the inducing trials of the training task) were excluded. One subject in the prime-diverted group with an error rate of 95% on the direct transfer task after training (Day 2) was also excluded. This left 44 subjects included for analysis (prime-attended group: $n = 20$, 15 females, mean age = 19.40 ± 1.96 years; prime-diverted group: $n = 24$, 15 females, mean age = 19.17 ± 1.49 years).

Apparatus

Subjects were seated in dimly lit private cubicles. Stimuli were presented on a 17-inch monitor (60 Hz, spatial resolution = 1,280 × 1,024) located approximately 75 cm from the

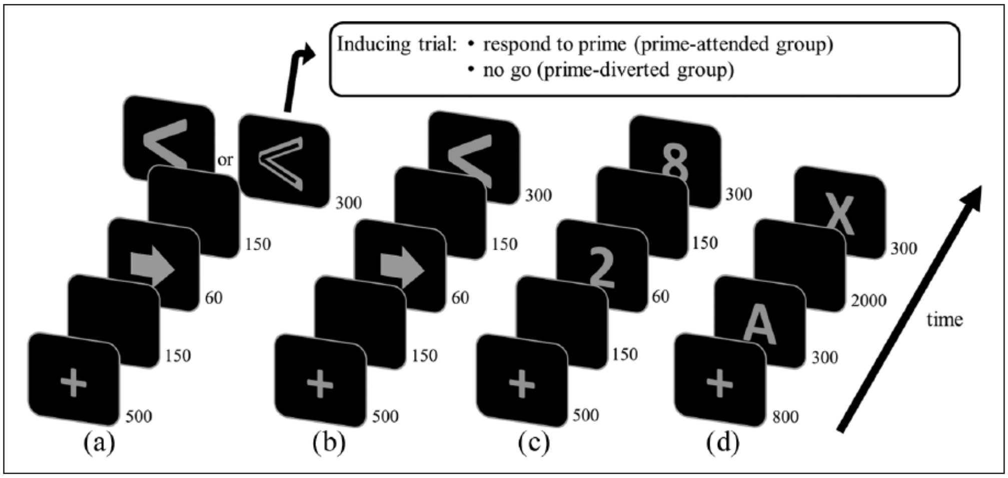

Figure 1. Examples of training and transfer tasks: (a) training task: arrow priming task with attentional manipulation (i.e., 20% inducing trials); (b) direct transfer task: arrow priming task without attentional manipulation; (c) close transfer task: number priming task; (d) far transfer task: AX-CPT. Numbers represent stimulus duration (in ms). Stimuli were presented sequentially on each trial in every task. All stimuli were presented in grey Arial font on a black background.

subject. Stimulus presentation and response registration were controlled by E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). Responses were entered on a response box (Cedrus RB-830; Cedrus Corporation, San Pedro, CA).

Design

Subjects came to the lab on three consecutive days (see Table 1). On Day 1, subjects performed the direct, close, and far transfer tasks (i.e., arrow priming task without attentional manipulation, number priming task, and AX-CPT, respectively). Performance on these tasks served as baseline measures. On the second day, subjects performed the training task (i.e., arrow priming task with an attentional manipulation) which served to increase attention to the prime in one group and decrease attention to the prime in the other group. After the training task on Day 2, subjects also performed the direct transfer task as a first post-test. On Day 3, the same transfer tasks as on Day 1 were administered, this time serving as post-tests. This task schedule was chosen to keep the total task load equal on all three days. Subjects spent around 60-70 min performing the tasks on each day. The order of the tasks on Day 1 was randomised. On Day 3, each subject completed the tasks in the same order as they did on Day 1.

Procedure

General task characteristics. Stimuli were presented sequentially on each trial in every task (see Figure 1). All stimuli were presented in grey Arial font on a black background. Stimuli in the training and direct transfer task were approximately 1.6° wide and 1.9° high. Stimuli in the close transfer and far transfer task were approximately 0.6° wide and 1.8° high. Trials were separated by an intertrial interval of 500 ms. Stimulus durations are included in Figure 1. Subjects in both groups were encouraged to respond as fast and as accurately as possible using the index fingers of both hands. All tasks were preceded by a practice block containing 40 (training task) or 20 (other tasks) trials with accuracy and response time (RT) feedback This practice block was repeated in each task until subjects reached 70% accuracy, in order to assure compliance with instructions.

Training task. The training task consisted of an arrow priming task (see Figure 1a). Target arrows pointing left or right were preceded by prime arrows also pointing to the left or right. Trials could be congruent (i.e., prime pointing in the same direction as the target; 70% of the trials) or incongruent (i.e., prime pointing in the opposite direction of the target; 30% of the trials). Trials were further divided in 80% main and 20% inducing trials. On the main trials, subjects had to respond to the direction of the target arrow (left or right). On the inducing trials, the target arrow was filled with a black line (see Figure 1a), informing the subject that different rules had to be followed on these trials. Specifically, for subjects in the prime-attended group, this involved indicating the direction of the prime instead of the target arrow. Whether a trial was of the main or inducing type could not be known until the target was presented. This means that the prime-attended group had to continuously attend to the prime and maintain this information until target presentation. Subjects in the prime-diverted group had to withhold responses to the target on inducing trials. This was done to divert attention away from the prime and towards the target.

Trials were aborted and feedback ("too slow") was provided in both groups when the response deadline of 2,300 ms was exceeded. A total of 500 trials was presented, with a self-paced pause after 100, 200, and 400 trials and a fixed pause of 5 min after 300 trials. The total duration of the task was approximately 1 hr. To increase motivation, subjects were awarded points for every correct response on inducing trials, which could be exchanged for candy at the end of the experiment. Subjects needed only one round of practice before reaching the 70% accuracy threshold, apart from two subjects in the prime-attended group who completed two rounds.

Direct transfer task. The direct transfer task was identical to the training task, but without the attentional manipulation (i.e., without inducing trials; Figure 1b). Subjects performed 160 trials with a self-paced pause after 80 trials. Subjects needed only one round of practice on each day to reach the accuracy threshold, except for three subjects (two in the prime-attended group, one in the prime-diverted group) who completed two blocks of practice on Day 1.

Close transfer task. The close transfer task was identical to the direct transfer task, but with number stimuli ranging from 1 to 9 (excluding 5) instead of arrows (Figure 1c). Subjects responded with a left or right button press when the target number was smaller or larger than five, respectively. On congruent trials, prime and target triggered the same response (e.g., both smaller than five). On incongruent trials, prime and target evoked different responses (e.g., prime smaller than five and target larger than five). The task consisted of 160 trials with a self-paced pause after 80 trials. Four subjects (one in the prime-attended group, three in the prime-diverted group) needed two, and one subject (prime-attended group) needed three rounds of practice before reaching the 70% accuracy threshold on Day 1. All other subjects needed only one round of practice on each day.

Far transfer task. The AX-CPT task was used as far transfer task. Similar to the other tasks, it also comprised a sequential presentation of two stimuli. On each trial, an A or B cue was followed by an X or Y probe (see Figure 1d). Four combinations of cue-probe pairs were thus presented: AX, AY, BX, and BY. On AX trials, a "target" response (i.e., a left button press) was required. These AX trials were presented on 70% of the trials. On the other trials (AY, BX and BY), subjects had to press the "non-target" button (i.e., a right button press). Each of these trial types occurred 10% of the time. Subjects performed 200 trials with a self-paced pause after 100 trials. All subjects reached the 70% accuracy threshold in a single practice block on both days.

The crucial trials in this task are the AY and BX trials. Due to the high frequency of AX trials (70%), a bias towards target responses is created. Presentation of the A cue will therefore create an expectancy of an AX trial and thus preparation of a target response. On AY trials, this expectancy is violated and conflict occurs between the prepared target response and the required non-target response. B cues, on the other hand, always signal a non-target response, irrespective of the target following the cue. Nevertheless, due to the high frequency of AX trials, the X probe on BX trials induces a bias towards a target response causing backward interference with the correctly prepared non-target response. Responses on AY and BX trials are expected to be differently affected when attention towards the cue is altered. With increased attention to the cue, the interference caused by the A cue on AY trials is expected to become larger, further slowing responses on these trials. However, the backward interference of the X probe on BX trials will become smaller due to a strengthened processing of the B cue, speeding responses on these trials. When attention to the cue is decreased, the opposite pattern is expected: smaller interference will speed responses on AY trials, while larger backward interference will slow responses on BX trials.

Statistical analysis

RTs (in ms) were analysed using linear mixed models. Full models were constructed for every task, including all fixed factors and their interactions. The random effects structure was modelled stepwise. For example, for tasks with the factors Congruency, Day, and Group, a model with only a random intercept for Subject was constructed first. Second, one model with a random slope for Congruency and one model with a random slope for Day were created. Finally, a model with both random slopes for Congruency and Day was constructed.[1] Each augmented model was statistically compared to the previous one(s) using the likelihood ratio (χ^2). Akaike information criterion (Akaike, 1974) is reported as a measure of model fit, with lower values indicating a better fit. The model with random effects structure that showed the best fit was selected (see Supplementary Material for details). Models were fitted using linear mixed models with the maximum likelihood procedure in the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) for R (R Core Team, 2016). Significance of the fixed effects of the optimal model was analysed using Type III analysis of variance (ANOVA). Kenward-Roger adjustments were applied to obtain F-statistics with approximate degrees of freedom (Janssens, De Loof, Pourtois, & Verguts, 2016; Kenward & Roger, 1997). Post hoc comparisons with Tukey's corrections were performed when appropriate.

Error rates were analysed similarly, using generalised linear mixed models with a logistic link function from the lme4 package (Bates et al., 2015). Since no adjustments of degrees of freedom are currently available for binary data, Wald's χ^2 is reported instead of an F-value.

Results

Training task

RTs. Only main trials following main trials were included to make sure responses contained no switching costs from

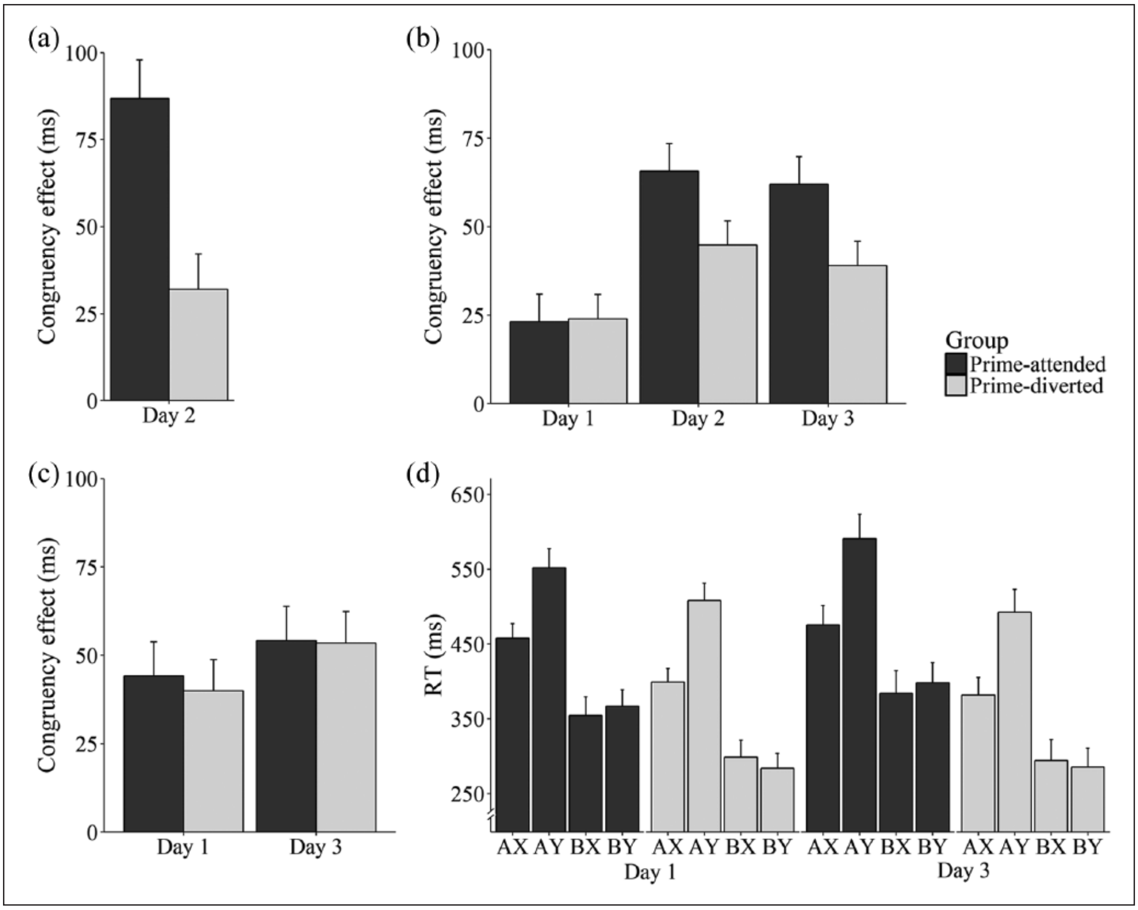

Figure 2. Congruency effects estimated by the models for the (a) training task, (b) direct transfer task, and (c) close transfer task. (d) Response time estimates on the far transfer task. Error bars represent standard errors.

inducing to main trials. The following trials were excluded: the first trial and the first trial after each pause (1.2%), error trials (1.4%), trials following errors (1.3%), no response trials (0.01%), and trials faster or slower than 2.5 standard deviation (*SD*) from the subject's mean per level of each condition (0.4%). The linear mixed model included the fixed factors Congruency (Congruent, Incongruent), Group (Prime-Attended, Prime-Diverted), and their interaction. A random intercept for Subject and a random slope for Congruency were also included. Results are reported in Figure 2a. A main effect of Congruency was observed, $F(1, 54.0) = 62.39$, $p < .001$, as well as a main effect of Group, $F(1, 44.20) = 12.69$, $p < .001$. Importantly, Congruency and Group interacted, $F(1, 54.00) = 13.30$, $p < .001$, with a larger CE for the prime-attended group (87 ms) than the prime-diverted group (32 ms; see Figure 2a). This shows that the training was effective.

Error rates. Only main trials following main trials were included. The first trials and the first trial after each pause (1.2%) were excluded, as well as no response trials (0.01%). Model building was similar to the RT analysis. A main effect of Congruency was found, $\chi^2(1) = 35.53$, $p < .001$, with higher error rates on incongruent (2.4%) than on congruent trials (0.3%). No other effects reached significance, $ps > .15$, including no differences in CE between the prime-attended (3.0%) and prime-diverted group (1.3%; that is, no interaction between Congruency and Group, $\chi^2(1) = 2.06$, $p = .15$).

Direct transfer task

RTs. The following trials were excluded: the first trial and the first trial after the pause (1.3%), error trials (2.6%), trials following errors (2.6%), no response trials (0.1%), and trials faster or slower than 2.5 *SD* from the subject's mean per level of each condition (2.2%). The linear mixed model included the fixed factors Congruency (Congruent, Incongruent), Group (Prime-Attended, Prime-Diverted), Day (1, 2, 3), and their interactions. A random intercept for Subject and random slopes for Congruency and Day were also added to the model.[2] Significant main effects of Congruency, $F(1, 44.1) = 77.67$, $p < .001$, and Day, $F(2, 43.4) = 12.02$, $p < .001$, were found. An interaction between Congruency and Day was also observed, $F(2, 18{,}520.6) = 67.83$, $p < .001$. Crucially, a three-way interaction was observed between Congruency, Day, and Group, $F(2, 18{,}520.6) = 10.08$, $p < .001$, indicating that the between-group difference in CE varied between the 3 days (see Figure 2b). None of the other effects reached significance, $ps > .12$.

Post hoc comparisons were performed on the model estimates to further interpret the obtained three-way interaction (see Figure 2b). No between-group difference in CE was found on Day 1 (−1 ms), $t(55.15) = 0.08$, $p = .94$. On Day 2 (i.e., directly after training), a larger CE was found for the prime-attended group (66 ms) than for the prime-diverted group (45 ms), $t(55.1) = 2.02$, $p = .048$. Crucially, this between-group CE difference on Day 2 (21 ms) was larger than the non-significant between-group CE difference on Day 1 (−1 ms), as revealed by the interaction between Congruency, Day (1 and 2), and Group, $t(18{,}511.4) = 3.72$, $p < .001$. On Day 3, there was still a larger CE for the prime-attended group (62 ms) than for the prime-diverted group (39 ms), $t(55.9) = 2.22$, $p = .031$. Again, the interaction between Congruency, Day (1 and 3), and Group revealed that the between-group difference was larger on Day 3 (23 ms) than on Day 1 (1 ms), $t(18{,}525.4) = 4.03$, $p < .001$. Between Days 2 and 3, the between-group difference in CE did not differ, $t(18{,}525.2) = 0.36$, $p = .93$. Overall, this pattern of results shows that directly after training (Day 2), the prime-attended group showed a larger CE than the prime-diverted group in the direct transfer task, and that this effect was maintained 1 day later (Day 3).

Error rates. The first trial and the first trials after the pause were excluded (1.3%), as well as no response trials (0.1%). Model building was similar to the RT analysis. Main effects of Congruency, $\chi^2(1) = 52.40$, $p < .001$, and Day, $\chi^2(2) = 7.63$, $p = .022$, were found. Congruency also interacted with Day, $\chi^2(2) = 27.78$, $p < .001$. Compared to Day 1 (2.0%), the CE was larger on Day 2 (2.8%), $z = 3.70$, $p < .001$, and Day 3 (3.8%), $z = 4.90$, $p \leq .001$. Congruency and Group also showed a marginally significant interaction, $\chi^2(1) = 3.48$, $p = .062$, with a larger CE for the prime-attended group (3.6%) than the prime-diverted group (2.2%). None of the other effects reached significance, $ps > .31$. Indeed, no three-way interaction between Congruency, Day, and Group was found, $\chi^2(2) = 0.54$, $p = .76$ (CE of prime-attended group minus prime-diverted group on Days 1-3: 2.0%, 0.9%, 1.3%).

Close transfer task

RTs. The following trials were excluded: the first trial and the first trial after each pause (1.3%), error trials (2.8%), trials following errors (2.9%), no response trials (0.2%), and trials faster or slower than 2.5 *SD* from the subject's mean per level of each condition (2.5%). The linear mixed model included the fixed factors Congruency (Congruent, Incongruent), Group (Prime-Attended, Prime-Diverted), Day (1, 3), and their interactions. A random intercept for Subject and random slopes for Congruency and Day were also added. Main effects were obtained for Congruency, $F(1, 55.8) = 60.01$, $p < .001$, and Day, $F(1, 42.8) = 7.52$, $p = .009$. Congruency and Day also interacted, $F(1, 12{,}387.8) = 7.37$, $p = .007$, with a larger CE at Day 3 (54 ms) than at Day 1 (42 ms). None of the other effects reached significance, all $ps > .09$. Crucially, no three-way interaction between Congruency, Day, and Group was found, $F(1, 12{,}487.8) = 0.16$, $p = .69$ (CE of prime-attended group minus prime-diverted group on Days 1 and 3: 4 and 1 ms), indicating that the between-group difference in CE after training (Day 3) did not differ from baseline (Day 1, see Figure 2c).

Error rates. The first trial and the first trials after the pause were excluded (1.3%), as well as no response trials (0.2%). Model building was similar to the RT analysis. A main effect of Congruency was found, with higher error rates on incongruent (3.5%) than on congruent trials (1.6%), $\chi^2(1) = 18.24$, $p < .001$. No other effect reached significance, $ps > .42$, including no three-way interaction between Congruency, Day, and Group, $\chi^2(1) = 0.49$, $p = .48$ (CE of prime-attended group minus prime-diverted group on Days 1 and 3: −0.7% and −0.4%).

Comparison between direct and close transfer task

To compare the transfer effects between tasks, a linear mixed model was fitted with the fixed factors Congruency (Congruent, Incongruent), Group (Prime-Attended, Prime-Diverted), Day (1, 3), task (direct transfer, close transfer), and their interactions. A random intercept for Subject and random slopes for Congruency and Day were also added to the model. This exploratory analysis revealed a significant four-way interaction, $F(1, 24{,}788.8) = 5.52$, $p = .019$. This supports the claim that the attentional manipulation affected performance more strongly on the direct transfer task than on the close transfer task.

Far transfer task

RTs. The following trials were excluded: the first trial and the first trial after the pause (1.0%), error trials (3.0%), trials following errors (2.7%), no response trials (0.01%), and trials faster or slower than 2.5 *SD* from the subject's mean per level of each condition (2.7%). The linear mixed model included the fixed factors Trial Type (AX, AY, BX, BY), Group (Prime-Attended, Prime-Diverted), Day (1, 3), and their interactions; a random intercept for Subject; and random slopes for Trial Type and Day. Main effects were obtained for Trial Type, $F(3, 62.4) = 172.00$, $p < .001$, and Group, $F(1, 46.4) = 6.38$, $p = .015$. Pairwise comparisons revealed larger RTs on AY trials (536 ms) compared to all other trials, *p*s < .001; larger RTs on AX trials (428 ms) compared to BX (333 ms) and BY (334 ms) trials, *p*s < .001; and no RT difference between BX and BY trials, $p = .93$. The prime-attended group responded slower (447 ms) than the prime-diverted group (368 ms). Trial Type also interacted with Day, $F(3, 15{,}582.0) = 2.80$, $p = .039$. Pairwise comparisons revealed that this interaction was due to an increase in RT over days that was larger on BY trials (17 ms) than on AX trials (0 ms), $t(15{,}552.8) = 2.27$, $p = .024$ (see Figure 2d).

No other effects reached significance, *p*s > .10, including no three-way interaction between Trial Type, Day, and Group, $F(3, 15{,}582.0) = 0.64$, $p = .59$. This indicates that the between-group difference (prime-attended minus prime-diverted group) between trial types after training (Day 3) did not significantly differ from before training (Day 1). For example, on Day 1, the difference between AY and BX trials in the prime-attended group was 198 ms, versus 207 ms for the prime-diverted group (i.e., a between-group difference of −9 ms). On Day 3, the difference between AY and BX trials in the prime-attended group was 209 ms, versus 199 ms for the prime-diverted group (i.e., a between-group difference of 10 ms).

Error rates. The first trial and the first trials after the pause (1.0%) were excluded, as well as no response trials (0.01%). The model building was similar to the RT analysis, but only Trial Type was included as a random slope. An effect of Trial Type was observed, $\chi^2(3) = 185.59$, $p < .001$. Pairwise comparisons revealed more errors on AY trials (10.4%) compared to all other trial types, *p*s < .001. Error rates were also (marginally) significantly higher on BX trials (2.9%) than on AX trials (1.3%), $z = 2.52$, $p = .057$, and BY trials (1.1%), $z = 2.71$, $p = .034$. None of the other effects reached significance, all *p*s > .35, including no three-way interaction between Trial Type, Day, and Group, $\chi^2(3) = 1.29$, $p = .73$. This indicates that the between-group difference (prime-attended minus prime-diverted group) between trial types after training (Day 3) did not significantly differ from before training (Day 1). For example, on Day 1, the difference between AY and BX trials in the prime-attended group was 6.7%, versus 7.5% for the prime-diverted group (i.e., a between-group difference of −0.8% ms). On Day 3, the difference between AY and BX trials in the prime-attended group was 6.3%, versus 9.6% for the prime-diverted group (i.e., a between-group difference of −3.3%).

Discussion

In this study, we assessed cross-task generalisation of attentional modulation in cognitive control. Subjects were trained to either direct attention towards a potentially distracting prime (prime-attended group) or divert attention away from this prime (prime-diverted group). Pre-tests were administered the day before training and generalisation was measured directly after training (direct transfer task) and 1 day later (direct, close, and far transfer tasks).

First, results showed that the attentional modulation induced during training was effective. A larger CE on RTs was obtained for the prime-attended group than for the prime-diverted group. This indicates that the prime had a larger effect in the group that had to focus attention on the prime on 20% of the trials. This effect was only observed on RTs and not on error rates, as was also the case for all other effects discussed.

Second, the training effect on RTs generalised to the direct transfer task, which was similar to the training task, but without the attentional manipulation. No between-group difference in CE was found on Day 1 before training, but a larger CE was found for the prime-attended group than for the prime-diverted group, directly after training (Day 2). Importantly, this between-group difference emerged even though the direct transfer task was completely identical for both groups, demonstrating training effectiveness. One day later (Day 3), the prime-attended group still showed a larger CE than the prime-diverted group, demonstrating generalisation. The robustness of this effect is particularly remarkable given that training was limited to only one session of 1 hr.

Third, the training effect did not transfer to tasks that were more distantly related to the trained task. No between-group difference in CE was observed on the close transfer task, even though only the stimuli from this task differed from the trained task (i.e., the arrows of the direct transfer task were substituted by numbers). An exploratory follow-up analysis comparing the transfer effect between direct and close transfer tasks indeed confirmed that the transfer effect was apparent in the direct transfer but not in the close transfer task. No transfer effects were found on the far transfer task either. Together, this suggests that the acquired strategy to focus more versus less on the prime was restricted to the specific features used during the training phase and only transferred to tasks with these same features (i.e., stimuli and task goal; Abrahamse et al., 2016; Egner, 2014).

Alternatively, the fact that the close and far transfer tasks were not administered immediately after training on Day 2, but only on Day 3, may also have affected results. It remains to be tested whether a close and/or far transfer effect would have been obtained on Day 2 and whether this effect would also have boosted effects on Day 3, as it may have done for the direct transfer task. In addition, it remains an open question whether more (prolonged) training sessions (although practically more cumbersome) can induce long-lived transfer effects to tasks with fewer shared features. Also, transfer effects may benefit from stronger attentional manipulations. For example, strong training effects have been shown after explicitly instructing subjects how to direct attention towards or away from the cue of an AX-CPT (Braver, Paxton, Locke, & Barch, 2009; Edwards, Barch, & Braver, 2010; Paxton, Barch, Storandt, & Braver, 2006). However, because such instructions are explicitly tailored to specific features of the trained task, they may not be optimal to induce general changes, and effects may remain limited to the trained task (Spierer, Chavan, & Manuel, 2013).

Apart from a between-group difference in CE between baseline and post-tests on the direct transfer task, a group-independent increase of the CE was also found over consecutive days (see also Figure 2). Although not anticipated, this effect is likely due to the proportion of congruent and incongruent trials used. With 70% congruent trials, a beneficial strategy is to use the prime as an accurate predictor of the response (Schmidt & Besner, 2008). This involves the preparation of the correct response already at prime presentation, which then would speed up the response provided at target presentation on the 70% congruent trials. On the incongruent trials, however, the prepared response is incorrect and should be suppressed, requiring additional time. Together, this leads to a larger CE on tasks using 70% congruent trials compared to tasks where the proportions of congruent and incongruent trials are balanced or biased towards incongruent trials (Bugg & Crump, 2012; Logan & Zbrodoff, 1979). The repetitive administration of a task with 70% congruency may have stimulated subjects to adopt this prime-oriented strategy increasingly strongly over days. Due to this group-independent increase of the CE over days, it is difficult to tell whether the attentional manipulation was effective only in the prime-attended group, only in the prime-diverted group, or in both. It is therefore unclear whether actual improvements occurred in the prime-diverted group. Nevertheless, it should be stressed that the proportion congruency manipulation was identical in both groups and therefore cannot explain the observed group-differences on the training task and the direct transfer task.

The lack of generalisation to remotely related tasks in this study appears at odds with other paradigms that induce similar attentional modulations. With cognitive bias modification, for example, subjects can be trained to bias attention away from negative stimuli (e.g., MacLeod & Mathews, 2012). In general, this paradigm requires subjects to respond to a probe at the location where a negative or neutral stimulus has just appeared (MacLeod, Rutherford, Campbell, Ebsworthy, & Holker, 2002). By pairing the probe mainly to the neutral stimulus, the subject implicitly learns to direct attention away from the other, negative stimulus. Cognitive bias modification appears to have widely generalised effects. For example, it can decrease anxiety in people with reported difficulty with public speaking (Amir, Weber, Beard, Bomyea, & Taylor, 2008) and improve treatment outcomes in alcoholic patients (Wiers, Eberl, Rinck, Becker, & Lindenmeyer, 2011). Such effects are thought to arise through reduced emotional responses (Beard, Sawyer, & Hofmann, 2012) or by decreasing approach biases towards motivational cues (Kakoschke, Kemps, & Tiggemann, 2017). Cognitive bias modification is therefore effective in subjects with increased anxiety or stress levels (MacLeod & Mathews, 2012), or individuals with problematic food intake or substance use (Verdejo-Garcia, 2016). In this study, there were no emotional or motivational cues, nor clinical populations. To what degree the presence of such factors facilitates attentional changes remains a topic for future training studies, which should systematically investigate the trainability of different components of cognitive control in different populations.

Finally, all between-group effects were only observed for RTs and not for error rates. Given the low error rates on the training, direct transfer, and close transfer tasks, the tasks probably were too easy to elicit erroneous responses. Alternatively, subjects may have prioritised accuracy over speed. Whether the training induced differences in speed-accuracy trade-off remains an open question. For example, if the prime-attention strategy was more difficult to apply, then this may have decreased the speed of information uptake compared to the prime-diversion strategy. Alternatively, subjects in the prime-attended group may have adopted a more conservative response style after training (leading to slow but accurate responses). However, more detailed analysis of these mechanisms, for example, by means of drift diffusion models, was not possible due to the low error rates (Voss, Nagler, & Lerche, 2013).

In conclusion, we have effectively modified subjects' attentional settings through a 1-hr training session. This attentional modification generalised to the next day, suggesting that the obtained changes were of a persistent nature. No generalisation was found to other tasks that were more remotely related to the trained task, suggesting that the induced attentional settings were limited to specific task features (i.e., stimuli).

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Supplementary material

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Notes

1. No random slope for the interaction between Congruency and Day was added, since the variance explained by this term would overlap with the variance explained by the interaction between the fixed factors Congruency, Day, and Group (i.e., since each subject is in one of the two groups, allowing the congruency effect to vary between days and subjects would obscure between-group differences). This also applies to the analysis of the far transfer task where the factor Congruency is replaced by the factor Trial Type.
2. One subject from the prime-attended group was removed from this analysis because of an undue influence on the model parameters: Cook's distance exceeded the cut-off value of $4/n$ and dfbeta exceeded $2/\sqrt{n}$ for nine out of 12 parameters (n=number of subjects; Belsley, Kuh, & Welsch, 1980). The analysis repeated with this subject included did not lead to substantive changes in results: the crucial three-way interaction was still observed, $F(2, 18{,}960.5)=5.54$, $p=.004$.

References

Abrahamse, E., Braem, S., Notebaert, W., & Verguts, T. (2016). Grounding cognitive control in associative learning. *Psychological Bulletin*, *142*, 693–728.

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*, 716–723.

Amir, N., Weber, G., Beard, C., Bomyea, J., & Taylor, C. T. (2008). The effect of a single-session attention modification program on response to a public-speaking challenge in socially anxious individuals. *Journal of Abnormal Psychology*, *117*, 860–868.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. doi:10.18637/jss.v067.i01

Beard, C., Sawyer, A. T., & Hofmann, S. G. (2012). Efficacy of attention bias modification using threat and appetitive stimuli: A meta-analytic review. *Behavior Therapy*, *43*, 724–740.

Belsley, D., Kuh, E., & Welsch, R. (1980). *Regression diagnostics: Identifying influential data and sources of collinearity*. New York, NY: John Wiley.

Berkman, E. T., Kahn, L. E., & Merchant, J. S. (2014). Training-induced changes in inhibitory control network activity. *The Journal of Neuroscience*, *34*, 149–157.

Boot, W. R., Simons, D. J., Stothart, C., & Stutts, C. (2013). The pervasive problem with placebos in psychology: Why active control groups are not sufficient to rule out placebo effects. *Perspectives on Psychological Science*, *8*, 445–454.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*, 624–652.

Braem, S., Abrahamse, E. L., Duthoo, W., & Notebaert, W. (2014). What determines the specificity of conflict adaptation? A review, critical analysis, and proposed synthesis. *Frontiers in Psychology*, *5*, 1134.

Braem, S., Verguts, T., & Notebaert, W. (2011). Conflict adaptation by means of associative learning. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 1662–1666.

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. *Trends in Cognitive Sciences*, *16*, 106–113.

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *106*, 7351–7356.

Bugg, J. (2014). Conflict-triggered top-down control: Default mode, last resort, or no such thing? *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *40*, 567–587.

Bugg, J., & Crump, M. J. C. (2012). In support of a distinction between voluntary and stimulus-driven control: A review of the literature on proportion congruent effects. *Frontiers in Psychology*, *3*, 367.

Ditye, T., Jacobson, L., Walsh, V., & Lavidor, M. (2012). Modulating behavioral inhibition by tDCS combined with cognitive training. *Experimental Brain Research*, *219*, 363–368.

Edwards, B. G., Barch, D. M., & Braver, T. S. (2010). Improving prefrontal cortex function in schizophrenia through focused training of cognitive control. *Frontiers in Human Neuroscience*, *4*, 32.

Egner, T. (2008). Multiple conflict-driven control mechanisms in the human brain. *Trends in Cognitive Sciences*, *12*, 374–380.

Egner, T. (2014). Creatures of habit (and control): A multi-level learning perspective on the modulation of congruency effects. *Frontiers in Psychology*, *5*, 1247.

Enge, S., Behnke, A., Fleischhauer, M., Küttler, L., Kliegel, M., & Strobel, A. (2014). No evidence for true training and transfer effects after inhibitory control training in young healthy adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*, 987–1001.

Janssens, C., De Loof, E., Pourtois, G., & Verguts, T. (2016). The time course of cognitive control implementation. *Psychonomic Bulletin & Review*, *23*, 1266–1272.

Kakoschke, N., Kemps, E., & Tiggemann, M. (2017). Approach bias modification training and consumption: A review of the literature. *Addictive Behaviors*, *64*, 21–28.

Kenward, M. G., & Roger, J. H. (1997). Small sample inference for fixed effects from restricted maximum likelihood. *Biometrics*, *53*, 983–997.

Logan, G. D., & Zbrodoff, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory & Cognition*, *7*, 166–174.

MacLeod, C., & Mathews, A. (2012). Cognitive bias modification approaches to anxiety. *Annual Review of Clinical Psychology*, *8*, 189–217.

MacLeod, C., Rutherford, E., Campbell, L., Ebsworthy, G., & Holker, L. (2002). Selective attention and emotional vulnerability: Assessing the causal basis of their association through the experimental manipulation of attentional bias. *Journal of Abnormal Psychology*, *111*, 107–123.

Maraver, M. J., Bajo, M. T., & Gomez-Ariza, C. J. (2016). Training on working and inhibitory control in young adults. *Frontiers in Human Neuroscience*, *10*, 588.

Millner, A. J., Jaroszewski, A. C., Chamarthi, H., & Pizzagalli, D. A. (2012). Behavioral and electrophysiological correlates of training-induced cognitive control improvements. *NeuroImage*, *63*, 742–753.

Oelhafen, S., Nikolaidis, A., Padovani, T., Blaser, D., Koenig, T., & Perrig, W. J. (2013). Increased parietal activity after training of interference control. *Neuropsychologia*, *51*, 2781–2790.

Paxton, J. L., Barch, D. M., Storandt, M., & Braver, T. S. (2006). Effects of environmental support and strategy training on older adults' use of context. *Psychology and Aging*, *21*, 499–509.

R Core Team. (2016). *R: A language and environment for statistical computing* [Computer software]. Vienna, Austria: R Foundation for Statistical Computing.

Schmidt, J. R., & Besner, D. (2008). The Stroop effect: Why proportion congruent has nothing to do with congruency and everything to do with contingency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 514–523.

Servan-Schreiber, D., Cohen Jonathan, D., & Steingard, S. (1996). Schizophrenic deficits in the processing of context. *Archives of General Psychiatry*, *53*, 1105–1112.

Spierer, L., Chavan, C. F., & Manuel, A. L. (2013). Training-induced behavioral and brain plasticity in inhibitory control. *Frontiers in Human Neuroscience*, *7*, 427.

Thorell, L. B., Lindqvist, S., Nutley, S. B., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science*, *12*, 106–113.

Torres-Quesada, M., Funes, M. J., & Lupiáñez, J. (2013). Dissociating proportion congruent and conflict adaptation effects in a Simon-Stroop procedure. *Acta Psychologica*, *142*, 203–210.

Verdejo-Garcia, A. (2016). Cognitive training for substance use disorders: Neuroscientific mechanisms. *Neuroscience and Biobehavioral Reviews*, *68*, 270–281.

Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: Dealing with specific and nonspecific adaptation. *Psychological Review*, *115*, 518–225.

Verguts, T., & Notebaert, W. (2009). Adaptation by binding: A learning account of cognitive control. *Trends in Cognitive Sciences*, *13*, 252–257.

Voss, A., Nagler, M., & Lerche, V. (2013). Diffusion models in experimental psychology: A practical introduction. *Experimental Psychology*, *60*, 385–402.

Wiers, R. W., Eberl, C., Rinck, M., Becker, E. S., & Lindenmeyer, J. (2011). Retraining automatic action tendencies changes alcoholic patients' approach bias for alcohol and improves treatment outcome. *Psychological Science*, *22*, 490–497.

Wühr, P., Duthoo, W., & Notebaert, W. (2015). Generalizing attentional control across dimensions and tasks: Evidence from transfer of proportion-congruent effects. *The Quarterly Journal of Experimental Psychology*, *68*, 779–801.

Yeung, N. (2013). Conflict monitoring and cognitive control. In K. N. Ochsner & S. Kosslyn (Eds.), *The Oxford handbook of cognitive neuroscience, Vol. 2: The cutting edges* (pp. 275–299). Oxford, UK: Oxford University Press.