Training cognitive control through domain-general response inhibition does not change children's brains or behavior

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Cognitive control is required for the organisation of thoughts and actions and critical for the pursuit of long-term goals. Childhood cognitive control relates to a host of other domains of functioning and predicts later-life success and well-being. Here we use a randomized-control trial to test whether cognitive control can be improved through an 8-week intervention in 235 children aged 6-12 years targeting response inhibition and whether this leads to changes in multiple behavioral and neural outcomes, compared to a response-speed training. We find that with exception of long-lasting improvements of closely related measures of cognitive control, training had no impact on any behavioral (i.e. decision-making, academic achievement, mental health, fluid reasoning, creativity) or neural (i.e. task-dependent and intrinsic brain function, grey and white matter structure) outcomes. Bayesian analyses provide strong evidence of absent training effects. We conclude that targeted training of response inhibition does nothing to change children's brains or their behavior.

Cognitive control refers to a set of processes critical for guiding thoughts, feelings and actions in a flexible, goal-directed manner[1]. Childhood cognitive control is positively associated with a range of outcomes in other domains, notably social skills[2-6], academic performance[7,8], and mental health[9], and more crucially is predictive of these outcomes later in life[10-12]. Cognitive control undergoes protracted development from childhood into early adulthood[13-15]. This development is underpinned by the maturation of late-developing frontoparietal and frontostriatal neural circuitry[16,17], supposedly affording extended plasticity[18]. Given its critical role in healthy and productive development, coupled with the prolonged plasticity of its underlying neural circuitry, cognitive control has been a primary target for interventions[19,20], and particularly so in childhood[21]. Interventions are costly in terms of time, money and opportunity yet, there is continued debate over how successful they actually are.

Cognitive control interventions have primarily focused on improving its hypothesized constituent processes, namely working memory, cognitive flexibility and to a lesser extent also response inhibition[22,23]. There is broad consensus that these functions can be improved through training, albeit in a relatively narrow and often task-specific manner (i.e. near transfer)[24,25]. However, changes in other distally related domains of cognitive functioning and real-world outcomes (i.e. far transfer) have been much less consistently observed[23,26-34]. While views differ on whether cognitive training can actually lead to far transfer, the quality of evidence has been consistently questioned[35,36]. Given the likelihood of small effect sizes, criticisms have focused on underpowered samples and poorly specified training mechanisms[35,37,38]. Further, training regimes often lack core features minimally required for far transfer, such as continuously variable, diverse and complex input[19,39,40], while assessment of training-related outcomes mostly focus only on short-term effects and a limited number of outcome measures[41]. Finally, the frequent absence of active control groups prohibits drawing any inference on the reasons, let alone mechanisms for any transfer effects. Here we address whether cognitive control training transfers onto other domains of functioning. We do so in a highly powered sample of children using best practice recommendations for training regimes in terms diversity, complexity, and variability of training input[35,42] and assessing a wide array of behavioral and neural outcome measures both short- and long-term. As such we offer one of the most rigorous and comprehensive tests of this question to date.

Unlike the majority of cognitive control interventions, which focus on working memory training[23], here, we target *response inhibition* as the primary mechanism of action. Inhibition involves a set of highly relevant and widely used processes including response inhibition or stopping, response selection and contextual monitoring[43]. As such, inhibition may offer a set of cognitive control processes that lend themselves well to training in terms of their domain

general nature as well as the specifically identified training mechanism[44-49]. Using a randomized control trial we assess the impact of an 8-week cognitive control training with response inhibition as the active ingredient in our experimental group. We compare performance changes on a host of outcome measures with an active control group training response speed, before and after training as well as at a 1-year follow-up. Outcome measures were chosen based on their well-established relationship with cognitive control and response inhibition specifically, and included social and intertemporal decision-making[4-6,50], academic achievement[7,8], fluid reasoning[51], mental health (i.e. internalizing and externalizing symptoms)[9,52] as well as creativity[53]. To understand the underlying neurocognitive basis of potential training effects we also sampled a wide assay of neural indices of brain function, structure and connectivity. In addition to whole-brain analyses we focused on regions implicated in cognitive control, including the inferior frontal gyrus[54,55] and cingulo-opercular and fronto-parietal networks[56]. As well as assessing the impact of the training regime as a whole, we also sought to test two recent hypotheses concerning cognitive control training, namely 1) that far transfer effects emerge only over time[41], and 2) that near transfer effects mediate far transfer effects[57]. Finally, we made use of the occurrence of a naturally occurring stressor, Covid-19, to test the commonly held view that cognitive control might buffer against the onset of mental health problems[52,58]. Training duration was chosen to be eight weeks, which has been previously shown to be sufficient for far transfer[27,41].

We developed a highly motivating gamified interface to train response inhibition through variations of the stop signal task (experimental group) or response speed (control group). Both groups received identical training in terms of narrative, stimuli and intensity and the only difference between the groups was how participants were instructed to respond to the stop stimuli (inhibit for the experimental group and respond for the control group). Training involved a high degree of variation of training contexts and mechanisms and further ensured adaptiveness of the training protocol (Figure 1 Methods) by means of trial-by-trial adaptation (using a staircase procedure) based on performance, such that trials were scaled appropriately to individual's abilities for both groups. We refer to closely-related domains as "near transfer", which are outcome measures with a highly similar task structure as to what was trained[59]. Everything else we refer to below as "far transfer". Power calculations estimated that to obtain even a small group by session interaction effect of f = 0.1 with a power of 0.95 at an alpha Bonferroni corrected for the present number of measures (19; corrected alpha = 0.0025) requires a minimal sample size of 119 participants. The present sample of 235 children is almost twice that and therefore amply powered. Leveraging such a large sample also allows us to establish evidence of absence of the effects of cognitive control training by using Bayesian factor hypothesis testing[60]. All main hypotheses and analyses for this study

were preregistered: https://osf.io/bn75g/. Correction to control for false discovery rate with multiple testing of pre-post training effects was done using the using the Benjamini-Hochberg Procedure[61].

Results

Associations between cognitive control and outcome measures before training

We first tested how cognitive control performance was associated with each of our outcome measures. To remove task-related variance specific to any assessment of cognitive control, we obtained a single factor of cognitive control derived from multiple cognitive control measures (see Methods). We observed significant positive associations between cognitive control performance and several of the outcome measures in the expected direction (Figure 1): Delay of gratification (i.e. percentage delayed choices in intertemporal choice task; t (226) = 2.44, p = 0.015)); academic achievement (t (217) = 2.53, p = 0.012); fluid reasoning (i.e. WASI scores; t (216) = 2.27, p = 0.024); externalising symptoms (t (184) = -2.15, p = 0.032), as well as mean diffusivity of right fronto-striatal tracts (t (145) = -2.81, p = 0.005). Cognitive control performance was thus predictive of a host of other outcomes, as commonly reported in the literature.

Training Indices

Training took place over an 8-week period. The motivation to train was high to begin with (Experimental Group = 5.30; Control Group = 5.30; out of 1-7) and decreased as training went on (F (6, 308.75) = 16.42, p < 0.001; Figure 2a). There were no group differences in overall motivation between groups (t (395.13) = -0.50, p = 0.61; BF_{10} = 0.23; Figure 2a), nor an interaction between Session and Group (F (6,308.75) = 1.45, p = 0.194). Further, on average, individuals in both groups trained a similar number of sessions (Experimental Group: N = 16.60; Control Group: N = 16.99). There was no significant difference in the amount trained between both groups (t (205.33) = 0.33, p > 0.740; BF_{10}= 0.16; Figure 2b). To assess whether each group improved on the trained cognitive function throughout the intervention, we examined changes over the training sessions in the SSRT (Experimental Group) and Go RT (Control Group) respectively. For this, we looked at the slope of change in each trained cognitive functions using a mixed model with training weeks added as a predictor. There was a main effect of session where both groups improved on their trained cognitive functions over the training weeks (Experimental Group: F (1, 2292.60) = 121.30, p < 0.001, η^2 = 0.05; Control

Group: F (1, 3197.5) = 185.57, $p < 0.001$, $\eta^2 = 0.05$; Figure 2c). Thus, groups did not differ in training intensity or motivation and showed moderate improvements during training in the targeted processes.

Short-term training-related changes

Near transfer

As primary measure of near transfer we looked at probability of successful stopping and response times to "Go" stimuli. The latter are of interest for both indexing training success for the response speed group, as well as providing a measure of proactive slowing[62] for the experimental group. A mixed model revealed a significant interaction between Session and Group in probability of successful stopping in the SSRT (F (1,221.00) = 27.31, $p_{FDRcorr} < 0.001$, $\eta^2 = 0.11$; Figure 3a). Follow-up paired t-tests comparing pre-post training scores revealed that probability of successful stopping increased in the experimental group (t (215) = -5.96, $p < 0.001$. However, no significant change was found in the control group (t (218) = 1.43, $p = 0.92$). We also observed a significant interaction between Session and Group in Go RT (F (1, 227.28) = 31.75, $p_{FDRcorr} < 0.001$, $\eta^2 = 0.12$; Figure 3b). Follow-up paired t-tests comparing pre-post training scores revealed that reaction times increased in the experimental group (t (228) = -5.02, $p < 0.001$) and decreased in the control group (t (228) = 2.94, $p = 0.021$).

Far transfer – behavioral indices

Cognitive control: Training cognitive control was operationalised by targeting response inhibition. We assessed the impact of training response inhibition on other sub-processes associated with cognitive control (i.e. inhibition as measured by tasks other than the SSRT, shifting and working memory). Given the potentially different impact of training on both speed and accuracy[63], we performed factor analyses across all cognitive control tasks separately for error rates and reaction times (see Methods). This yielded two factors for error rates (one jointly for inhibition and shifting; and one for memory) and one single factor for reaction times. For error rates, there was a Session by Group interaction found with the inhibition/shifting factor (F (1, 215.68) = 10.678, $p_{FDRcorr} = 0.006$, $\eta^2 = 0.05$; Figure 4a); Follow-up paired t-tests however revealed that neither group changed significantly from pre- to post-training. For the memory factor there was no Session by Group interaction (F (1, 212.72) = 0.090, p = 0.764, $\eta^2 < 0.001$, $BF_{10} = 0.188$; Figure 4b). For the reaction time factor there was a significant Session by Group interaction (F (1,213.71) = 18.60, $p_{FDRcorr} < 0.001$, $\eta^2 = 0.08$; Figure 4c). Pre-post t-test comparisons in the experimental group revealed an increase from pre- to post-training (t (213) = -2.94, $p = 0.022$) and a decrease for the control group (t (212) = 3.16 $p = 0.011$).

Decision Making: For the role of the proposer in the Dictator Game for coins shared, there was no significant Session by Group interaction (F (1, 199.18) = .144, p = 0.705, η^2 < 0.001, BF_{10} = 0.201; Figure 4d). For the role of the responder in the Ultimatum Game for offers accepted, there was no significant Session by Group interaction (F (1, 196.49) = 2.36, p = 0.126, η^2 = 0.01, BF_{10} = 0.176; Figure 4e). In the intertemporal choice task, there was no significant Session by Group interaction in the total percentage of delayed choices (F (1, 203.60) = 1.01, p = 0.317, η^2 = 0.004, BF_{10} = 0.150; Figure 4f).

Academic Performance: There was no significant Session by Group interaction for total academic scores (F (1, 217.35) = 0.266, p = 0.606, η^2 = 0.001, BF_{10} = 0.159; Figure 4g).

WASI: There was no significant Session by Group interaction found for WASI scores (F (1, 211.92) = 0.351, p = 0.554, η^2 = 0.001, BF_{10} = 0.169; Figure 4h).

Mental Health: There was no significant Session by Group interaction found for either internalising (F (1, 125.47) = 4.10, p = 0.159, BF_{10} = 0.194; Figure 4i) or externalising problems (F (1, 123.94) = 0.972, p = 0.326, η^2 = 0.007, BF_{10} = 0.228; Figure 4j).

Creativity: There was no significant Session by Group interaction for total creativity scores (a sum score of the five measures from TTCT; F (1, 209.32) = 3.373, p = 0.068, η^2 = 0.02, BF_{10} = 0.448; Figure 4k).

Far transfer – neural indices:

fMRI: While we report brain regions classically implicated in inhibition during successful vs unsuccessful stop trials in our developmental sample (Table 5SM), when looking at the whole-brain, there was no significant interaction between Session and Group for any voxel. We also focussed our analysis on the right IFG, a core hub of cognitive control and response inhibition in particular[55]. For the ROI analysis, parameter estimates for each participant were extracted from the right IFG. A mixed model revealed a significant effect of Group (F (1, 271) = 11.43, p < 0.001, η^2 = 0.04; higher activation overall for the Control group compared to the Experimental group), and no interaction between Session and Group (F (1, 271) = 3.87, p = 0.050, η^2 = 0.01, BF_{10} = 1.105; Figure 5a). Follow up t-test showed that there was no significant change in either group before and after training.

Cortical thickness:

To assess potential training-related changes in cortical grey matter structure, we looked at the whole brain. There was no significant interaction between Session and Group for any voxel. We also obtained parameter estimates of cortical thickness for each participant were extracted from the right IFG. A mixed model revealed no interaction between Session and Group was found (F (1, 139.85) = 0.016, p = 0.901, η^2 < 0.001, BF_{10} = 0.200; Figure 5b).

Resting state connectivity: We looked at changes to connectivity profiles in circuits known to be implicated in cognitive control and response inhibition (REFS), such as cingulo-opercular (CON) and fronto-parietal networks (FPN). Connectivity in the CON and FPN networks were extracted for each participant. Mixed models revealed no interaction between Session and Group in either of the two networks (CON: F (1, 141.34) = .053, p = 0.819, η^2 < 0.001, BF_{10} = 0.180; Figure 5c; FPN: F (1, 143.14) = 0.162, p = 0.688, η^2 = 0.001, BF_{10} = 0.187; Figure 5d).

DTI: Fractional anisotropy and mean diffusivity, two measures of white matter microstructure, were extracted from connections between the frontal lobes and striatal areas of the right hemisphere, given their known role in cognitive control and response inhibition (REF). Mixed models revealed no significant interactions between Session and Group in either fractional anisotropy (F (1, 141.63) = 0.134, p = 0.715, η^2 < 0.001, BF_{10} = 0.188; Figure 5e) or mean diffusivity (F (1, 144.24) = 0.019, p = 0.891, η^2 < 0.001, BF_{10} = 0.211; Figure 5f) in right frontal-striatal Putamen.

Long-term training-related changes

Near transfer

We also tested if any training-related changes might persist or indeed emerge over time, as has been argued previously[41], by comparing performance on outcome measures between training groups one year post training. For probability of successful stopping in the SSRT, there was a significant interaction between Session and Group (F (1,227.16) = 8.68, $p_{FDRcorr}$ = 0.018, η^2 = 0.04; Figure 6a). Follow-up paired t-tests revealed that probability of successful stopping remained increased in the experimental group (t (217) = -4.38, p = 0.001) after one year period; however, no significant change was found in the control group (t (218) = -0.202, p = 1.000). For reaction time to the Go signal, there was a significant interaction between Session and Group (F (1, 235.94) = 13.32, $p_{FDRcorr}$ < 0.003, η^2 = 0.05; Figure 6b). Follow-up paired t-tests revealed that reaction times remained elevated in the experimental group (t(231) = - 6.992, p < 0.001); however, no significant change was found in the control group (t(230) = -1.844, p = 0.399).

Far transfer

Cognitive control: No significant changes remained in executive function tasks one year post training. These analyses were performed on a subset of tasks that were carried out at the follow-up due to Covid restrictions. There was no Session by Group interaction found in memory span in the CORSI task (F (1, 228.05) = 0.147, p = 0.702, η^2 < 0.001, BF_{10} = 0.152; Figure 7a), proactive control, as measured by the AX-CPT (F (1, 445) = 0.340, p = 0.560, η^2 < 0.001 , BF_{10} = 0.165; Figure 7b), or cognitive flexibility (F (1, 227.71) = 0.178, p = 0.183, η^2 = 0.008, BF_{10} = 0.294; Figure 7c).

Decision Making**:** There was no significant Session by Group interaction for any of the decision-making measures (Sharing in the Dictator Game: (F (1, 204.53) = 2.74, p = 0.099, η^2 = 0.01, BF_{10} = 0.450; Figure 7d); proportion of accepted offers in the Ultimatum Game (F (1, 198.66) = 0.385, p = 0.536, η^2 = 0.002, BF_{10} = 0.174; Figure 7e); Percentage delayed choice in the intertemporal choice task (F (1, 202.89) = 0.116, p = 0.733, η^2 < 0.001, BF_{10} = 0.166; Figure 7f).

Mental Health: There was no significant Session by Group interaction found for internalising problems (F (1, 154.70) = 2.23, p = 0.138, η^2 = 0.01, BF_{10} = 0.207; Figure 7g) or externalising problems (F (1, 147.47) = 0.573, p = 0.450, η^2 = 0.004, BF_{10} = 0.162; Figure 7h).

Mediation of far transfer by near transfer

A common argument in defence of the large heterogeneity within far transfer effects from training studies is that this depends crucially on whether near transfer is found[57]. We examined if changes in near transfer was in any way predictive of changes in far transfer. Our measure of near transfer was probability of successful stopping. We found that near transfer was not predictive of performance change on any far transfer measure.

Training effect on apathy and mental health before and after COVID lockdown

Much research has been dedicated to establishing that cognitive control might serve as a buffer to the onset of mental health problems[52,58]. While our present sample was not at risk, data collection took place during Covid-19, which presented significant challenges to mental health due to school closures and lockdowns[64]. We examined whether training cognitive control would buffer against any negative impact of Covid-19 measures on mental health. We studied apathy and mental health using the Apathy Evaluation Scale (AES-C) and Strengths & Difficulties Questionnaires (SDQ) for age 4-17 before and after COVID lockdown. We found that both groups were comparable in terms of positive cases of Covid, as well as perceived stress (see Supplementary Material). Crucially, while we found that a significant increase in

Apathy following COVID lockdown (F (1,178.29) = 29.82, p < 0.001; Figure 8a) this was not buffered by response inhibition training (F (1, 178.78) = .014, p = 0.905, η^2 < 0.001, BF_{10} = 0.188; Figure 8a). There was no buffering effect of training on the strength and difficulties scores following COVID lockdown (F (1, 154.32) = 3.05, p = 0.083, η^2 = 0.008, BF_{10} = 0.141; Figure 8b).

Controlling for SES

To test for the robustness and generalisability of our effects, we re-ran all analyses of short- and long-term near and far transfer effects while also controlling for SES. Controlling for SES did not change any of the outcomes.

Discussion

The critical role of cognitive control in healthy and productive development and positive later life outcomes has attracted enormous interest from researchers and policy makers seeking to understand how cognitive control development can be supported. However, consensus on whether this is possible has been hard to reach, primarily due to shortcomings in study designs and underpowered samples. Here we surmount these limitations to address whether cognitive control can be improved by means of a targeted response inhibition training, and whether such training has lasting wider impact on cognitive and neural functioning. We developed an 8-week intervention administered to 235 6-12 year old children in a randomized-control trial including an active control group training response speed. We found that our training led to specific improvements in the trained functions (i.e. response inhibition and response speed), which lasted up to 1-year post training. We further found that response inhibition training led to more cautious responding on a battery of cognitive control tasks. Crucially however, we did not find any evidence to support the idea that training response inhibition leads to changes in other domains, such as decision-making, academic achievement, fluid reasoning, mental health or creativity. Further, there was no evidence that our training led to any changes in brain function, structure or connectivity. There was also no indication of training effects emerging over time, nor did the presence of near transfer effects mediate the likelihood of far transfer. Finally, training response inhibition did not act as a buffer to mental health problems as a result of significant social stressors such as Covid-19. Bayesian tests provide substantial evidence in support of the evidence of absent training effects (see Tables 1 and 2). In sum, response inhibition training appears to do nothing to alter children's brain or their behavior in long-lasting ways.

Research on the effectiveness of cognitive control interventions has been riddled with contradictory findings[34,65,66]. However, consensus exists that this is best arbitrated by high-quality evidence[35], namely through randomized control trials with an active control group[35,36], clearly defined training mechanisms[35,37,38] implemented in a variable, dynamic and adaptive training schedule[19,39,40], across a large sample of participants and with a comprehensive set of outcome measures taken at multiple timepoints. The present study represents such an approach, following best practices of the field[35,42] to interrogate whether a core facet of cognitive control, response inhibition can be improved and whether this leads to changes in other domains of functioning. We find that each group improved throughout the intervention on their trained process and that training effects were also found manifest on near transfer tasks up to 1 year after the end of training, suggesting that the training was highly effective at improving the targeted cognitive processes. We also find that the proactive slowing found in the experimental group became manifest as general slowing on other cognitive control tasks. While it has been shown that training response inhibition can increase proactive control[67], the absence of reduced errors on cognitive control tasks in the present study suggests that such slowing does not bestow any strategic advantage. The fact that the two training groups changed improved on the targeted function strengthens the evidence of absent training effects on any far transfer measure or underpinning neurocognitive outcome. Bayesian analyses overwhelmingly demonstrate evidence of absence of transfer effects on any of the tested domains or brain mechanisms implicated in cognitive control. Further, the present study also addresses two recent hypotheses for the large heterogeneity of effects in cognitive training studies. The first of these proposes that the occurrence of far transfer depends on and is indeed mediated by the occurrence of near transfer[57]. We did not find evidence to support this claim here. Similarly, it has also been argued that far transfer effects might emerge over time and can therefore only be detected by testing again at least 1-year after the end of an intervention[41]. Again, we did not find any evidence for such effects. Finally, we were able to leverage the unique opportunity of Covid-19, as a large-scale and unintended stressor that occurred during the period of our study, allowing us to test a commonly held assumption, namely whether cognitive control training would buffer against the onset of mental health difficulties following a stressor[12,52]. We did not find any evidence of such an effect, and in fact we find moderately strong evidence of absence of an effect of appreciable magnitude. In sum, the present study provides one of the strongest and most comprehensive pieces of evidence against the possibility of training cognitive control in such targeted ways to improve associated domains of functioning, at least as instantiated through a response inhibition intervention.

A fundamental feature of virtually all cognitive control interventions is to attempt bringing about improvements via directly increasing capacity of the targeted function (i.e. *extend number of*

items held in working memory; *accelerate speed* of inhibition or flexibility)[25]. This approach is predicated on the assumption that cognitive control is a limited capacity or resource[68], with little regard for what might motivate its use. The present study demonstrates that such an approach does nothing to change children's behavior or underlying neural architecture, at least not through targeting response inhibition. Indeed, resource accounts of cognitive control while popular for many years are being debunked on both theoretical and empirical grounds[69] and replaced with theories that consider cognitive control as inherently goal oriented processes[70]. A growing body of empirical evidence and computational modelling shows that cognitive control is assigned a value as a function of subjectively perceived effort and the likely reward or goal priority[70-72]. Critically, these insights have been successfully leveraged very recently in the context of aiming to improve cognitive control. For instance, effort-contingent rewards introduced during cognitive control tasks, by means of objective assessments of effort, led to an increased preference of effort in new tasks, such as difficult problems of arithmetic[73,74]. In conjunction with the present findings that cognitive control cannot be improved through artificially inflating capacity, this raises the tantalising possibility that cognitive control can be improved in ways that lead to changes in other domains via targeting motivation and effort expenditure, something that has yet to be tested in developmental populations. We note some limitations. While the overall duration was longer than other recent studies demonstrating far transfer[27,41] there is a possibility that the present training was insufficient in terms of dose or implementation. Further, our sample came from above average SES backgrounds, and while all effects hold when controlling for this, we acknowledge that our findings may not generalise to other samples differing significantly in terms of SES or other background characteristics.

Here we follow best practice recommendations to designing cognitive trainings to test whether cognitive control can be improved in durable ways through training response inhibition and whether this leads to changes in associated domains of functioning in an unprecedented sample of children and number of outcome measures. While trained functions improved in both groups and did so up to 1-year post training, and response inhibition training led to more cautious task responding generally, our training did nothing to change children's behaviour or associated neural mechanisms. Given the considerable policy implications of how children can be supported in their development, these findings strongly caution against any further investment in seeking to improve response inhibition specifically and cognitive control more generally through trainings that canonically aim to boost these capacities wholesale.

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