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Less supervision by the executive system after disruption of the right prefrontal cortex leads to increased gambling because superficially attractive–but risky–choices are not suppressed. Similarly, people might gamble more in multitask situations because concurrent executive processes usually interfere with each other. Here we investigated whether multitasking could reduce rather than increase gambling in a novel monetary decision-making paradigm. We found that performing a stop-signal task, which induces cautious motor responding, reduced gambling in a multitask situation (Experiment 1). We then found that a short period of inhibitory training lessened gambling at least two hours later in time (Experiments 2-3). Our findings indicate that proactive motor control interacts strongly with monetary gambling. The link between control systems at different cognitive levels might be exploited to develop new methods for rehabilitation of addiction and impulse-control disorders.

Flexible behaviour and decision-making require an executive control system, which oversees subordinate processes and intervenes when outcomes become suboptimal (Monsell & Driver, 2000). Impairments in executive control lead to maladaptive behaviour because irrelevant motor actions are not inhibited. Similarly, less supervision by the executive system leads to impaired decision-making because distracting information and suboptimal choices are not suppressed. Studies in the clinical and neuroscience domains suggest that executive control of the motor system may share mechanisms with high-level decision-making. For instance, the latency of stopping a motor response is prolonged in pathological gamblers (e.g. Goudriaan, Oosterlaan, de Beurs, & van den Brink, 2006; but see Lipszyc & Schachar, 2010). Similar response-inhibition deficits have been observed in other impulse-control disorders, such as ADHD (Chamberlain & Sahakian, 2007; Nigg, 2001), or in individuals with substance dependence (Bechara, Noel, & Crone, 2006; de Wit, 2009). Similarly, cognitive neuroscience studies suggests that brain areas associated with inhibiting motor output also regulate risk-taking behaviour by suppressing superficially attractive but risky options (Cohen & Lieberman, 2010; Knoch et al., 2006). For example, Knoch et al. (2006) showed using transcranial magnetic stimulation that temporarily disrupting the right dorsolateral prefrontal cortex (DLPFC)–which is important for executive control of motor actions (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Garavan, Ross, & Stein, 1999; Ivanoff, Branning, & Marois, 2008)–led to increased gambling. Based on such findings, researchers have proposed that efficient control of impulses and urges in different domains relies on overlapping inhibitory mechanisms that allow people to suppress thoughts, actions, and decisions that are inappropriate, suboptimal, or potentially harmful (Chambers, Garavan, & Bellgrove, 2009; Crews & Boettiger, 2009; Goudriaan, Oosterlaan, de Beurs, & Van den Brink, 2004). However, direct support for such claims is scarce and mostly limited to correlational findings.

Therefore, we sought to uncover direct evidence that inhibitory motor control shares mechanisms with decision-making when gambling by examining how these processes interact in multitask situations. Intuitively, people assume that the brain isolates decision-making in different domains, with problems at higher cognitive levels (e.g. “should I take a day off or go to work?”) solved independently of those at motor levels (e.g. “should I reach for that hot saucepan?”). However, behavioural scientists have shown that making multiple decisions simultaneously typically leads to impoverished behaviour (Marois & Ivanoff, 2005; Pashler & Johnston, 1998). For example, using a cell phone in the car hinders driving performance (Strayer & Johnston, 2001). Similarly, monetary decision-making might becomes less regulated in multitask situations because concurrent executive processes usually interfere with each other. Therefore, people might gamble more in multitask situations compared to single-task situations because the executive system would be less able to suppress the tendency to pick higher and more appealing—yet also more risky—amounts. But are the effects of multitasking on gambling and decision-making necessarily detrimental? Here we asked whether executive control in a concurrent task might actually *reduce* rather than increase gambling. Specifically, we examined whether suppressing motor output whilst making monetary decisions encouraged participants to gamble less. Evidence of such a 'control transfer' between cognitive domains would not only provide direct support for the hypothesis that there is an overlap in executive mechanisms, but could also open new avenues for the treatment of psychiatric disorders that are linked to impaired inhibitory control, such as ADHD, substance abuse, and pathological gambling.

We examined the interaction between motor control and gambling using a novel behavioural task (Figure 1A). Participants were presented with 6 free-choice options on every trial and indicated their choice through a manual response. Each option was associated with a certain amount that could be won; however, participants were informed that the higher the amount, the less probable a win. Thus, selecting higher amounts constitutes a more 'risky' bet, whereas selecting lower amounts constitutes a safer bet. Risk-taking in our task refers to preferring relatively high amounts with a high probability of losing (and in case of the most risky options, a negative expected value; see Supplementary Information) over lower amounts with a lower probability of losing (Boyer, 2006), and it is the behaviour pathological gamblers engage in when, for example, wagering on horse races.

In Experiment 1, participants performed the gambling task throughout the session. In some blocks (i.e. the '*dual task*' blocks), they also undertook a secondary task. The nature of the secondary task depended on the group they were assigned to. In the first group (*double-response* condition), the secondary task required participants to occasionally execute an additional response when an extra signal occurred (Figure 1B). Monitoring for occasional signals and preparing additional responses increases dual-task demands (Verbruggen & Logan, 2009c). If executive processes at different levels interfere with each other, then participants should place riskier bets in '*dual-task*' blocks (i.e. blocks with the secondary task) than in '*single-task*' blocks (i.e. blocks without the secondary task) because the executive system would be less able to suppress the tendency to choose the riskier amounts (Cohen & Lieberman, 2010; Knoch et al., 2006).

In the second group (*stop* condition), participants had to stop the planned manual choice response when the occasional signal occurred. Opposing predictions were made for the stop condition. According to the *interference account* (see above), cross-task interference in multitask situations should cause participants to place riskier bets in dual-task blocks than in single-task blocks. By contrast, the *transfer account* holds that occasional stopping should induce a general state of cautiousness that may propagate across cognitive domains. When preparing to stop, people make proactive adjustments and become more cautious in executing motor responses (Aron, 2011; Jahfari, Stinear, Claffey, Verbruggen, & Aron, 2010; Liddle et al., 2009; Verbruggen & Logan, 2009c). If there is an overlap between mechanisms that regulate motor cautiousness and mechanisms that control gambling behaviour then cautiousness may transfer between domains;

consequently, preparation for stopping motor responses might encourage risk-*aversive* behaviour. Finally, according to the *independence account*, the cognitive processes involved in motor inhibition and gambling are mechanistically independent; therefore, performing a double-response or stop task should not influence monetary decision-making.

To anticipate the outcome of Experiment 1, we found support for the transfer account. We therefore conducted two additional experiments in which a stop/double-response task was completed *prior* to the gambling task, to test whether motor inhibition training leads to more cautious gambling behaviour later in time.

## Experiment 1

### Methods and Materials

**Participants**. Forty-four adults participated for monetary compensation (£6 per hour, plus money won in the gambling task). Table 1 shows participant characteristics and amounts won. Groups were matched for sample size, gender and age. There were no group differences in impulsivity (assessed by the Barratt Impulsiveness Scale – 11) or general risk-seeking behaviour (assessed by the Stimulating-Instrumental Risk Inventory). All experiments were approved by the local research ethics committee (School of Psychology, Cardiff University).

**Procedure.** Stimuli were presented on a 19-inch LCD monitor against a grey background. The task was run using PsychToolbox (www.psychtoolbox.org). On each trial, 6 vertical bars were presented next to each other (Figure 1). Each bar was associated with a certain amount and a specific response key (the 'd', 'f', 'g', 'h', 'j', or 'k' key of a keyboard). Subjects were instructed to select one of the amounts by pressing the corresponding key (e.g. in Figure 1, if they wanted to select '112', they would press 'h'), and they were informed that the probability of winning decreased as the amount increased. On each trial, we presented six amounts to offer participants a wide variety of choice options. The amounts and response keys were presented below the six vertical bars. The order of the amounts varied from trial to trial to prevent choice from being driven by spatial-attention or response-bias effects (e.g. selecting higher amounts could reflect a spatial-attention or rightward response bias if these were consistently presented on the right of the screen).

Each trial in single-task blocks started with the presentation of the 'start' bars, amounts, and the associated keys (Figure 1A). The bars appeared between two horizontal lines. After 3.5 sec the bars started rising together. All bars reached the top line after 1.33 sec on 'low-bar' trials, and after 1.67 sec on 'high-bar' trials (the distance between bottom- and top line was approximately 7.5 cm on 'low bar' trials & 9 cm on 'high bar' trials). We manipulated bar height to test for effects of choice latency (see Supplementary Information). Trials ended 0.250 sec after the bars reached the top line. Participants had to execute the choice response before the end of the trial but not sooner than

0.250 sec. before the bars reached the top line. We used the moving bars and the response-window restrictions to ensure that stop signals (see below) could presented at an optimal moment (see also Coxon, Stinear, & Byblow, 2007). Feedback was presented at the end of each trial (Figure 1A), and indicated how much they had won/lost and what the current balance was. The feedback screen was then replaced by a blank screen after 2.5 sec and the following trial started after a further 0.5 sec.

In dual-task blocks, participants had to select one of six amounts and indicated their choice response when the yellow bars reached the top line on 2/3 of the trials, just as in the single-task blocks (see Figure 1A & previous paragraph). However, on 1/3 of trials in the dual-task blocks, the top of the rising bars turned black ('*signal*' trials) just before reaching the top line (see Figure 1B). On signal trials in the double-response group, participants pressed the space bar of the keyboard with either thumb after they had indicated their monetary choice (i.e. after they pressed the 'd', 'f', 'g', 'h', 'j', or 'k' key of the keyboard). They had to press the space bar within 0.250 sec after the bars reached the top line. In the stop group, participants had to refrain from responding on signal trials. In both groups, the moment of signal presentation was dynamically adjusted for each individual. Initially, the bars turned black 0.266 sec before the top line was reached. When participants successfully stopped their response or pressed the alternate key in time (i.e. within 0.250 sec after the bars reached the top line), this delay was decreased by 0.033 sec, making it harder to successfully stop or execute the double-response on the next trial. When participants failed to stop or execute the double-response in time, the delay was increased by 0.033 sec. Note that at the beginning of each block, participants were informed whether or not signals could occur (i.e. whether the block was a single-task or dual-task block).

On each trial in both single- and dual-task blocks, participants could win or lose points. The exact amount depended on the stake (low, medium, or high). Amounts [with *p(win)*] participants could win in the low-stake condition were: 112 (*0.15*), 64 (*0.27*), 32 (*0.39*),16 (*0.51*), 6 (*0.63*), 2 (*0.75*). On losses, they lost half the chosen amount. Amounts decreased exponentially to make the higher amounts more attractive. Without revealing the exact probabilities, participants were informed at the beginning of the experiment that p(win) was lower for higher amounts. Because we could not infer which response participants were planning to execute on successful stop-signal trials, the number of points won or lost on signal trials was fixed (i.e. trials on which the top of the bar turned black before the top line was reached). Participants won 10 points on successful signal trials, and lost 10 points on unsuccessful signal trials in both the stop and double-response groups. Thus, on double-response response trials, participants always won/lost 10 points, regardless of their choice response. Similarly, on unsuccessful stop trials, participants always lost 10 point, regardless of the amount they indicated with their incorrectly executed choice response.

For medium stakes, all amounts were x 2; for high stakes, amounts were x 4. We manipulated the stakes for several reasons: to increase selection demands, to encourage processing of the different amounts on each trial, and to encourage participants to consider the relative risk/benefit of each amount. The three stakes occurred in random order with equal probability and had to be inferred by the participants from the amounts that were presented below the bars. The starting balance was 2500 points. At the end of the experiment, the total amount won was converted to money (1000 points = £1).

The experiment started with a short practice phase that consisted of a single-task block and a dual-task block. A discussed above, in the single-task block, the bars remained yellow on all trials and participants executed a single choice response only. In the dual-task block, 2/3 of trials were identical to single-task trials; on the remaining 1/3 of trials, the top of the bars turned black and participants either executed a dual-task response (in the double-response group) or withheld all responses (in the stop group). The balance of points won or lost was reset after this practice phase. The experimental phase consisted of four single-task blocks and four dual-task blocks of 36 trials each. There was a short break between each block, and the order of the block types was fixed (ST–DT–ST–DT...). On each trial, a cue (*"NO-SIGNAL BLOCK"* or *"SIGNAL BLOCK"*) was presented above the top line to remind participants about the block type.

**Betting scores.** For each participant, we calculated a '*betting score*' by taking the average of all choices (Range: 1-6). Choice 1 corresponded to the smallest amount, with the highest probability of winning (hence safest bet). Choice 6 was the highest amount, with the lowest probability of winning (hence most 'risky' bet; see above). Consequently, a higher average betting score indicated that participants preferred riskier bets with a lower probability of winning. See Tables 2 (Experiment 1) and 3 (Experiments 2-3) for overviews of the analyses of the betting scores.

## Results and Discussion

Results of Experiment 1 confirmed the effectiveness of the tracking procedures (percentage failed double-responses = 46%; percentage failed stops = 47%). Thus, there was no consistent difference in success rates on signal trials between the groups [$F < 1$]. Even though we did not use separate tracking procedures for each stake, additional analyses showed that the percentage of failed signal trials was similar for each stake (low = 47%, medium = 46%, high = 49%; $p > .39$). This was true for both groups (interaction between stake and group: $p > .18$).

To test the effect of multitasking on gambling, we compared betting scores between dual-task and single-task blocks. We concentrated specifically on no-signal trials (i.e. trials on which the bars remained yellow and participants had to execute a single choice response). This allowed us to isolate the behavioural effects of *monitoring* for extra signals and *preparing* to either make a double response or to stop the first response (in 'dual-task' blocks), compared to conditions with identical stimuli but without such demands (in 'single-task' blocks).

Experiment 1 showed that participants in the double-response group tended to place *more risky* bets (i.e. bets with a higher probability of losing) in dual-task blocks than in single-task blocks

(Figure 2A; mean betting score dual-task = 2.77, single-task = 2.72), but this effect failed to reach significance. More importantly, however, participants in the stop group showed the opposite result: they not only became more cautious when executing their choice responses (as indexed by longer choice latencies; see Supplementary Information), they also placed overall *safer* bets in dual-task blocks in which stop signals could occur than in single-task blocks, $F(1,23) = 4.7$, $p = .04$, $\eta_p^2 = 0.19$ (Figure 2A; mean betting score dual-task = 2.62, single-task = 2.77). The effect of block type in the stop group shows that preparing to stop motor responses encourages cautious monetary decisions, and that this 'cautiousness transfer' counteracts and reverses the detrimental effects that are usually associated with multitasking. Thus, multitasking does not necessarily lead to increased gambling; concurrent executive processes can make people generally risk-aversive when these processes regulate cautiousness at a motor level[1]. This conclusion was supported by a significant two-way interaction of Block Type x Group (Table 2).

Additional analyses of specific choices in Experiment 1 showed that participants in the stop group tended to select the most risky bets (choice option 6) less often in dual-task blocks than in single-task blocks (Figure 2B)[2]. Furthermore, for the dual-task blocks in the stop group, there was a preference for choice option 1 (the safest option), which had a lower expected value (EV) than choice options 3-5[3]. Thus, it appears that participants in the stop group became *overly cautious* in dual-task blocks, as taking a certain amount of risk was rewarded in our gambling task. Further analyses also showed that the difference between block types in the stop condition was not caused by differences in choice latencies, effects of probability learning, estimation of the expected value of the choice options, block order, or priming of participants to focus more on either wins or losses (Supplementary Information). Finally, a closer inspection of the distribution of selected keys/

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[1] We replicated this finding in a pilot experiment (N = 40) in which we used fixed signal delays. In this experiment, there was Group x Block Type x Stake interaction (p = .008). Separate comparisons showed that in the stop group, the dual-task effect corresponded to a reliable decrease in betting scores for the low [F(1,19) = 8.0, p = .01] and medium stakes [F(1,19) = 6.0, p = .02]; there was also a strong trend for the high stakes [F(1,19) = 3.9, p = .06]. In the double-response group, the dual-task effect instead led to increased betting at low stakes [F(1,19) = 5.2, p = .03]; there was no reliable dual-task effect for medium and high stakes (both p's > .12). Thus, multitasking tended to increase betting in the double-response group but decrease betting in the stop group. However, because probability of stopping was lower than probability of responding in time on a double-response signal trial, we sought to replicate this finding in Experiment 1, where the moment of signal presentation was dynamically adjusted in both groups (see Method section & Figure 1B).

[2] In the stop group of the pilot experiment, we found that p(choice = 1) was higher (p < .029) and p(choice = 5) was lower (p < . 0027) in the dual-task blocks than in the single-task blocks. In addition, p(choice = 6) tended to differ between block types, p < .056. When we combined the data of Experiment 1 and the pilot experiment to increase power (N = 44), we found that p(choice = 1) was significantly higher in dual-task blocks (.270) than in single-task blocks (.215), p = .003. By contrast, p(choice = 6) was reliably lower in dual-task blocks than in single-task blocks [p = .0097; dual-task = .048; single-task = .062]; a similar difference was observed for p(choice = 5) [p = .028; dual-task = 0.081 vs. single-task = 0.097]. None of the other differences reached significance (all p's > .11)

[3] As discussed in the Supplementary Information, we manipulated expected values to ensure that there were two choice options with a negative EV, three options with positive EVs but different probabilities of winning, and one option with a high probability of winning but a positive EV closer to zero.

fingers demonstrated that in all conditions, participants took amounts into account when they made their choice (Table E4, Supplementary Information).

## Experiments 2-3

Experiment 1 demonstrates that simultaneously regulating motor performance and making monetary decisions does not necessarily lead to increased gambling. On the contrary, preparing to withhold a motor response encourages a cautious executive-control state that generalises to seemingly unrelated monetary decisions. Next we asked if motor cautiousness would also influence monetary gambling when these processes are separated in time. A recent study showed that performing an inhibition task in which participants had to ignore words led to 'depletion' of executive control; this caused more risk-taking behaviour in a subsequent gambling task (Freeman & Muraven, 2010). This finding seems at odds with the results of Experiment 1. However, we propose that in our gambling task, proactive motor slowing—which is prominent in the stop task but not necessarily in other inhibition tasks—counteracted any depletion effects and encouraged risk-aversive monetary decision-making. In Experiments 2-3, we tested whether this transfer of cautiousness would still be present when the gambling task followed the stop task. The experiments consisted of two phases: a training phase, which did not involve gambling, and a test phase, in which participants chose between different amounts they could win. The test phase did not involve an additional task; therefore all blocks were identical to the single-task blocks from Experiment 1.

### Methods and Materials

**Participants.** One hundred and thirty-five adults participated for monetary compensation (£6 per hour, plus money won in the gambling task). Table 1 shows participant characteristics and amounts won. Within each experiment, groups were again matched for sample size, gender and age, and there were no group differences in impulsivity or general risk-seeking behaviour.

**Procedure.** The gambling task was identical to the single-task blocks of Experiment 1: participants had to execute a single choice response on each trial and no signals were presented. Therefore we focus on the unique methods of Experiments 2-3. Experiment 2 included three groups. The control group started immediately with the gambling task. The double-response and stop groups started with a training phase in which the primary task was to identify a go stimulus (square vs. diamond) as rapidly and accurately as possible (Figure 3). Participants responded with their left or right hands, respectively ('C' or 'M' on a keyboard).

On no-signal trials in the training phase, participants had to respond before the shape disappeared. On signal trials (25%), the outline of the shape turned bold after a variable delay (SOA). On these trials, participants in the double-response group had to press the space bar as quickly as possible with either thumb after they pressed 'C' or 'M'; whereas participants in the stop group were instructed to refrain from responding on signal trials. The SOA between the go stimulus (the shape) and signal was initially set at 0.250 sec. In the stop group, the SOA was continuously adjusted according to a tracking procedure that converged on a probability of stopping of .50 (Verbruggen & Logan, 2009b). The SOA decreased by 0.05 sec when participants responded on a signal trial, and increased by 0.05 sec when they successfully stopped. In the double-response group, we simulated a tracking procedure to produce a similar range of SOAs to the stop group (see ref. Verbruggen & Logan, 2009c, for a similar procedure). In the simulation, we used an estimate of the latency of the stop process (estimated stop latency= 0.225 sec. This value was based on our previous work; e.g. Verbruggen & Logan, 2009a). When the latency of the first response on a double-response trial was shorter than SOA + 0.225 sec, SOA decreased by 0.05 sec (viz., signal-respond); when the latency of the first response on a double-response trial was longer than SOA + 0.225 sec., SOA increased by 0.05 sec (viz., signal-inhibit).

The training phase of Experiment 2 consisted of 10 blocks of 72 trials (~ 30 minutes in total), with a short break between each block. Participants received a 2-minute break after the training phase, followed by the test phase, which included 7 blocks of 12 trials. The control group started immediately with the test phase. During the test phase, participants completed the same gambling task as described in the 'single-task' blocks of Experiment 1 (thus, all trials were no-signal trials in the test phase). The training phase of Experiment 3 consisted of 15 blocks of 56 trials (~ 35 minutes in total). The test phase followed the training phase after 2 hours. During this 2-hour delay, participants were free to leave the lab, but were asked to report what they had done after they returned for the test phase. There were 14 blocks in the test phase of Experiment 3.

**Results and Discussion**

Results of Experiment 2 revealed a reliable aftereffect of executive-control training on gambling behaviour (Figure 4). Participants in the stop group took 10-15% less monetary risk than participants in the double-response group [$F(1,52) = 6.1$, $p = .02$, $\eta_p^2 = .11$] and the control group, which did not receive any training [$F(1,52) = 10.8$, $p = .002$, $\eta_p^2 = .17$]. This demonstrates that motor cautiousness in the stop task transferred to monetary decision-making, even when the stop and gambling tasks did not overlap in time. There was a numerical trend for higher betting scores in the double-response group than in the control group, which would be consistent with a depletion account; however, the difference was not significant ($p = .29$). Thus, the cognitive characteristics of the training phase were crucial: cautiousness transferred from the training phase to the test phase only when the training phase involved stopping, and not when it involved executing a second response. This conclusion was supported by a significant main effect of Group (Table 3).

In Experiment 3, we tested whether the transfer was still present when the delay between the training phase and the test phase was increased. Participants again performed either the double-response task or stop task in the training phase, but now followed 2 hours later by the test phase.

Consistent with Experiment 2, we found that participants in the stop-group took 10-15% less risk than participants in the double-response group [Figure 4; $F(1,52) = 4.9$, $p = .03$. $\eta_p^2 = 0.09$].

Taken together, the results of Experiments 2-3 show that cautiousness at a motor level influences gambling behaviour, even when motor training and monetary decision-making occur at least two hours apart. The effects in the test blocks did not correlate with the outcome of the stop process in the training phase and were not caused by differences in choice latencies (Supplementary Information). Furthermore, analyses of choice proportions showed that after stop training, participants specifically avoided the two most risky bets (Figure 5). Based on these findings, we propose that the requirement to occasionally stop a motor response can train people to become cautious and less impulsive when they make monetary decisions. This increased cautiousness might overcome the previously observed effect of depleting the executive control system (Freeman & Muraven, 2010).

Interestingly, a recent study showed that participants who were instructed to be cautious in a stop-training task consumed less food in a subsequent test phase than those participants who were instructed to respond as quickly ('impulsive') as possible (Guerrieri, Nederkoorn, Schrooten, Martijn, & Jansen, 2009). Unfortunately, the lack of an appropriate control condition in this previous study obscures the underlying basis of this effect, which could have arisen due to increased cautiousness, increased impulsivity, or a combination of both (Guerrieri et al., 2009). Nevertheless, these findings are consistent with our observation that engaging in an inhibitory motor task can boost behavioural caution and reduce impulsivity.

Future work should further explore how stopping-induced cautiousness and reduced motor impulsivity can transfer to various clinically relevant behaviours, including consumption of food and alcohol, and cigarette smoking (see also Friese, Hofmann, & Wiers, 2011). Mechanisms that regulate stopping and motor cautiousness might also overlap with mechanisms that govern the choice between a small, immediate award compared with a larger but delayed reward (Kim & Lee, 2011; but see also Dalley, Everitt, & Robbins, 2011). If there is indeed such an overlap, we would predict that stop training should bias intertemporal choice toward larger delayed rewards.

## Conclusions

A convergence of evidence shows that decision-making depends on two information streams: automatic processes that are associative and often emotionally-driven, and reasoning processes that are rule-governed and rational (for a review, see Evans, 2008). Suppression of the former in favour of the latter requires executive control processes. Here we focused on how executive processes regulate decision-making when people gamble. When gambling, most people realise that the odds are against them; in economic terms, they often know that the expected value of high-risk gambles is negative. As such, research on gambling can reveal important information about how people regulate choice when they are presented with superficially attractive but risky options.

We found that situational factors have a substantial impact on the executive control of decision-making in a gambling task. Experiment 1 demonstrates that motor cautiousness reduces risky betting in a novel gambling task, thus showing that concurrent executive processes need not interfere detrimentally. Instead, control in the motor domain can transfer to other decision-making domains, in this case monetary gambling. Furthermore, we found that training people, even briefly, in controlling their own motor actions can induce cautious and risk-aversive decision-making for at least two hours afterward (Experiments 2-3). In these experiments, occasional motor inhibition reduced monetary risk-taking by ~10-15%. Interestingly, this effect size is comparable to previous studies that have manipulated risk-taking using brain stimulation methods. For instance, Knoch et al (2006) found a 15% *increase* in risk-taking via the Cambridge gambling task after TMS of right DLPFC, while Fecteau et al (2007) found a 10% *decrease* in risk-taking using the Balloon Analogue Risk Task following prefrontal transcranial direct current stimulation (TDCS). Combined with evidence that TDCS can potentiate learning (Nitsche et al., 2008), these findings suggest that brain stimulation could augment the training effects we have found.

We propose that increased motor cautiousness, which is a prominent feature of the stop task, reduced risk-taking behaviour when making monetary decisions. Future studies should examine whether similar effects can be obtained through alternative methods of inducing motor caution, for example by instructing people to favour accuracy over speed in a standard choice task. Many studies have shown that participants are more cautious when they are instructed to respond as accurately as possible, and we have previously proposed that strategy adjustments in the speed/accuracy paradigm resemble those in the stop-signal paradigm (Verbruggen & Logan, 2009c).

From a theoretical perspective, our results suggest that executive processes at motor domains share mechanisms with monetary decision-making and gambling. Recent cognitive neuroscience studies have shown that frontal brain areas involved in action monitoring and response inhibition might also be involved in monetary decision-making in gambling tasks (Clark, 2010; Knoch et al., 2006). Similarly, studies have shown that the latency of stopping a motor response is prolonged in pathological gamblers (e.g. Goudriaan et al., 2006). However, such correlational findings are difficult to interpret securely. Instead, our results show that motor control can have a direct impact on monetary gambling. This functional overlap suggests that inhibitory motor control and gambling share executive resources, which opens new avenues for the investigation of cognitive and neural mechanisms of executive control at different processing levels.

More generally, our results show that exerting executive control over actions and decisions can be practiced (see also Friese et al., 2011; Muraven, 2010). These findings have potential clinical relevance because impairments in executive control, and particularly stopping, have been linked to the development of several impulse-control disorders, including ADHD, substance abuse and pathological gambling (Chambers et al., 2009; Verbruggen & Logan, 2008). Furthermore, recovery from addiction requires inhibition of repetitive addictive behaviour (Crews & Boettiger, 2009). Consistent with the idea that response inhibition is critical for recovery, Goudriaan et al (2008) found that motor disinhibition was a strong predictor of relapse in gamblers. Similarly, motor-inhibition efficiency predicted the treatment outcome in people with eating disorders (Nederkoorn, Jansen, Mulkens, & Jansen, 2007). Therefore, the link we find between proactive motor-control and monetary gambling suggests promising new avenues for clinical therapy that target motor inhibition.

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## References

Aron, A. R. (2011). From reactive to proactive and selective control: Developing a richer model for stopping inappropriate responses. *Biological Psychiatry*, *69*(12), e55-68. doi:10.1016/j.biopsych.2010.07.024

Bechara, A., Noel, X., & Crone, E. A. (2006). Loss of willpower: Abnormal neural mechanisms of impulse control and decision making in addiction. *Handbook of Implicit Cognition and Addiction*, 215-232.

Bogacz, R., Wagenmakers, E. J., Forstmann, B. U., & Nieuwenhuis, S. (2010). The neural basis of the speed-accuracy tradeoff. *Trends Neurosci*, *33*(1), 10-6. doi:10.1016/j.tins.2009.09.002

Boyer, T. W. (2006). The development of risk-taking: A multi-perspective review. *Developmental Review*, *26*(3), 291 - 345. doi:10.1016/j.dr.2006.05.002

Chamberlain, S. R., & Sahakian, B. J. (2007). The neuropsychiatry of impulsivity. *Current Opinion in Psychiatry*, *20*(3), 255-261.

Chambers, C. D., Garavan, H., & Bellgrove, M. A. (2009). Insights into the neural basis of response inhibition from cognitive and clinical neuroscience. *Neuroscience and Biobehavioral Reviews*, *33*(5), 631-646. doi:10.1016/j.neubiorev.2008.08.016

Clark, L. (2010). Decision-Making during gambling: An integration of cognitive and psychobiological approaches. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *365*(1538), 319-30. doi:10.1098/rstb.2009.0147

Cohen, J. R., & Lieberman, M. D. (2010). The common neural basis of exerting self-control in multiple domains. In *Self control in society, mind, and brain.* (pp. 141-62). Oxford Scholarship Online Monographs.

Coxon, J. P., Stinear, C. M., & Byblow, W. D. (2007). Selective inhibition of movement. *Journal of Neurophysiology*, *97*(3), 2480-9. doi:10.1152/jn.01284.2006

Crews, F. T., & Boettiger, C. A. (2009). Impulsivity, frontal lobes and risk for addiction. *Pharmacology, Biochemistry, and Behavior*, *93*(3), 237-47. doi:10.1016/j.pbb.2009.04.018

Dalley, J. W., Everitt, B. J., & Robbins, T. W. (2011). Impulsivity, compulsivity, and top-down cognitive control. *Neuron*, *69*(4), 680-94. doi:10.1016/j.neuron.2011.01.020

Evans, J. S. (2008). Dual-Processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology*, *59*, 255-78. doi:10.1146/annurev.psych.59.103006.093629

Fecteau, S., Knoch, D., Fregni, F., Sultani, N., Boggio, P., & Pascual-Leone, A. (2007). Diminishing risk-taking behavior by modulating activity in the prefrontal cortex: A direct current stimulation study. *Journal of Neuroscience*, *27*(46), 12500-12505. doi:10.1523/jneurosci.3283-07.2007

Freeman, N., & Muraven, M. (2010). Self-Control depletion leads to increased risk taking. *Social Psychological and Personality Science*, *1*(2), 175-181. doi:10.1177/1948550609360421

Friese, M., Hofmann, W., & Wiers, R. W. (2011). On taming horses and strengthening riders: Recent developments in research on interventions to improve self-control in health behaviors. *Self and Identity*, in press.

Garavan, H., Ross, T. J., & Stein, E. A. (1999). Right hemispheric dominance of inhibitory control: An event-related functional MRI study. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(14), 8301-8306.

Goudriaan, A. E., Oosterlaan, J., de Beurs, E., & Van den Brink, W. (2004). Pathological gambling: A comprehensive review of biobehavioral findings. *Neuroscience and Biobehavioral Reviews*, *28*(2), 123-41. doi:10.1016/j.neubiorev.2004.03.001

Goudriaan, A. E., Oosterlaan, J., de Beurs, E., & van den Brink, W. (2006). Neurocognitive functions in pathological gambling: A comparison with alcohol dependence, tourette syndrome and normal controls. *Addiction*, *101*(4), 534-47. doi:10.1111/j.1360-0443.2006.01380.x

Goudriaan, A. E., Oosterlaan, J., De Beurs, E., & Van Den Brink, W. (2008). The role of self-reported impulsivity and reward sensitivity versus neurocognitive measures of disinhibition and decision-making in the prediction of relapse in pathological gamblers. *Psychol Med*, *38*(1), 41-50. doi:10.1017/S0033291707000694

Guerrieri, R., Nederkoorn, C., Schrooten, M., Martijn, C., & Jansen, A. (2009). Inducing impulsivity leads high and low restrained eaters into overeating, whereas current dieters stick to their diet. *Appetite*, *53*(1), 93-100. doi:10.1016/j.appet.2009.05.013

Ivanoff, J., Branning, P., & Marois, R. (2008). Fmri evidence for a dual process account of the speed-accuracy tradeoff in decision-making. *Plos One*, *3*(7), e2635. doi:10.1371/journal.pone.0002635

Jahfari, S., Stinear, C. M., Claffey, M., Verbruggen, F., & Aron, A. R. (2010). Responding with restraint: What are the neurocognitive mechanisms? *Journal of Cognitive Neuroscience*, *22*(7), 1479-92. doi:10.1162/jocn.2009.21307

Kim, S., & Lee, D. (2011). Prefrontal cortex and impulsive decision making. *Biological Psychiatry*, *69*(12), 1140-6. doi:10.1016/j.biopsych.2010.07.005

Knoch, D., Gianotti, L. R. R., Pascual-Leone, A., Treyer, V., Regard, M., Hohmann, M., & Brugger, P. (2006). Disruption of right prefrontal cortex by low-frequency repetitive transcranial magnetic stimulation induces risk-taking behavior. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *26*(24), 6469-6472. doi:10.1523/jneurosci.0804-06.2006

Liddle, E. B., Scerif, G., Hollis, C. P., Batty, M. J., Groom, M. J., Liotti, M., & Liddle, P. F. (2009). Looking before you leap: A theory of motivated control of action. *Cognition*, *112*(1), 141-58. doi:10.1016/j.cognition.2009.03.006

Lipszyc, J., & Schachar, R. (2010). Inhibitory control and psychopathology: A meta-analysis of studies using the stop signal task. *Journal of the International Neuropsychological Society*, 1-13. doi:10.1017/S1355617710000895

Marois, R., & Ivanoff, J. (2005). Capacity limits of information processing in the brain. *Trends in Cognitive Sciences*, *9*(6), 296-305. doi:10.1016/j.tics.2005.04.010

Monsell, S., & Driver, J. (2000). Banishing the control homunculus. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII.* (pp. 3-32). Cambridge, MA: MIT Press.

Muraven, M. (2010). Building self-control strength: Practicing self-control leads to improved self-control performance. *Journal of Experimental Social Psychology*, *46*(2), 465-468. doi:10.1016/j.jesp.2009.12.011

Nederkoorn, C., Jansen, E., Mulkens, S., & Jansen, A. (2007). Impulsivity predicts treatment outcome in obese children. *Behav Res Ther*, *45*(5), 1071-5. doi:10.1016/j.brat.2006.05.009

Nigg, J. T. (2001). Is ADHD a disinhibitory disorder? *Psychological Bulletin*, *127*(5), 571-98.

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., . . . others. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, *1*(3), 206-23. doi:10.1016/j.brs.2008.06.004

Pashler, H. E., & Johnston, J. C. (1998). Attentional limitations in dual-task performance. In H. E. Pashler (Ed.), *Attention .* (pp. 155-80). Hove, England: Psychology Press.

Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-Task studies of simulated driving and conversing on a cellular telephone. *Psychological Science*, *12*(6), 462-6.

Verbruggen, F., & Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends in Cognitive Sciences*, *12*(11), 418-24. doi:10.1016/j.tics.2008.07.005

Verbruggen, F., & Logan, G. D. (2009a). Automaticity of cognitive control: Goal priming in response-inhibition paradigms. *J Exp Psychol Learn Mem Cogn*, *35*(5), 1381-8. doi:10.1037/a0016645

Verbruggen, F., & Logan, G. D. (2009b). Models of response inhibition in the stop-signal and stop-change paradigms. *Neuroscience and Biobehavioral Reviews*, *33*(5), 647-61. doi:10.1016/j.neubiorev.2008.08.014

Verbruggen, F., & Logan, G. D. (2009c). Proactive adjustments of response strategies in the stop-signal paradigm. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(3), 835-54. doi:10.1037/a0012726

de Wit, H. (2009). Impulsivity as a determinant and consequence of drug use: A review of underlying processes. *Addiction Biology*, *14*(1), 22-31. doi:10.1111/j.1369-1600.2008.00129.x

**Figure 1**

A. Each trial in Experiment 1 began with six choice options in a random order. After 3.5 sec, the bars started rising together and reached the top line after a delay (arrows are for indicative purposes only). The long time intervals (average = 5 sec.) and the initial phase in which the bars did not rise ensured that there was minimal time-pressure to make a decision. The choice amounts depended on the stake (low, medium, or high). Amounts [with *p(win)*] participants could win in the low-stake condition were: 112 (*0.15*), 64 (*0.27*), 32 (*0.39*),16 (*0.51*), 6 (*0.63*), 2 (*0.75*). Medium-stake and high-stake amounts were 2x and 4x higher, respectively, than low-stake amounts. On wins, participants received the chosen amount; on losses, they lost half the amount. At the end of a trial, participants were told how much they had won or lost, and what their current balance was.

B. On signal trials (1/3 of the trials in dual-task blocks), the top of the bars turned black before the top line was reached. On these trials, participants either tried to withhold a response (stop group) or they generated an extra response by pressing an alternate key (double-response group). Signal trials occurred only in dual-task blocks. The moment of signal presentation was dynamically adjusted to ensure that participants succeed in executing the space-bar response in time (double-response group) or withholding their response (stop group) on approximately 50% of the signal trials (see Method section).

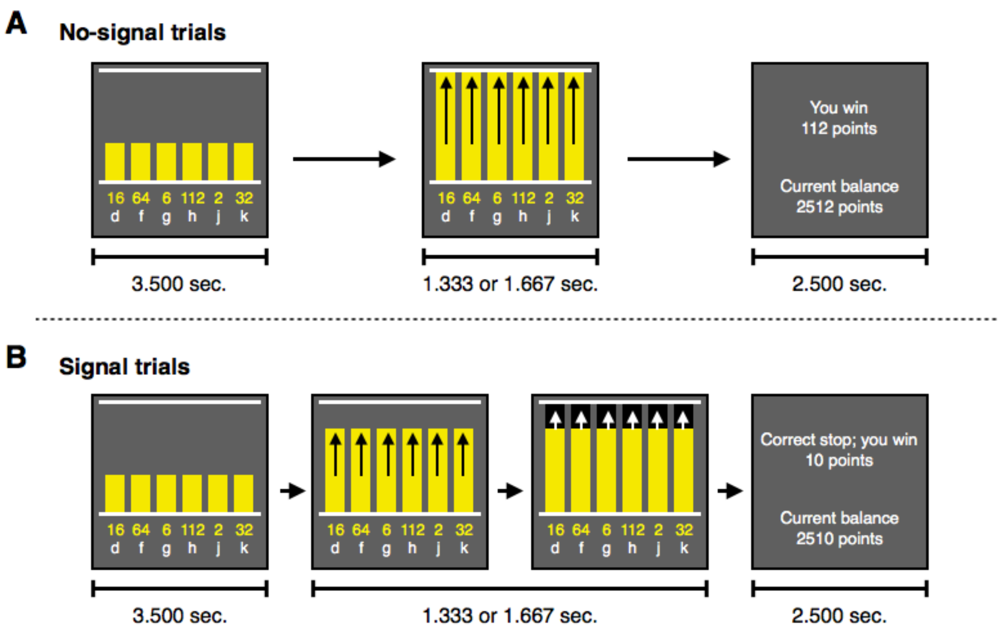

**Figure 2**

A. Betting scores of *no-signal trials* in Experiment 1 for each group (double-response, stop) and block type (single-task, dual-task). There was a Group x Block Type interaction (Table 2). The dual-task effect in the stop group corresponded to a reliable decrease in betting scores in dual-task blocks compared with single-task blocks; there was no reliable difference in betting scores in the double-response group [F < 1].

B. The proportion of each choice option [p(choice)] for the stop groups of Experiment 1. Choice option 1 was the safest bet; choice option 6 was the riskiest bet. In Experiment 1, p(choice = 1) tended to be higher, whereas p(choice = 4) and p(choice = 6) tended to be lower in the dual-task blocks than in the single-task blocks (*p*'s < .08).

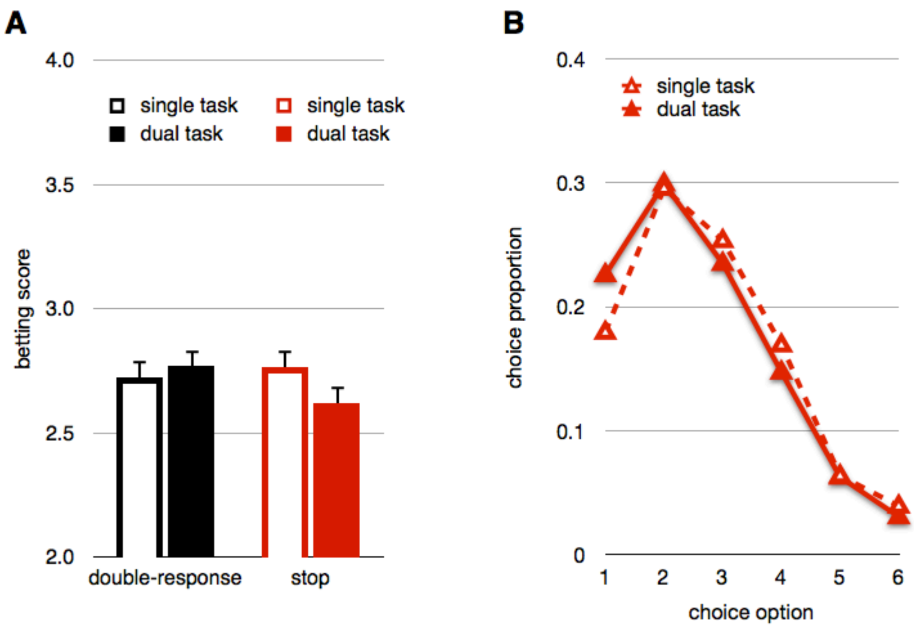

**Figure 3**

Example of a trial sequence in the training phase of Experiments 2-3 (see Methods for further details). On no-signal trials, participants responded to the stimulus shape. On signal trials, the outline of the shape turned bold after a variable delay (SOA). On these trials, participants either tried to withhold a response (stop group) or they generated an extra response by pressing an alternate key (double-response group). Signal trials occurred in all blocks. No points were awarded in the training phase. Time intervals for no-signal and signal trials are in sec.

**Figure 4**

A. Betting scores for each group (double-response, stop, control) and block in Experiment 2. The test phase included 7 blocks of 12 trials. The effects of Group and Block were significant, but there was no Group x Block interaction (Table 3). Follow-up analyses showed that the stop group was more risk-averse than both the control group and the double-response group; the control and double-response groups did not reliably differ.

B. Betting scores for each group (double-response, stop) and block in Experiment 3. The test phase included 14 blocks of 12 trials, conducted two hours after the stop or double-response task. Significant main effects of Group and Block were observed; there was no significant Group x Block interaction (Table 3).

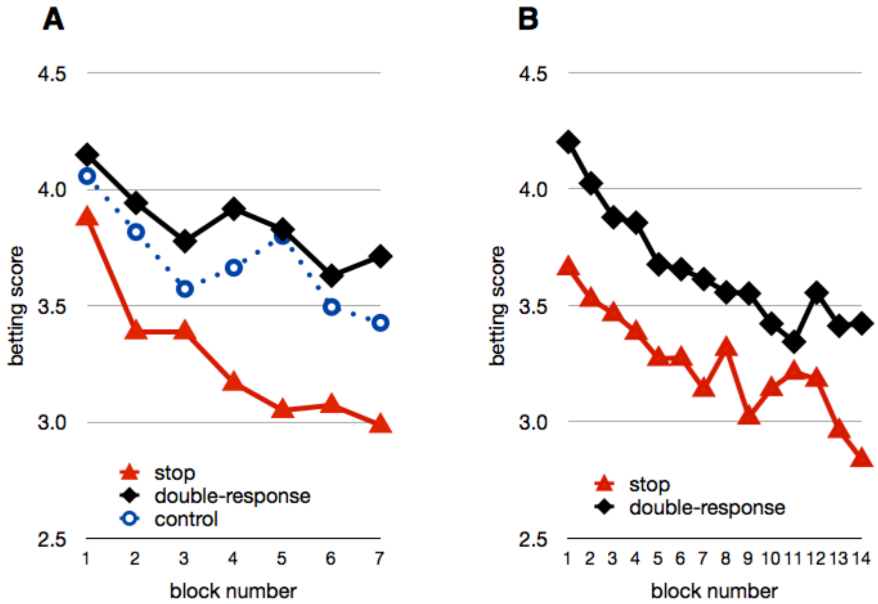

**Figure 5**

The proportion of each choice option [p(choice)] for the groups of Experiments 2-3. Choice option 1 was the safest bet; choice option 6 was the riskiest bet. In Experiment 2 **(A)**, we found differences between the control group and the stop group for p(choice = 5), $p < .001$, and p(choice = 4), $p < .029$. When we collapsed across choice options 1-3, the difference between control and stop was marginally significant ($p = .05$). There were differences between the double-response group and the stop group for p(choice = 6), $p < .027$, and p(choice = 5), $p < .016$. When we collapsed across choice options 1-3, the difference between double-response and stop group was also significant ($p < .022$). In Experiment 3 (**B**), p(choice = 1) was higher in the stop group than in the double-response group, $p < .011$. When we collapsed across choice options 5-6, the difference between the groups was also significant, $p < .05$.

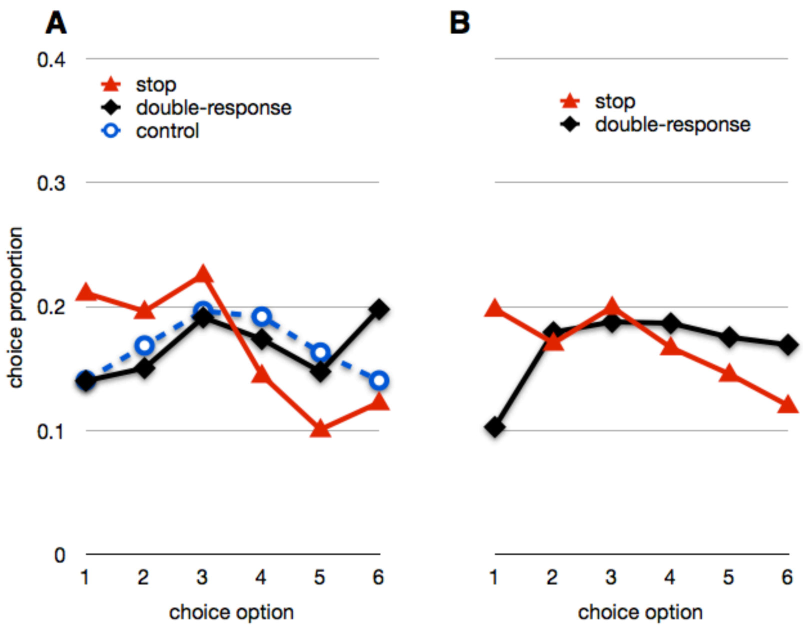

**Table 1: Participant characteristics**

| | Experiment 1 | Experiment 2 | Experiment 3 |
|---|---|---|---|
| # participants | 44 | 81 | 54 |
| % female | 52 | 63 | 69 |
| Age | 24.0<br>(range: 18-40) | 23.6<br>(range: 18-41) | 21.3<br>(range: 18-33) |
| Money won | £0.5<br>(range: 0-1.9) | £1.5<br>(range: 0-4.2) | £1.5<br>(range: 0-4.2) |
| BIS | 62 (SD = 21) | 65 (SD = 9.8) | 65 (SD = 8.9) |
| SIR | 39 (SD = 6.3) | 37 (SD = 6.6) | 39 (SD = 7.3) |

BIS = Barratt Impulsiveness Scale – 11; Range total BIS score: 30-125

SIR = Stimulating-Instrumental Risk Inventory. Score 45 or below – avoiding taking risks, 55 and above – take risks

**Table 2:** Overview of analyses of variance for Experiment 1. We analyzed betting scores by means of a mixed ANOVA with Block Type (single-task vs. dual-task) and Stake (low, medium, high) as within-subjects factors and Group (double-response vs. stop) as a between-subjects factor. *p's* < .05 are **bold**. The main effect of Stake indicated that betting scores were lower when stakes were high (mean betting scores: high = 2.29; medium = 2.68; low = 3.18).

| | *df* | *F* | *p* |
|---|---|---|---|
| Group (G) | 1,46 | 0.05 | 0.83 |
| Block Type (BT) | 1,46 | 1.15 | 0.29 |
| Stake (S) | 2,92 | 135.3 | **0.001** |
| G X BT | 1,46 | 4.29 | **0.04** |
| G x S | 2,92 | 1.14 | 0.33 |
| BT x S | 2,92 | 0.94 | 0.40 |
| G x BT x S | 2,92 | 0.38 | 0.69 |

**Table 3**: Overview of analyses of variance for the test phase of Experiments 2-3. For each experiment, we analysed betting scores by means of a mixed ANOVA with Block (Experiment 2: test block 1-7; Experiment 3: test block 1-14) and Stake (low, medium, high) as within-subjects factors and Group (double-response, stop or control) as the between-subjects factor. Because there were not enough observations for a full factorial analysis, we performed separate tests for Block and Stake. *p's* < .05 are **bold.** The main effect of Stake indicated that betting scores were lower when stakes were high (mean betting scores Experiment 2: high = 3.33; medium = 3.54; low = 3.92; high = 3.30; medium = 3.37; low = 3.69).

| | Experiment 2 | | | Experiment 3 | | |
|---|---|---|---|---|---|---|
| | *df* | *F* | *p* | *df* | *F* | *p* |
| Group (G) | 2,78 | 6.44 | **0.003** | 1,52 | 4.89 | **0.03** |
| Block (B) | 6,468 | 8.17 | **0.001** | 13,676 | 6.42 | **0.001** |
| Stake (S) | 2,156 | 41.26 | **0.001** | 2,104 | 13.97 | **0.001** |
| G X B | 12,468 | 0.66 | 0.79 | 13,676 | 0.51 | 0.92 |
| G x S | 4,156 | 0.63 | 0.64 | 2,104 | 0.69 | 0.51 |

# Supplementary Information

## Amounts, probabilities of winning, and expected values of the free-choice options

Table E1 shows for each free-choice option the associated amounts for the three stakes (high, medium, low), probability of winning [p(win)], and expected value [EV = p(win) * amount - (1-p(win)) * amount/2]. Amounts in the medium stake = 2 x low stake; amount in the high stake = 4 x low stake. Amounts decreased exponentially to make the higher amounts more attractive. The highest and lowest amounts for each stake never occurred in the other stake conditions.

Table E1 shows that the expected value of the 6 free-choice options differed. The two most risky options (choice options 5-6) had a negative expected value. We included these options because superficially attractive options, associated with relatively high amounts but with a negative EV, are common in gambling situations (for instance in the lottery, on racing odds, or slot machines). On the other side of the choice spectrum, we included a choice option with a high probability of winning but with a relatively low EV (choice option 1). We included this option to test whether stopping-induced cautiousness could encourage risk-aversive behaviour even when consistently choosing the safest amount leads to smaller gains. Finally, the EV of the other options was higher but probabilities of winning were different.

If our stop manipulations specifically altered 'optimal decision making', we would expect to observe differences in the likelihood of selecting choice option = 3 (i.e. the option with the highest EV). To anticipate the results, Figures 2B & 5 (main text; see also footnote 2 main text) show that across experiments, participants specifically avoided the high-risk bets with a negative expected value (options 5-6) and preferred bets with a low positive expected value but high probability of winning (option 1) in stop blocks or after stop training.

## Analyses of average standard deviation (SD) of the betting scores and choice latencies in the gambling task for Experiment 1–3

In addition to the analyses of the betting scores, we analysed the average standard deviation (SD) of the betting scores by means of mixed ANOVAs to assess whether concurrent motor tasks (Experiment 1) or training (Experiments 2–3) resulted in more random or variable choice behaviour. We also examined latencies of the choice response on no-signal trials (*choice latency = 'time choice response' – 'time top line is reached'*. Negative latencies indicate that subjects responded before the top line was reached). Summaries of the analyses appear in Table E2 (Experiment 1) and Table E3 (Experiments 2-3).

In Experiment 1, mean SD of betting scores was generally comparable for dual-task (mean SD: 1.05) and single-task blocks (mean SD: 1.05). Thus, multitasking did not result in more random or variable responding. There was a main effect of stake (Table E2); mean SD decreased when stake increased (low: 1.11, medium: 1.06, high: 0.98). There was no reliable difference between the groups. The analyses of latencies of the choice response revealed a two-way interaction between

Block Type and Group. For the stop group, choice latencies were longer in the dual-task blocks (+60 ms) than in the single-task blocks (-2.9 ms; $F_{1,23}$ = 69.1, $P$ = .001). A similar, albeit smaller difference was found for the double-response group: choice latencies were longer in the dual-task blocks (+38 ms) than in the single-task blocks (+0.5 ms; $F_{1,23}$ = 28.4, $P$ = .001).

In Experiment 2, there were no effects on standard deviation or latency of the choice response in the test phase (Table E3; the mean choice latencies were -7, -7, and +7 ms for stop, double-response, and control groups, respectively). In Experiment 3, there was a significant main effect of Block and an interaction between Group and Block for SD (Table E3). Inspection of the data showed that SD decreased over blocks. Furthermore, there was a numerical trend for a higher SD after stop training than after double-response training at the beginning of the experiment. However, none of the individual post-hoc contrasts (stop vs. double-response) reached significance (all uncorrected $p$'s > .13). There was no reliable difference in choice latencies (stop = -10 ms, double-response = 7 ms;Table E3).

**Supplementary analyses Experiment 1: Effects of baseline risk-taking, choice latency & bar height, learning, block order, and differential weighting of wins & losses.**

Experiment 1 indicates that motor control modulated monetary gambling. When subjects prepared to stop a motor response, they placed safer bets. Figure E1 shows that this 'dual-task effect' did not correlate with the baseline betting scores in the single-task blocks.

Additional analyses confirmed that the difference between dual-task and single-task blocks in the stop group was not caused by latency differences. Choice-indication latencies were 63 ms longer in the dual-task blocks (in which stop signals could occur) than in the single-task blocks. Even though this difference is very small relative to the duration of a trial (average = 5 sec.), we wanted to exclude the possibility that the choice differences between dual-task and single-task blocks were merely due to latency differences. To test this, we analysed betting scores in the stop group as a function of bar height (see Figure 1 of main manuscript). Subjects had less time to decide on 'low-bar' trials than on 'high-bar' trials (time difference = 333 ms). If the effect of motor cautiousness on gambling is mediated by decision time then the effect of block type should be larger for 'low-bar' trials than for 'high-bar' trials. However, bar height did not interact with the effect of Block Type (dual-task vs. single-task) [$F(1,23)$ = 0.5, $p$ = 0.47] for the stop group. For 'low-bar' trials, betting scores were 2.75 and 2.62 for single-task and dual-task blocks, respectively. For 'high-bar' trials, betting scores were 2.78 and 2.61 for single-task and dual-task blocks, respectively. There was no main effect of bar height [$F(1,23)$ = 0.01, $p$ = .93].

Third, we tested whether the dual-task effect increased or decreased during the experimental session. Even though subjects were told that wins were less probable for higher amounts, the exact probabilities were not revealed. Thus, there was a small probability-learning element to our task, which could have been influenced by occasional stopping. Participants were also not told what the expected value was of each choice option. Occasional stopping could have interfered with estimating these values. Therefore, we re-analyzed betting scores by means of a 2 (Group: double-response vs. stop) x 2 (Block Type: single-task vs. dual-task) x 2 (Part: first half vs. second half of the experimental session) mixed ANOVA. There was a main effect of Part [$F(1,46) = 10.6$, $p = .002$], and a reliable interaction between Part and Group [$F(1,46) = 6.7$, $p = .01$]. Subjects in the double-response group tended to place safer bets in the second part of the session (mean betting score = 2.48) than in the first half of the session (mean betting score: 3.03). A similar, albeit smaller, effect of part was found in the stop group (mean betting score second half = 2.66, betting score first half: 2.72). The three-way interaction between Part, Group and Block Type was not reliable [$F(1,46) = 0.8$, $p = .38$], which suggests that the dual-task effect did not change during the experimental session. This is inconsistent with a learning account.

Fourth, we controlled for effects of block order. On average, single-task blocks occurred earlier than dual-task blocks. The double-response condition suggests that the effect of stopping was not due to an order confound. Furthermore, there was no interaction between part and the dual-task effect (see above). Thus, we think that it is unlikely that the effects were due to block order. Nevertheless, we re-analysed the data by means of a 2 (Group: double-response vs. stop) x 2 (Block Type: single-task vs. dual-task) x 2 (Part: first half vs. second half of the experimental session) mixed ANOVA after omitting blocks 1 and 8. Thus, on average dual-task blocks occurred earlier than single-task blocks in this new analysis. There was still an interaction between group and block type [$F(1,46) = 3.94$, $p = .05$]. Mean betting scores double-response group = 2.69 (single-task) and 2.77 (dual-task); mean betting scores stop group = 2.74 (single-task) and 2.59 (dual-task). The three-way interaction between Part, Group and Block Type was not reliable ($F < 1$).

Finally, it is also very unlikely that our stop-manipulation generally primed subjects to focus more on either wins or losses, or that the manipulation influenced probability learning or estimating the expected value of the choice options. If preparation for stopping influenced the respective weighting of wins and losses, then the ‘dual-task’ effect should have been largest for the ‘high’ stake trials on which subjects could win or lose the greatest amounts. Previous work has shown that a differential focus on wins vs. losses has stronger effects when stakes are high (e.g. Kühberger, Schulte-Mecklenbeck, & Perner, 2002). However, we found that the dual-task effect did not increase with stake ($p = .69$; see Table 2, main text).

**Supplementary analyses Experiments 2-3: Correlations between training- and test performance**

Response latencies of no-signal trials in the training phase are shown in Figure E2. In the training phase, subjects were not rewarded for successful stopping or penalised for unsuccessful stopping. Furthermore, they were told that it was normal that they could only stop on approximately half of the trials. Thus, it seems highly unlikely that the effects observed in the present study were mediated by the outcome of the stop process. This was supported by the absence of significant correlations between stop measures and betting scores (see Figure E3); note that because a tracking procedure was used, p(respond) was close to .50 for all subjects. Combined, these analyses show that the effect of occasional stopping did not correlate with the outcome of the stop process, which is consistent with the findings of Experiment 1.

Note that the findings of Experiments 2-3 also go beyond recently reported effects of incidental cues on framing and decision-making. In particular, it was shown that incidental cues that had acquired an association with winning or losing in a training phase could bias decision-making under risk when these cues were presented again during a gambling task (Guitart-Masip, Talmi, & Dolan, 2010). This is consistent with the idea that learning and practice can have an important impact on decision-making. However, in Experiments 2-3 of the present study, participants did not win or lose points in the training phase. Furthermore, different task stimuli and cues were used in the training and test phases. Consequently, the after-effects of stopping in Experiments 2-3 cannot be explained by learned associations between incidental cues and winning or losing. Instead, the training effects we observed appear more general: engaging inhibitory motor control in the stop task primed subjects to become risk-averse in an unrelated gambling task.

**References**

Guitart-Masip, M., Talmi, D., and Dolan, R. (2010). Conditioned associations and economic decision biases. Neuroimage 53, 206-214.

Kühberger, A., Schulte-Mecklenbeck, M., & Perner, J. (2002). Framing decisions: Hypothetical and real. Organizational Behavior and Human Decision Processes, 89(2), 1162-1175.

**Table E1: Points, probability of winning, and expected values of the free-choice options.**

| | Stake | | | | |
|---|---|---|---|---|---|
| High | Medium | Low | Average points | p(win) | EV |
| 8 | 4 | 2 | 5 | 0.75 | 3 |
| 24 | 12 | 6 | 14 | 0.63 | 6 |
| 64 | 32 | 16 | 37 | 0.51 | 10 |
| 128 | 64 | 32 | 75 | 0.39 | 6 |
| 256 | 128 | 64 | 149 | 0.27 | -14 |
| 448 | 224 | 112 | 261 | 0.15 | -72 |

Note: We present rounded values in this table because participants could win only 'full' points in the experiment.

**Table E2: Overview of analyses of variance for Experiment 1.**

We analysed average standard deviations (SD) of betting scores and latencies of the choice response by means of a mixed ANOVA with Block Type (single-task vs. dual-task) and Stake (low, medium, high) as within-subjects factors and Group (double-response vs. stop) as between-subjects factor. *P's* < .05 are **bold**.

| | *SD (betting score)* | | | *Latency choice response* | | |
|---|---|---|---|---|---|---|
| | *df* | *F* | *p* | *df* | *F* | *p* |
| Group (G) | 1,46 | 2.30 | 0.14 | 1,46 | 0.75 | 0.39 |
| Block Type (BT) | 1,46 | 0.01 | 0.93 | 1,46 | 94.3 | **0.001** |
| Stake (S) | 2,92 | 8.39 | **0.001** | 2,92 | 0.84 | 0.44 |
| G X BT | 1,46 | 1.25 | 0.27 | 1,46 | 5.87 | **0.02** |
| G x S | 2,92 | 1.22 | 0.30 | 2,92 | 1.12 | 0.33 |
| BT x S | 2,92 | 2.51 | 0.09 | 2,92 | 2.00 | 0.14 |
| G x BT x S | 2,92 | 0.80 | 0.45 | 2,92 | 1.38 | 0.26 |

**Table E3: Overview of analyses of variance for the test phase of Experiments 2-3.**

For each experiment, we analysed separately betting scores, standard deviations of betting scores and latencies of the choice response by means of a mixed ANOVA with Block (Exp.2: test block 1-7; Exp.3: test block 1-14) and Stake (low, medium, high) as within-subjects factors and Group (double-response, stop or control) as between-subjects factor. Because there were not enough observations for a full factorial analysis, we performed separate tests for Block and Stake. *P's* < .05 are **bold.**

| | *SD (betting score)* | | | *Latency choice response* | | |
|---|---|---|---|---|---|---|
| | *df* | *F* | *p* | *df* | *F* | *p* |
| Experiment 2 | | | | | | |
| Group (G) | 2,78 | 0.16 | 0.85 | 2,78 | 0.29 | 0.75 |
| Block (B) | 6,468 | 1.56 | 0.16 | 6,468 | 0.12 | 0.99 |
| Stake (S) | 2,156 | 2.22 | 0.11 | 2,156 | 1.24 | 0.29 |
| G X B | 12,468 | 1.31 | 0.21 | 12,468 | 0.52 | 0.90 |
| G x S | 4,156 | 0.60 | 0.66 | 4,156 | 0.45 | 0.77 |
| Experiment 3 | | | | | | |
| Group (G) | 1,52 | 0.02 | 0.89 | 1,52 | 0.67 | 0.41 |
| Block (B) | 13,676 | 1.85 | **0.03** | 13,676 | 1.28 | 0.22 |
| Stake (S) | 2,104 | 0.03 | 0.97 | 2,104 | 0.02 | 0.98 |
| G X B | 13,676 | 1.77 | **0.03** | 13,676 | 0.92 | 0.53 |
| G x S | 2,104 | 0.34 | 0.71 | 2,104 | 0.58 | 0.57 |

**Table E4.** The proportion of each choice response for the groups and block types in Experiment 1 and the groups of Experiments 2-3. The expected proportion for each cell = 0.166. Even though there appears to be a small overall bias towards responses 'h' and 'j', close inspection of the individual data suggests that all the participants took the amounts associated with each response into account (i.e. they did not select the same key throughout the whole experiment). This is also supported by the analyses of the choice proportions (main text): if participants selected responses instead of amounts, the proportions should be similar for all choice options. As can be seen in Figures 2 & 5 in the main text, this was not the case.

| | 'd' | 'f' | 'g' | 'h' | 'j' | 'k' |
|---|---|---|---|---|---|---|
| Experiment 1 | | | | | | |
| double-response | | | | | | |
| single-task | 0.118 | 0.154 | 0.168 | 0.197 | 0.201 | 0.162 |
| dual-task | 0.115 | 0.153 | 0.181 | 0.226 | 0.187 | 0.138 |
| stop | | | | | | |
| single-task | 0.132 | 0.177 | 0.173 | 0.192 | 0.180 | 0.146 |
| dual-task | 0.140 | 0.176 | 0.169 | 0.183 | 0.186 | 0.146 |
| Experiment 2 | | | | | | |
| stop | 0.138 | 0.175 | 0.164 | 0.166 | 0.192 | 0.165 |
| double-response | 0.143 | 0.170 | 0.166 | 0.179 | 0.185 | 0.158 |
| control | 0.155 | 0.160 | 0.168 | 0.166 | 0.188 | 0.163 |
| Experiment 3 | | | | | | |
| stop | 0.160 | 0.177 | 0.152 | 0.168 | 0.184 | 0.159 |
| double-response | 0.147 | 0.162 | 0.169 | 0.177 | 0.195 | 0.149 |

**Figure E1: Correlation between the ‘dual-task effect’ and ‘betting score’ in single-task blocks**

The correlation between the ‘dual-task effect’ and the betting score in the single-task blocks (which is an estimate of baseline risk taking in our gambling task) for Experiment 1. No significant correlation was observed (r = 0.07, *P* = .74), which suggests that the dual-task effect was not influenced by baseline risk taking.

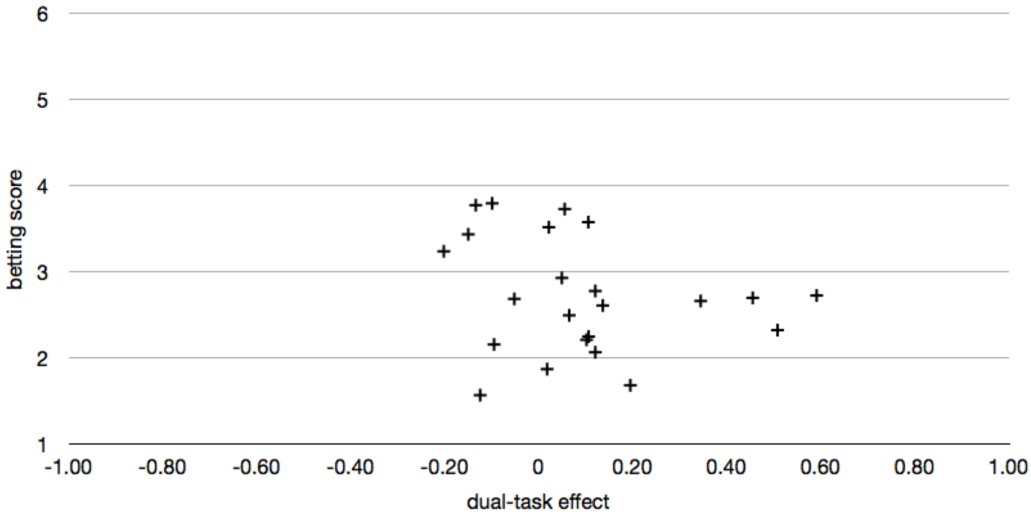

**Figure E2: Response latencies Experiments 2-3**

Response latencies of no-signal trials in the training phase of Experiment 2 and 3 as a function of block number and group. In Experiment 2 **(A)**, there was a main effect of Group (*P* < .001). There was also an interaction between Group and Block (*P* < .011). RTs decreased over practice in the double-response group but not in the stop group. Possibly, proactive control adjustments counteracted the effect of practice on response latencies in the stop group. In Experiment 3 **(B)**, there were main effects of Group (*P* < .001) and Block (*P* < .001). Again, there was an interaction between Group and Block (*P* < .017): RTs decreased more over practice in the double-response group than in the stop group. Again, this could be due to proactive control adjustments in the stop group.

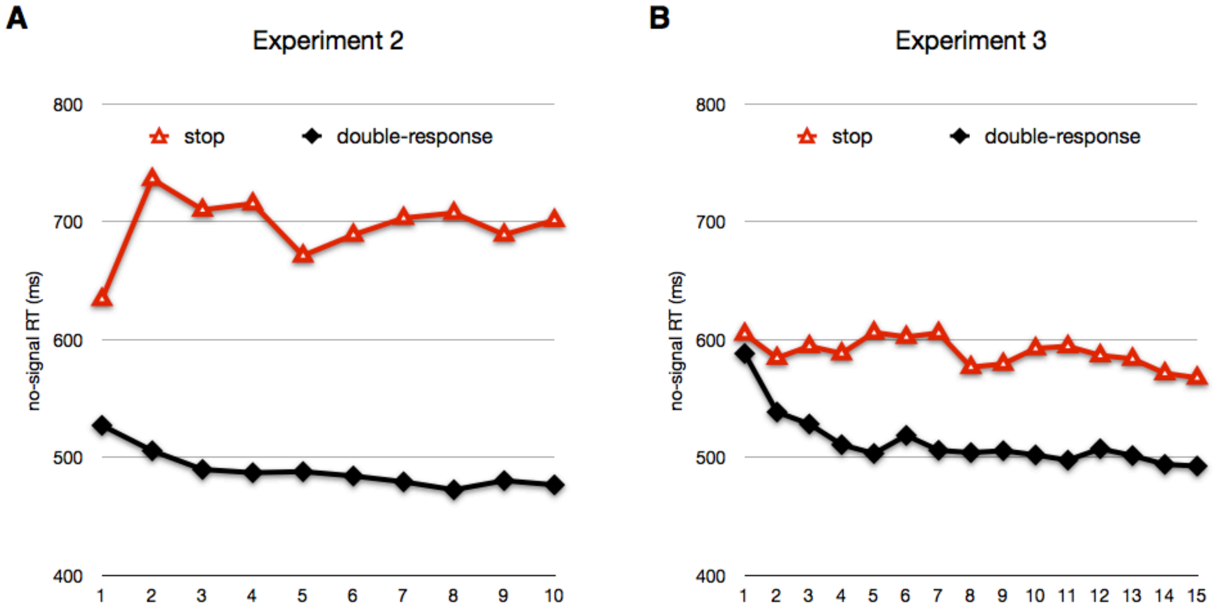

**Figure E3: Correlations between stop measures and betting scores in Experiments 2-3**

The latency of the stop process was estimated using the integration method. Mean latency of the stop process was 0.206 sec. in Experiment 2 and 0.217 sec. in Experiment 3. The correlation between the latency of the stop process and betting scores was non-significant in both Experiment 2 ($r$ = .02 $P$ = .90) and Experiment 3 ($r$ = -.15 $P$ = .46) **(A)**. Similarly, the correlation between the probability of responding on signal trials and betting scores was non-significant in Experiments 3 ($r$ = .04, $P$ = .84) and 4 ($r$ = .02, $P$ = .95)**.** Mean probability of responding on stop-signal trials was .49 and .50, for Experiment 2 and 3, respectively **(B)**.