

# The Effect of fMRI (Noise) on Cognitive Control

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Stressful situations, the aversiveness of events, or increases in task difficulty (e.g., conflict) have repeatedly been shown to be capable of triggering attentional control adjustments. In the present study we tested whether the particularity of an fMRI testing environment (i.e., EPI noise) might result in such increases of the cognitive control exerted. We found that participants were *more* effective in controlling episodic retrieval of previous stimulus-response bindings (Experiment 1), in switching to a new task (Experiment 2), and shielding a current goal from distracting response tendencies (Experiment 3) if they were exposed to challenging task situations, such as 70 dB echo planar imaging noise sampled from an fMRI scanner. These findings have considerable theoretical implications in questioning the widespread assumption that people are equally devoted to easy and more challenging tasks, and methodological implications in raising the possibility that experiments carried out in fMRI scanners or under otherwise challenging conditions systematically overestimate contributions from cognitive control processes.

**Keywords:** event file, task-switching, Simon task, cognitive control, fMRI

For about two decades, an increasingly amount of neuroscientific studies have been using fMRI to investigate cognitive processes, a method that provides restricted temporal but highly resolved spatial information about the brain areas involved in a given mental operation or task. It seems obvious to most researchers that the findings obtained in an fMRI scanner can be straightforwardly related to findings obtained outside the scanner; indeed, some authors have even refrained from collecting behavioral measures inside the scanner and directly related performance measured outside the scanner to fMRI results (e.g., Marois, Chun, & Gore, 2000).

However, it is obvious that testing situations differ considerably between an fMRI environment and a behavioral laboratory setting.

Moreover, recently the scanning environment has been shown to increase endocrinological stress responses (e.g., heightened cortisol levels) especially for scanner-naïve (inexperienced) participants (e.g., Tessner, Walker, Hochman, & Hamann, 2006) and in adolescent participants (Eatough, Shirtcliff, Hanson, & Pollak, 2009).

Apart from many setting-related differences, one particularly salient characteristic of an fMRI environment to often sound attenuated behavioral testing environments is the high level of noise created by the fast echo planar imaging (EPI) pulse sequences used in MRI (MRI/fMRI; Okada & Nakai, 2003). Most people find this noise challenging, disturbing and/or annoying. Therefore, one may wonder in as much extensive EPI noise levels might represent an additional challenge or difficulty that potentially biases the cognitive performance itself. That this is a realistic possibility was suggested to us by two observations.

First, high (loud) EPI noise has been shown to be a particularly effective distractor even in a visual task and to change brain activity substantially: Higher noise produces increased change in blood oxygenation level dependent (BOLD) responses bilaterally in temporal, occipital, and prefrontal cortices, and the cerebellum, and decreased BOLD responses (i.e., smaller signal changes) bilaterally in the anterior cingulate cortex (ACC) and the putamen. This has been claimed to support the idea that attentional networks are more strongly recruited to compensate for interference due to increased scanner noise (Tomasi, Caparelli, Chang, & Ernst, 2005). If the tonic baseline activation of control areas is elevated, so the consideration, less extra activation can be observed if control is temporarily recruited on more difficult trials. Consistent

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This article was published Online First December 26, 2011.

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We thank Evelien Buijs for her invaluable assistance in testing the participants of this study and collecting the data. The research of L.S.C. and of W.P.M. v.d.W. is supported by personal VENI grants awarded by the Dutch Organization for Scientific Research (NWO).

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with that, a PET study has shown that scanner noise increases the regional cerebral blood flow in the ACC (Mazard et al., 2002).

Second, we recently developed a (rather complicated) version of Kahneman, Treisman, and Gibbs' (1992) preview task with face and house stimuli for use in an fMRI scanner (cf., Keizer, Colzato & Hommel, 2008). This task allows for the study of involuntary episodic retrieval of feature bindings upon the repetition of one or multiple visual features (Hommel, 2004). Comparing the behavioral findings obtained in pilot studies carried out inside and outside the scanner suggested that some of the retrieval-related effects were smaller inside the scanner. Given that retrieval in this task is unnecessary and thus, involuntary, this observation may suggest that the higher noise level inside the scanner led to a stronger engagement of control processes, which may have worked against retrieval. Indeed, involuntary retrieval is more pronounced in people low in fluid intelligence (Colzato, van Wouwe, Laverdier, & Hommel, 2006a), in young children and elderly individuals (Hommel, Kray & Lindenberger, 2011), and in cannabis users (Colzato & Hommel, 2008), which are all groups that are impaired with respect to cognitive control in general and the ACC-dorsolateral prefrontal cortex (DLPFC) circuit assumed to resolve cognitive conflict in particular.

Given these observations, it is possible that fMRI studies provide a distorted picture of cognitive processing with respect to both behavioral and imaging results. In particular, one might wonder whether high noise levels, likely representing a challenging, stressful, and/or annoying situation, might trigger compensatory responses in terms of increased attentional control thus, leading to performance improvements (e.g., Kofman, Meiran, Greenberg, Balas, & Cohen, 2006; Plessow, Fischer, Kirschbaum, & Goschke, *in press*). If so, this would have important consequences as fMRI studies would systematically overestimate the amount of cognitive control exerted in a given task and they would show more activation of control-related brain areas than normal. But how and why would the scanner environment and scanner noise in particular result in increased amounts of attentional control?

First of all, noise is known to generally increase arousal and stress levels. Unfortunately, despite several decades of research dedicated to the influence of noise-induced stress and drive levels (arousal) on cognitive performance, to date results remain rather inconclusive (Loeb, 1986; Smith & Broadbent, 1985). This might be mainly due to substantial differences in procedures, inconsistent and often relatively vague definitions of noise and stress (e.g., continuous vs. phasic noise), and the observation that the effects of noise also critically depend on the intensity of the applied noise level (Broadbent, 1971, p.416). Using predominantly traditional Stroop tasks (Stroop, 1935) some authors, for example, found speeded responses and reduced interference when being stressed by loud bursts of white noise compared to unstressed controls without noise (O'Malley & Gallas, 1977; O'Malley & Poplawsky, 1971; see also Booth & Sharma, 2009 for a similar approach). Such findings have typically been interpreted in terms of an increased selectivity under stress (noise-induced) or high drive levels in general overload the cognitive system. As a consequence, the attentional focus is adjusted to task-relevant processing thus, reducing interference by less relevant information (e.g., Callaway, 1959; Easterbrook, 1959; see also Chajut & Algom, 2003 and Wells & Matthews, 1994 for recent discussions). Although plausible, other authors demonstrated increased interference under

noise-induced stress (e.g., Hartley & Adams, 1974) or increased anxious states (e.g., Eysenck, Derakshan, Santos, & Calvo, 2007), so that straightforward conclusion from the noise literatures have to be rather handled with care.

A second possibility of how scanner noise might lead to increases in attentional control can be traced back to early ideas of Hillgruber (1912). His "difficulty law of motivation" says that the difficulty of an action is the motive for investing more effort and devoting more cognitive control to reach the task goal. He assumed that increasing task difficulty automatically ("drive-like") increases will power without conscious deliberation (cf., Ach, 1935), an idea that has lived on in several disguises (e.g., Kahneman, 1973; Kukla, 1972; Sanders, 1983; for a review, see Brehm & Self, 1989). One particularly influential disguise is currently under lively debate, which relates to the question of how people learn from or even avoid stimulus-induced action errors. Based on modeling work and neuroscientific observations, Botvinick, Braver, Barch, Carter, and Cohen (2001) suggested that registering a conflict or registering its aversiveness (Botvinick, 2007) leads to a stronger focus of attention on task-relevant stimuli or stimulus dimensions, so that distractor-induced response conflict (such as in a Stroop or flanker task) can be minimized or avoided on the next occasion. However, Botvinick et al. were mainly interested in explaining trial-to-trial effects—that is, in the question of how we learn from previous conflict—but recent observations by Egner and Hirsch (2005) suggest that registering conflict may even have immediate attentional consequences. In particular, these authors obtained evidence that ACC-mediated conflict detection leads to a stronger activation of task-relevant cortical representations induced by signals from the DLPFC, which is assumed to translate the action goal into top-down support for goal-related processes (e.g., Desimone & Duncan, 1995; Miller & Cohen, 2001). In a sense, then, there is both behavioral and neuroscientific evidence for Hillgruber's (1912) claim that increasing the challenge of the task spontaneously increases one's effort to compensate for and to overcome that challenge. In such a conception, however, noise would represent or be perceived as a challenge and/or aversive signal which, following Botvinick (2007), is capable of triggering attentional adjustments (e.g., increased attentional control).

However, up to now only a few studies have looked into the particular impact of scanner noise on brain activation (e.g., Elliott, Bowtell, & Morris, 1999; Tomasi et al., 2005) and, to our knowledge, no evidence has been reported that scanner noise would affect behavioral measures. Accordingly, we set out to provide an empirical test that scanner noise affects behavior in general and cognitive-control processes in particular, and that it does so in a way that fits with Hillgruber's law; namely, that it increases the exertion of cognitive control. Given that fMRI environments differ from behavioral laboratories in more ways than just noise, which may create confounds, we carried out all experiments outside the scanner in the same lab and just manipulated the presence or absence of previously recorded EPI noise. We used three tasks to look into the impact of this noise.

First, we attempted to formally verify our informal observation that involuntary episodic retrieval is less pronounced in the presence of noise (Experiment 1). Second, given that our preview task cannot be considered to provide a process-pure measure of cognitive control, we used two further paradigms that are commonly assumed to tap into cognitive control processes. In particular, we

implemented a more standard task-switching design to investigate the flexibility of task set shifting (Experiment 2) and a Simon task to investigate the shielding of the current goal from competing response tendencies (Experiment 3).

### Experiment 1

The preview design developed by Kahneman et al. (1992) is commonly used to investigate feature integration. In its most Spartan version (Hommel & Colzato, 2004), participants carry out a speeded response (R2) to the second of two stimuli (S2) but ignore the first (S1). The features of S1 and S2 vary randomly, so that S2 may repeat all, some, or none of the features of S1. Interestingly, complete repetitions (of say shape and color) and alternations yield better performance than partial repetitions (if, say, shape repetition goes with color alternation or vice versa). This suggests that the codes of the features of S1 are automatically bound into a kind of episodic object file (to use the term of Kahneman et al., 1992), which is retrieved if one or more features are repeated. If the repetition is complete, no harm is done as S2 activates the very same codes. If the repetition is only partial, however, a wrong and misleading code gets activated. For instance, if S1 is a green square and S2 is a green circle, the presentation of S2 will activate the < green > code which spread activation to the < square > code it was just bound with—which would then compete with the actually valid < circle > code (Hommel, 1998, 2004).

Hommel (1998) has extended this design to investigate stimulus-response binding. To allow for response repetition and alternation, S1 now does require a response (R1). However, in order to allow for S1 and R1 to vary independently, R1 is not mapped onto any feature of S1 but precued at the beginning of each trial (see Figure 1). Hence, S1 only serves as a trigger to execute R1. This version of the design also produces partial-repetition costs, now related to stimulus and response repetition. That is, if task-relevant stimulus features and the response are repeated, or if both the stimulus features and the response alternate, performance is better than if a stimulus feature is repeated and the response alternates, or vice versa (Hommel, 1998). This suggests that carrying out a response close in time to a stimulus is sufficient to create a binding between the task-relevant aspects of stimulus and response. If a relevant feature of either the stimulus

or the response, or both, is repeated the previous binding is reactivated, which creates competition between stimulus codes and/or response codes if the repetition is not complete.

As mentioned above, the binding of stimulus and response features seems to be an automatic process and so is the retrieval of the just-created episodic binding upon processing a new feature-overlapping stimulus-response episode. Interestingly, however, the partial-repetition costs indicating automatic retrieval are exaggerated in populations that are known to have control differences, suggesting that some control of episodic retrieval is possible. If so, and if exposing participants to scanner noise would indeed induce a stronger effort to control, we should be able to demonstrate that young adults show evidence of decreased episodic retrieval under noise conditions. Accordingly, we hypothesized that partial-repetition costs for the binding between the task-relevant stimulus feature (shape) and the response would be reduced under noise conditions.

### Method

**Participants.** Eighteen young healthy adults served as subjects for partial fulfillment of course credit or a financial reward. Participants served in two experimental sessions (one under no noise and one under noise conditions) separated by 3–7 days. Informed consent was obtained from all participants after the nature and possible consequences of the study were explained to them; the protocol was approved by the local ethical committee (Leiden University, Faculty of Social and Behavioral Sciences).

Participants were selected with the Mini International Neuropsychiatric Interview (M.I.N.I.; Lecrubier et al., 1997), a brief diagnostic tool that screens for several psychiatric disorders including depression, obsessive-compulsive disorder, and substance abuse. Participants with a known history of drug abuse or psychopathology and those who were taking medication were excluded. All experimental sessions were held at the same time in order to prevent time-of-day effects. Participants were asked to refrain from all caffeine-containing foods and beverages for 12 hours prior to the experimental sessions, not to consume alcohol the night before the experimental session, and to have a normal night rest. All reported having normal or corrected-to-normal vision, and were not familiar with the purpose of the experiment.

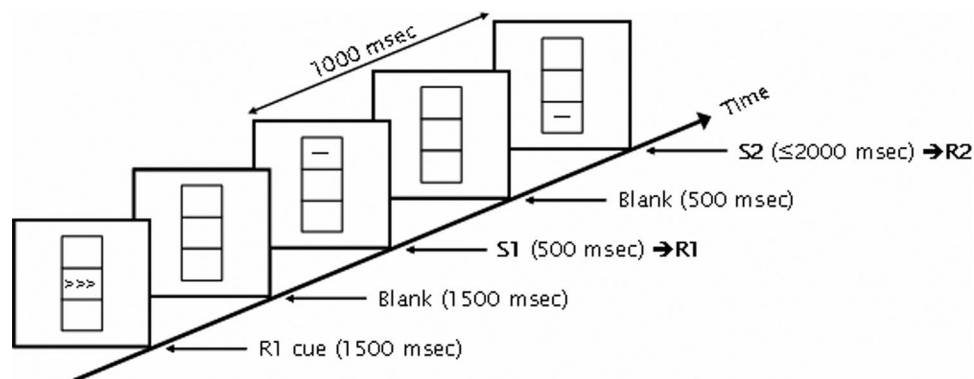


Figure 1. Sequence of events in Experiment 1 (cf., Hommel, 1998).

**Apparatus and stimuli.** The experiment was controlled by a Targa Pentium III computer, attached to a Targa 17" monitor. Participants faced three gray square outlines, vertically arranged, as illustrated in Figure 1. From viewing distance of about 60 cm, each of these frames measured  $2.6^\circ \times 3.1^\circ$ . A vertical line ( $0.1^\circ \times 0.6^\circ$ ) and a horizontal line ( $0.3^\circ \times 0.1^\circ$ ) served as S1 and S2 alternatives, which were presented in red or green in the top or bottom frame. Response cues were presented in the middle frame (see Figure 1), with rows of three left- or right-pointing arrows indicating a left and right keypress, respectively. Responses to S1 and to S2 were made by pressing the left or right shift-key of the computer-keyboard with the corresponding index finger. No-noise and noise conditions were created by presenting participants with white noise (0 dB) and acoustic noise (70 dB) sampled from fast pulse sequences in echo planar imaging (EPI) at 3-Tesla MRI, respectively, by headphones.

**Procedure and design.** A randomized cross-over design with counterbalancing of the order of conditions was used to control for expectancy effects. Each of the two sessions took 50 min where participants worked through the task adopted from Hommel (1998), see Figure 1. They faced three gray, vertically arranged boxes in the middle of a monitor and carried out two responses per trial. R1 was a delayed simple reaction with the left or right key, as indicated by a 100%-valid response cue (left- or right-pointing arrow in the middle box) that preceded the trigger stimulus S1 by 3,000 ms. S1 varied randomly in shape (a thin vertical or horizontal line), color (red or green), and location (top or bottom box). R1 was to be carried out as soon as S1 appeared, independent of its shape, color, or location; that is, subjects were encouraged to respond to the mere onset of S1. R2 was a binary-choice reaction to the shape of S2 (vertical or horizontal orientation), which also appeared in red or green, and in the top or bottom box, 1,000 ms after S1 onset. Responses to S1 and to S2 were made by pressing the left or right shift-key of the computer keyboard with the corresponding index finger. Each session was composed of a factorial combination of the two possible shapes, colors, and locations of S2, the repetition versus alternation of shape, color, location, and the response, and three replications per condition.

## Results

After excluding trials with missing ( $> 1,500$  ms) or anticipatory responses ( $< 200$  ms), mean reaction times (RTs) and proportions of errors for R2 were analyzed (see Table 1 for means). ANOVAs were run with noise condition (no-noise vs. noise), the repetition versus alternation of response (R1→R2), stimulus shape, color, and location (S1→S2) as within-participant factors.

There were no main effects of noise condition in RTs,  $F < 1$ ,  $\eta^2 = .06$  or error rates,  $F < 1$ ,  $\eta^2 = .04$ , and there was no indication of any general speed-accuracy trade-off (see Figure 2). Replicating earlier findings (Hommel & Colzato, 2004; Hommel, 1998), RTs revealed a significant main effect of location,  $F(1, 17) = 12.60$ ,  $p < .01$ ,  $\eta^2 = .42$ , which reflects inhibition of return—the common observation that attending to an actually irrelevant stimulus impairs later responses to relevant stimuli appearing in the same location (e.g., Maylor, 1985; Posner & Cohen, 1984). We obtained significant interactions between shape and location,  $F(1, 17) = 31.11$ ,  $p < .001$ ,  $\eta^2 = .66$ , between shape and color,  $F(1, 17) = 6.00$ ,  $p < .05$ ,  $\eta^2 = .28$ , between response and shape,  $F(1, 17) = 26.46$ ,  $p < .001$ ,  $\eta^2 = .54$ , and response and location,  $F(1, 17) = 31.95$ ,  $p < .001$ ,  $\eta^2 = .67$ —repeating one but not the other (stimulus or response) feature slowed down responding.

The noise condition impacted only the task-relevant binding of shape and response, thus producing a three-way interaction,  $F(1, 17) = 8.69$ ,  $p < .01$ ,  $\eta^2 = .32$ . Figure 2 suggests that the shape-by-response interaction was reliable for both,  $F(1, 17) = 26.46$ ,  $p < .001$ ,  $\eta^2 = .54$ ,  $F(1, 17) = 22.28$ ,  $p < .001$ ,  $\eta^2 = .46$ , no-noise and noise conditions, respectively. However, it is also noticeable that the interaction is reduced in the noise condition that was expected to evoke a higher degree of cognitive control. In other words, challenging control minimized partial-repetition costs for task-relevant features, just as expected.

The error rates followed the same pattern: location produced a main effect,  $F(1, 17) = 14.27$ ,  $p < .01$ ,  $\eta^2 = .48$ , response and interacted with shape,  $F(1, 17) = 20.97$ ,  $p < .001$ ,  $\eta^2 = .44$ , location,  $F(1, 17) = 12.66$ ,  $p < .001$ ,  $\eta^2 = .42$ . Both interactions were due to fewer errors when both features were repeated or both alternated, compared to conditions where one feature but not the

Table 1

*Means of Mean Reaction Times for Responses To Stimulus 2 (RT; in ms) and Percentages of Errors on R2 (PE), as a Level of Condition (Noise vs. No-Noise), the Match Between Response 1 and Response 2, and the Feature Match Between Stimulus 1 and Stimulus 2*

Response	Noise				No-noise			
	Repeated		Alternated		Repeated		Alternated	
	RT <sub>R2</sub>	PE <sub>R2</sub>	RT <sub>R2</sub>	PE <sub>R2</sub>	RT <sub>R2</sub>	PE <sub>R2</sub>	RT <sub>R2</sub>	PE <sub>R2</sub>
Neither	480	14.8	447	2.8	479	14.6	435	3.0
C(olor)	471	15.7	445	3.2	480	16.4	439	3.5
L(ocation)	487	17.1	478	5.3	482	12.9	469	4.2
S(hape)	468	7.2	472	9.3	469	9.3	486	11.1
CL	499	13.4	479	8.3	495	11.0	487	8.5
SL	463	5.1	490	15.7	455	5.3	483	17.6
SC	462	7.6	469	9.0	460	7.6	482	13.9
SLC	448	3.2	485	17.1	443	3.2	499	21.5



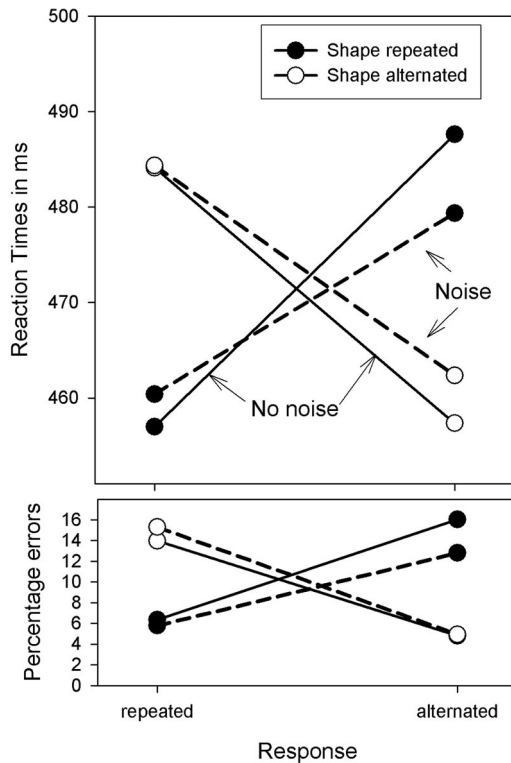


Figure 2. Mean reaction times and error percentages for R2 as a function of noise (no-noise = straight line and noise = dotted line), repetition versus alternation of stimulus task-relevant feature and response.

other was repeated. Noise condition interacted only with shape (the task relevant feature),  $F(1, 17) = 5.61$ ,  $p < .05$ ,  $\eta^2 = .22$ , for which the repetition was an advantage only for the noise session.

## Discussion

We replicated previous findings that the partial repetition of combinations of stimulus features, and of stimulus features and the response produced worse performance than complete repetitions and alternations (Hommel, 1998). More importantly for present purposes, however, scanner noise reduced these partial-repetition costs, just as predicted. Interestingly, the pairings of other features also produced partial-repetition costs, which, however, were not affected by noise. This rules out trivial or theoretically less interesting explanations in terms of noise-induced memory loss or general distraction. In our study, shape was the only task-relevant feature, whereas color and stimulus location were irrelevant. Given that prefrontal cortex is implicated in updating relevant, but not irrelevant, information, and that prefrontal cortex is implied in cognitive control functions (Braver, Barch, & Cohen, 1999; Rougier, Noelle, Braver, Cohen, & O'Reilly, 2005), it makes sense that a condition that we consider likely to evoke a higher level of cognitive control impacted the directly task-related features only. Indeed, previous demonstrations of population-specific modulations of control retrieval were also restricted to bindings between task-relevant stimuli and responses (Colzato & Hommel, 2008; Colzato et al., 2006a; Hommel et al., 2011).

We thus consider the present findings to be consistent with the hypothesis that the greater task challenge imposed by the scanner noise induced a higher level of cognitive control, which again allowed for the more efficient handling of stimulus-response bindings (cf., Colzato et al., 2006a). More specifically, a stronger cognitive-control effort led to a greater flexibility and efficiency in managing and updating such bindings, and/or for the more selective retrieval of previous bindings. This observation fits well with the idea that cognitive control is associated with the control of access to, and the efficient updating of, working memory (Braver & Barch, 2002; Braver & Cohen, 2000; Cohen & O'Reilly, 1996). Most importantly, the present findings are consistent with the idea that facing a noisy environment that is likely to challenge, and thus increase the base level of cognitive control has a very specific impact on behavior.

## Experiment 2

The outcome of Experiment 1 provides first support for the idea that challenging situations, such as the presence of distracting scanner noise, prime and strengthen control operations. Even though this validates our informal observation that noise reduces partial-repetition costs, one may, however, argue that the theoretical link between this finding and Hillgruber's law is rather indirect. For instance, we are unable to rule out that noise also affected the binding of the feature codes related to S1. To provide more direct and more unequivocal evidence for the proposed connection between noise and the recruitment of control operations we therefore went on to test whether noise would also affect performance in a task-switching design.

Having participants switch between mutually incompatible tasks is commonly taken to tap into the recruitment of cognitive-control operations and the implementation of task sets (Monsell, 2003). The idea is that switching to a new task requires the participant to restructure his or her cognitive system in such a way that the task-relevant stimuli are associated with the appropriate actions, so to translate the task instruction into an operational cognitive short-term structure (Meyer & Kieras, 1997; Monsell, 1996). This restructuring is necessary only when the task changes, so that experimental trials in which a task switch is required should produce worse performance than trials in which the task repeats. Indeed, there is ample evidence that performance in switching trials is impaired compared to repetition trials (e.g., Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995). In Experiment 2, we thus had participants switch between responding to the global versus local level of visual multilevel stimuli (see Figure 3)—a task that has previously been shown to produce substantial switching costs (Miyake et al., 2000; Shedden, Marsman, Paul, & Nelson, 2003).

Even though one cannot exclude that control operations are active even in repetition trials (e.g., to refresh the task goal; cf., Altman & Gray, 2002), most authors agree that switch trials call for more control. Accordingly, we would expect that noise would not only affect performance in task switching but that it would specifically target performance in switch trials. If noise leads to a stronger recruitment of control operations, one would expect that noise facilitates switching to a new task. In other words, Hillgruber's law would lead one to expect that noise (perceived as challenging, stressful, annoying experience) leads to a decrease of

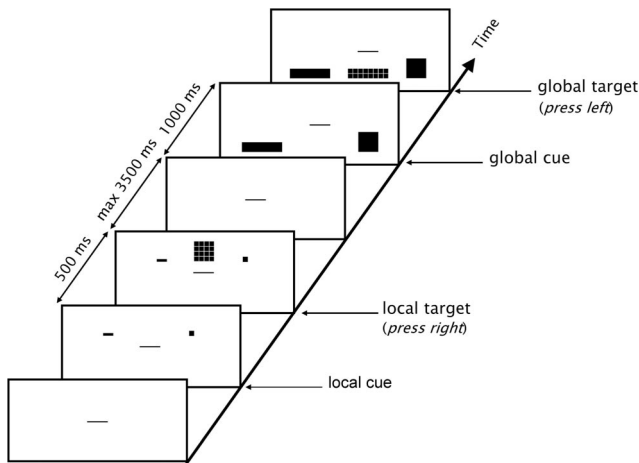


Figure 3. Sequence of events in a trial of the switch blocks in Experiment 2.

task-switching costs (Kofman et al., 2006) due to comparatively better performance in switch trials.

## Method

**Participants.** Fourteen volunteers were recruited by applying the same criteria as in Experiment 1. Participants again served in two experimental sessions (one under no-noise and one under noise conditions) separated by 3–7 days. One further participant was tested but excluded from the analysis because of an excessive overall error rate ( $> 45\%$ ).

**Apparatus and stimuli.** The experiment was controlled by a Switch computer attached to a Philips 17" monitor. Responses were made by pressing the "Z" or "?" of the QWERTY computer keyboard with the left and right index finger, respectively. The target stimuli were adopted from Huizinga, Dolan, and van der Molen (2006), and consisted of geometric figures (see Figure 3). Larger (global) rectangles/squares consisted of smaller (local) rectangles or squares. Global stimuli (i.e., squares or rectangles;  $93 \times 93$  pixels or  $93 \times 189$  pixels, respectively) were composed of many smaller "local" stimuli (i.e., squares or rectangles;  $21 \times 21$  pixels or  $8 \times 46$  pixels, respectively). The space between the local elements of a stimulus was three pixels. A global square consisted of 16 small squares or eight small rectangles; a global rectangle consisted of 32 small squares or 16 small rectangles. Stimuli

appeared above or below a horizontal line at the center of the screen. For half of the participants the stimuli for the global task appeared above, and the stimuli for the local task below the line, while the other half of the participants received the opposite mapping. No-noise and noise conditions were created as in Experiment 1.

**Procedure and design.** Participants responded to randomly presented rectangles or squares by pressing a left or right response button, respectively. Three blocks of trials were administered, two training blocks in which the instruction (global or local) was constant across all trials followed by the experimental block in which participants switch between the global and the local task. In one of the two training blocks, participants responded to the local figure, in the other block they responded to the global figure. The order of the training blocks was randomized across participants and each block consisted of 80 trials. In the third block participants alternated between predictable sequences of four "local" and four "global" trials (90 practice trials and 150 to-be-analyzed experimental trials). A cue indicated to which dimension (global or local) the participants should respond. Cues that related to the global (local) dimension consisted of a big (small) square, presented at one side of the target stimulus, and a big (small) rectangle, presented at the other side of the target stimulus. The color of cues and target was red. Both remained on the screen until a response was given or 3,500 ms had passed. The time interval between presentation of the cue and of the target stimulus was 500 ms and the interval between responses and the next presentation of the cue was 1,000 ms.

## Results

Mean RTs and proportions of errors were analyzed as a function of noise condition (no-noise vs. noise), target level (global vs. local), the congruency between the stimuli on the two levels (congruent vs. incongruent), and task switch (i.e., same vs. different target level as in previous trial: task repetition vs. alternation); see Table 2 for cell means. Four-way ANOVAs for dependent measures were run on RTs and error rates.

There were no main effects of noise condition on RTs,  $F(1, 13) = 1.38$ ,  $p = .26$ ,  $\eta^2 = .096$ , or error rates,  $F < 1$ ,  $\eta^2 = .03$ , indicating that noise had no general effect on performance. RTs revealed three reliable main effects: The effect of switch,  $F(1, 13) = 5.11$ ,  $p < .05$ ,  $\eta^2 = .28$ , was due to that repeating the task allowed for faster responding than switching between target levels (387 vs. 438 ms); the effect of target level,  $F(1, 13) = 32.47$ ,  $p < .001$ , was due to that global targets were responded to faster than local targets (438 vs. 387 ms).

Table 2

Means of Mean Reaction Times and Percentages of Errors (PE), as a Level of Condition (Noise vs. No-Noise), Switch (Level Repetition vs. Level Alternation), Target Level (Global vs. Local), and Congruency (Congruent vs. Incongruent)

	Noise								No-noise							
	Repetition				Alternation				Repetition				Alternation			
	Local		Global		Local		Global		Local		Global		Local		Global	
	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE
Switch task																
Congruent	410	8.5	471	6.8	468	10.0	420	5.5	425	5.8	377	6.7	486	9.7	458	8.1
Incongruent	389	1.1	365	0.7	422	0.0	390	1.1	391	1.4	367	0.9	453	2.1	409	0.7

.001,  $\eta^2 = .71$ , reflected the well-known global preference (Navon, 1977), that is, faster responses to globally than locally defined targets (395 vs. 431 ms); and the congruency effect,  $F(1, 13) = 10.85$ ,  $p < .001$ ,  $\eta^2 = .45$ , indicated interference from the nontarget level, that is, faster responses if the stimulus at the currently irrelevant level was congruent with the present target than if that stimulus was incongruent (398 vs. 427 ms).

More important for present purposes, noise condition interacted with task switch,  $F(1, 13) = 4.71$ ,  $p < .05$ ,  $\eta^2 = .27$ . As suggested by Figure 4, switching costs were reliable for both no-noise and noise conditions,  $F(1, 13) = 5.74$ ,  $p < .05$ ,  $\eta^2 = .31$ ,  $F(1, 13) = 4.06$ ,  $p < .05$ ,  $\eta^2 = .26$ , respectively. However, as predicted, switch costs were reduced in the noise condition. Also as predicted, this reduction was due to better performance on switch trials in the noise condition, suggesting that noise selectively targeted the condition in which cognitive control was needed most.

The error rates revealed only a main effect of congruency,  $F(1, 13) = 47.96$ ,  $p < .001$ ,  $\eta^2 = .80$ , reflecting the interference of the irrelevant target level, as indicated by a smaller proportion of errors on congruent compared to incongruent trials (0.4% vs. 2.2%).

## Discussion

Experiment 2 yielded three observations of theoretical interest. First, task-switching performance was affected by the presence of scanner noise. Even though it might seem more obvious to expect

that noise-induced stress *impairs* switching performance, the impact was positive—noise reduced switching costs (Kofman et al., 2006). This suggests that fMRI noise can be perceived as an additional challenge (e.g., stressor, aversive signal) that according to the ideas of Hillgruber (1912) or Botvinick (2007) triggers the exertion of more cognitive control. Second, as one would also predict from this approach, the impact of noise was restricted to switch trials, where control is needed, but did not affect performance on repetition trials. And third, it was only the task-switching factor that was impacted by noise. The absence of a noise main effect and other interactions including the noise factor rule out theoretically less interesting of explanations in terms of distraction, arousal, speed-accuracy trade-off or general motivation. For example, one might argue that faster switching under noise benefited from a less stable implementation of the task set in the previous (i.e., preswitch) trial. If so, however, one would expect that noise impairs performance on repetition trials and/or increases crosstalk between the two task sets, which again would have led to a more pronounced congruency effect under noise. As both of these effects were not observed, it seems safe to conclude that noise has a specific, positive effect on control processes.

As an aside, a particularly interesting observation is that the better performance in the noise condition was achieved without any measurable cost: noise made responses in the switching condition both faster *and* more accurate. This suggests that the measurements from the no-noise condition underestimate the true cognitive capacity of our participants. In more general terms, this raises the question how valid capacity estimates are if they are based on comparisons between conditions that differ in difficulty—as common in many areas, just think of dual-task costs, the attentional blink, or the Stroop task.

## Experiment 3

In Experiment 3 we aimed at testing a further cognitive control function, namely, the shielding of the currently active goal from competing response tendencies. For this we applied a typical selective attention paradigm in which relevant and irrelevant stimulus attributes compete for action control, that is, response execution. For example, in a Simon task (Simon, 1990) participants are required to respond with spatially arranged left and right responses to the identity of stimuli that are presented laterally on the screen. Although, stimulus location is completely task irrelevant it is generally assumed that the location feature automatically activates its spatially corresponding response code. This leads to faster responses when the stimulus location corresponds with the required response location (e.g., stimulus on the left requires a left hand response), but leads to delayed responses when the stimulus location activates response codes of the wrong response (e.g., stimulus on the left requires a right hand response). The difference between both conditions represents the so-called Simon effect an often used tool in the study of response interference and response inhibition. We particularly chose the Simon paradigm over other related selective attention tasks (e.g., Stroop, Flanker task) because the Simon task allows full control over possible conflicts between cognitive representations (for a detailed description see Hommel, in press). Although several models have been put forward to account for the Simon effect, most models agree on the assumption that the automatically activated irrelevant response code needs to

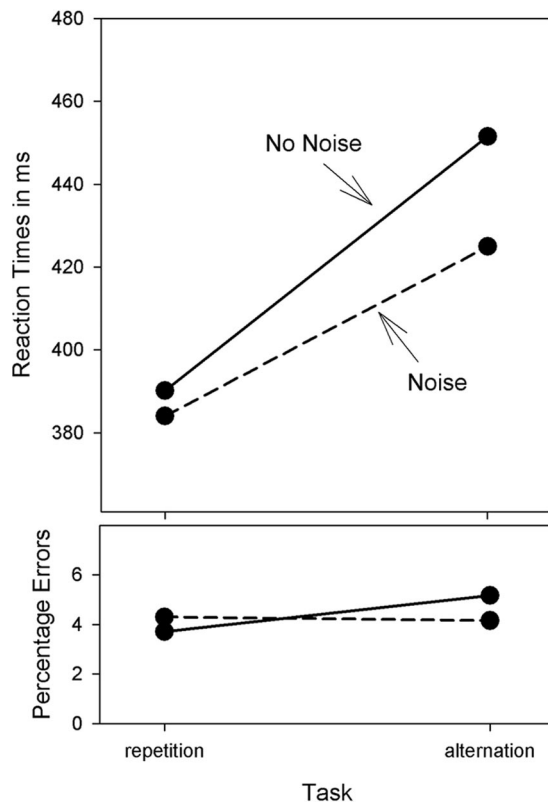


Figure 4. Mean reaction times and error percentages as a function of noise and task switch (repetition vs. alternation).

be inhibited (i.e., prevented from execution) in order to execute the correct response (De Jong, Liang, & Lauber, 1994; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Kornblum, Hasbroucq, & Osman, 1990; Ridderinkhof, 2002; for an overview see Proctor & Vu, 2006). In the present context one would therefore predict, that any increases in cognitive control should facilitate response selection by reducing the impact of the competing response.

## Method

**Participants.** Eighteen young adults participated in a no-noise and a noise session that were separated by 3–7 days. Recruitment and selection criteria were the same as in the previous experiments.

**Apparatus and stimuli.** The experiment was controlled by a PC attached to a color monitor. A small (.5 x .5 cm) dark gray fixation point was visible in the center of the screen throughout an experimental block. A green and a blue circle (1.5 cm in diameter) presented to the left or right of fixation served as imperative stimuli. The color and location of the circles varied randomly but appeared equally often within a block of trials. Viewing distance was about 60 cm. Responses were made by pressing the “z” or “?” buttons of the computer keyboard with the left or right index finger, respectively. No-noise and noise conditions were implemented as in the previous experiments.

**Procedure and design.** One condition consisted of a 30-min session in which participants made speeded discriminative responses to the color of the circle. Circles stayed on screen until the response was given or 1,500 ms had passed. Intervals between subsequent stimuli varied randomly but equiprobably, from 1,750–2,250 ms in steps of 100 ms. Participants were to ignore the location of the stimulus and had to base their response exclusively on its color. Half the participants were instructed to press the left button to blue circles and responded right to green circles. The color-hand mapping was reversed for the other half of the participants. Responses were to be given as fast as possible while keeping error rates below 15% on average. Performance feedback was provided at the end of a trial block. The task consisted of six blocks of 60 trials, the first of which served as a practice block.

## Results

Mean RTs and proportions of errors were analyzed as a function of Noise (noise vs. no-noise) and spatial stimulus-response Correspondence (corresponding vs. noncorresponding) as within-subject factors.

As in the previous experiments, there were no main effects of noise condition on RT,  $F < 1$ ,  $\eta^2 = .03$ , or on error rates,  $F < 1$ ,  $\eta^2 = .06$ , indicating that noise did not affect general performance. However, Correspondence produced a reliable effect on RT,  $F(1, 17) = 190.92$ ,  $p < .001$ ,  $\eta^2 = .92$ , showing a reliable Simon effect that is characterized by slower response latencies on noncorresponding (400 ms) than on corresponding trials (366 ms). More errors were committed on noncorresponding trials (10.8%) compared to corresponding trials (3.2%),  $F(1, 17) = 56.64$ ,  $p < .001$ ,  $\eta^2 = .77$ .

Importantly, Noise condition interacted with Congruency,  $F(1, 17) = 6.50$ ,  $p < .05$ ,  $\eta^2 = .28$ . As shown in Table 3 the Simon effect on RT was present in both the no-noise and the noise

Table 3

*Means of Mean Reaction Times and Percentages of Errors (PE) as a Function of Condition (Noise vs. No-Noise) and Correspondence (Corresponding vs. Noncorresponding), SEM In Parentheses*

	Noise		No-noise	
	RT	PE	RT	PE
Corresponding	365	3.3	367	3.1
Noncorresponding	395	9.7	404	11.8
Simon effect	29	6.4	37	8.8

conditions,  $F(1, 17) = 169.76$ ,  $p < .001$ ,  $\eta^2 = .91$ , and  $F(1, 17) = 112.45$ ,  $p < .001$ ,  $\eta^2 = .87$ , respectively. However, as predicted, the Simon effect was significantly reduced in the noise condition (30 ms) compared to the no-noise condition (38 ms). Analyses of error rates did not yield a significant interaction between Noise condition and Congruency,  $F(1, 17) = 2.53$ ,  $p = .13$ ,  $\eta^2 = .13$ .

## Discussion

Experiment 3 served to further test the assumption that the experience of loud fMRI noise can result in increased attentional control. We hypothesized that in a selective attention task, such as the Simon task, increased control levels result in reduced interference by irrelevant stimulus features (i.e., smaller Simon effects). As in Experiment 2, we did not obtain any main effects of noise. At the same time, however, the Simon effect was significantly reduced in the fMRI noise compared to the control condition.

Therefore, results of Experiment 3 provide further evidence that the experience of fMRI noise is capable of triggering increases in attentional control resulting in reduced response interference in a selective attention task.

## General Discussion

Even though the present experiments differed in various ways, they converge on the conclusion that the challenge of facing a continuously noisy environment has a predictable and specific impact on cognitive control operations. In Experiment 1, noise reduced the impact of previous episodic stimulus-response bindings on current performance, presumably by tighter control over stimulus-induced retrieval processes. At least with respect to the behavioral outcome, this observation puts the noise factor in the same line with fluid intelligence (Colzato et al., 2006a), aging (Hommel et al., 2011), and cannabis use (Colzato & Hommel, 2008). It is interesting to note that all of these factors share two characteristics: They have been associated with the functioning of the frontal cortex, and the DLPFC in particular, and with the modulation by dopaminergic pathways. The integrity of prefrontal systems has been claimed to be essential for fluid intelligence (Duncan, Emslie, Williams, Johnson, & Freer, 1996), to be impaired in healthy aging (Raz et al., 2005), and affected by the use of cannabis (Gessa, Melis, Muntoni, & Diana, 1998). Prefrontal systems have also been found to be involved in the control of episodic memory retrieval (Ranganath & Knight, 2003), which provides a link to our findings in Experiment 1. Apart from the



general consensus that prefrontal functioning strongly depends on dopaminergic transmitter systems, dopaminergic circuits have been implied in intelligence (Previc, 1999), aging (Li, Lindenberger, & Sikström, 2001), and working memory (Murphy, Arnsten, Goldman-Rakic, & Roth, 1996), and cannabis is suspected to increase the dopaminergic supply to prefrontal regions (Gessa et al., 1998).

In this context, it is particularly interesting that we found noise to impact stimulus-response bindings only but not bindings between stimulus features. Previous investigations of binding effects revealed that stimulus bindings, but not stimulus-response bindings, are sensitive to manipulations of muscarinic-cholinergic agonists and antagonists (Colzato, Erasmus, & Hommel, 2004; Colzato, Fagioli, Erasmus, & Hommel, 2005), whereas stimulus-response bindings, but not stimulus bindings, are affected by manipulations that target dopaminergic systems, such as cannabis (Colzato & Hommel, 2008), stress (Colzato, Kool, & Hommel, 2008), or affective stimuli (Colzato, van Wouwe, & Hommel, 2007). Not only does this suggest that object integration and object-action coupling are driven by different neurotransmitter systems, which fits with the observation that their effects are uncorrelated (Colzato, Warrens, & Hommel, 2006b), but it points to the possibility that cognitive control and the handling of episodic stimulus-response bindings are related to the same prefrontal circuit, presumably driven by the same dopaminergic neurotransmitter system (Braver & Cohen, 2000; Montague, Hyman, & Cohen, 2004).

In Experiment 2, noise selectively targeted performance on switch trials and it again seemed to facilitate cognitive control operations. Further evidence in those lines was provided by Experiment 3, in which noise lead to increased shielding of the relevant task goal from competing response alternatives. Noise facilitated the response selection process in the Simon task by reducing the impact of the competing response code, consequently, reducing the Simon effect.

For one, the fact that the same predictions fared well in apparently very different tasks increases our confidence in the validity of the underlying theoretical assumption, that is, fMRI noise recruits attentional control. For another, the parallel between the findings may speak to the issue of how task sets are actually implemented. Many theoretical approaches consider the implementation of a task set as the programming of control parameters (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997). However, there is also evidence that task sets may be stored and retrieved as a whole, whether this retrieval is induced by stimuli (Waszak, Hommel, & Allport, 2003), task cues (Mayr & Kliegl, 2000, 2003; Logan & Bundesen, 2003), or endogenously generated top-down signals (Gilbert & Shallice, 2002).

From that perspective, the cognitive operations tapped in the present experiments may not be too different: they may be responsible for the handling of episodic memories—be that individual stimulus-response bindings as in Experiment 1 or Experiment 3 or whole sets of stimulus-response bindings as in Experiment 2. In other words, if one considers task switching as consisting of the selective retrieval of the appropriate control structure from episodic memory (in the face of competing control structures, Mayr & Keele, 2000), successfully switching to a new task mainly consists in the proper handling of stimulus-response bindings.

Our findings have considerable methodological implications as well. Apparently, being exposed to fMRI noise can alter not only brain activation during cognitive tasks but also overt behavior. Tomasi et al. (2005) observed lesser task-related activation changes in prefrontal control networks under high-noise conditions and considered that this might reflect a stronger recruitment of control structures throughout the whole session. Hence, the noise challenge might increase the general degree of control, so that control-related changes in the activation of the neural structures are less pronounced and more difficult to detect. This consideration is fully consistent with our present observations. It is important to emphasize that the impact of fMRI noise on behavior was very specific: whereas general performance and a number of other effects were virtually unaffected, only the measures that are most indicative of cognitive-control operations showed a clear noise effect. Moreover, the direction of this effect was not necessarily as one would intuitively expect but points to *more* efficient control under more challenging conditions. Such a finding is in line with related observations from the stress literature in which it is argued that (noise-induced or psychosocial) stress might result in compensatory reactions such as increased tonic goal shielding and thus, increased attentional selectivity (e.g., Chajut & Algom, 2003; Plessow, Fischer, Kirschbaum, & Goschke, in press; Wells & Matthews, 1994). For one, this confirms the claim that at least some control deficits may result from the insufficient exploitation of one's cognitive resources (De Jong, Berendsen, & Cools, 1999; Hillgruber, 1912). For another, the observation that more cognitive control than usual is exerted under fMRI-typical noise implies that fMRI studies tend to either under- or overestimate the recruitment of, and the contributions from cognitive control operations—depending on the experimental design, the comparisons made, and the baseline chosen. With respect to the behavioral data, our findings suggest that the effect sizes of behavioral measures of conflict resolution in fMRI studies are systematically underestimated. As a consequence, generalizing from fMRI findings to behavioral observations and vice versa seems to be more problematic than commonly thought, at least as far as control processes are concerned. In a sense, then, investigating cognitive processes by means of fMRI (or methods that challenge participants in other ways) is inevitably facing Heisenberg's (1927) uncertainty principle, according to which the act of measurement can change what is being measured.

A final consideration concerns the mechanism by which noise or other challenges might recruit control operations. Hillgruber (1912) does not describe any such mechanism, and Botvinick et al.'s (2001) model simply assumes that conflict is monitored without specifying how this is achieved. One possibility is that people learn the cues that signal to them that and under which circumstances control might be challenged. The loss of control, and the negative feelings accompanying it (Seligman, 1975), may represent a kind of unconditional internal stimulus that can be predicted through the perception of noise or, if we consider the approach of Botvinick and colleagues, the registration of internal conflict (the conditional stimulus that is). If so, classical conditioning of the corresponding internal states would be conceivable. If we further assume that people make active attempts to avoid the negative feelings associated with real or anticipated control loss (Wortman & Brehm, 1975) and consider that the stronger activation of control systems or procedures are suitable means to achieve

that, it is easy to see that this might lead to an associative link from the cue signaling possible control loss to the stronger recruitment of control systems. Hence, noise and response conflict may only be two examples of a much larger number of control-loss cues that (have been learned to) automatically increase cognitive control (e.g., Botvinick, 2007).

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Received July 31, 2008

Revision received October 26, 2010

Accepted December 14, 2010 ■