Neural and cognitive mechanisms of creativity

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CHAPTER 6

Cognitive control of convergent and divergent thinking: A control-state approach to human creativity

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ABSTRACT

Five experiments sought to characterize the cognitive-control states driving convergent and divergent thinking. The creativity tasks served as primes that were expected to exert specific effects on cognitive control in other, unrelated probe tasks. Experiments 1-3 showed that convergent-thinking primes made conflict resolution in a global-local task, a semantic Stroop and a Simon task more efficient than divergent-thinking primes. Experiment 4 showed no relation between either prime task and stop-signal performance, thus ruling out contributions of inhibitory processes to the priming effect. Experiment 5 showed that divergent-thinking primes improved performance in an Attentional-Blink task. Findings suggest that convergent thinking induces a control state that emphasizes the top-down biasing of creative solutions and/or local competition between them, whereas divergent thinking is associated with reduced top-down control and/or local competition.

INTRODUCTION

Even though creativity is arguably the most important determinant of mankind's intellectual evolution, surprisingly little is known about how creativity actually works (Sternberg, Kaufman & Pretz, 2002). One important obstacle on the way to a systematic investigation of the mechanics of creativity results from disagreements regarding how to define the research question: should one aim to explain how creative products emerge, how more creative people differ from less creative ones, or which processes are involved in the creative act (see Brown, 1989; Runco, 2007)? These questions are further complicated by increasing evidence suggesting that creative acts rely on the interplay of multiple cognitive processes and neural networks (e.g., Dietrich, 2004; Eysenck, 1993; Heilman, 2005). To tackle some of these problems and avoid others, the present study considered creativity not as a *trait* that a given person may or may not have but, rather, as a particular type of behavior that emerges from a particular *state* (or a set of states) of the cognitive system that affects the way cognitive operations are run. Processes that are not directly involved in information processing but that target other processes are commonly thought of as control processes (Monsell, 1996), which renders our account a control-state approach to creativity.

According to Guilford (1950, 1967), the main ingredients of creativity are divergent and convergent thinking, even though we do not claim that these are the only processes involved in creative acts. Divergent thinking is taken to represent a style of thinking that allows many new ideas being generated, in a context where more than one solution is correct. The probably best example is a brainstorming session, which has the aim of generating as many ideas on a particular issue as possible. Guilford's (1967) Alternate Uses Task (AUT) to assess the productivity of divergent thinking follows the same scenario: participants are presented with a particular object, such as a pen, and they are to generate as many possible uses of this object as possible. In contrast, convergent thinking is considered a process of generating one possible solution to a particular problem. It emphasizes speed and relies on high accuracy and logic. Mednick's (1962) Remote Associates Task (RAT) that aims to assess convergent thinking fits with this profile: participants are presented with three unrelated words, such as "time", "hair", and "stretch", and are to identify the common associate ("long"). It makes sense to assume that divergent and convergent thinking are basic ingredients of many, if not all truly creative acts, which often comprise of a search for possibilities and options followed by the translation of the preferred option into reality (Hommel, in press).

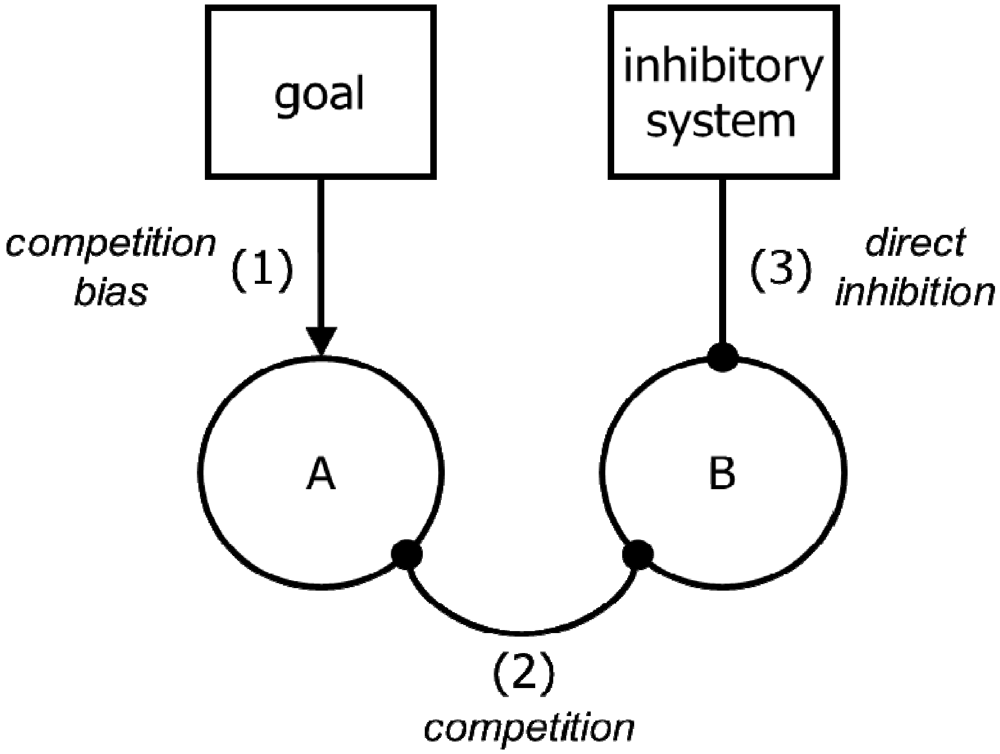

Figure 1: Possible mechanisms involved in selecting a goal-related target representation (of a perceptual or action event, or a thought) from a set of two competing alternatives. The target A might win the competition with an alternative B because: A is selectively supported by the goal representation through a facilitatory connection (Route 1: competition bias); A receives other types of associative support that suffices to outcompete B (Route 2: local competition); B is directly inhibited through some inhibitory control system (Route 3: direct inhibition).

Let us now consider the cognitive control states that would allow or be useful for divergent and convergent thinking. According to Colzato et al. (2008), the selection of stimulus or response representations (or thoughts, as in our case) can be controlled or biased in at least two different ways. Figure 1 sketches the situation where a decision needs to be made between alternative A (the “correct” or most appropriate alternative) and the competing alternative B. The competition between the two alternatives is represented by mutually inhibitory connections between their representations (Route 2), which captures the assumption that decision-making in biological systems is competitive (Bogacz, 2007). Competition is likely to yield winners and losers, so that it can be considered as a control mechanism that eventually will favor one alternative over others. Another, not necessarily exclusive way to facilitate the selection of the appropriate alternative is indicated in the figure as Route 1: The preferred alternative might receive top-down support from the representation of the action goal. This control strategy is underlying the biased-competition approach of Duncan, Humphreys, and Ward (1997), the conflict-resolution model of Cohen and colleagues (Botvinick, Braver, Barch, Carter & Cohen, 2001; Cohen, Dunbar & McClelland, 1990), the task-switching model of Gilbert and Shallice (2002), and many other control models.

As we assume that control states are affecting the way control is exerted, there are two major ways to modulate the processes captured in Figure 1. First, a control state might modulate the strength of top-down bias (Route 1) and, thus, increase or decrease the degree to which the goal representation supports one alternative in its competition with others. Second, a control state might modulate the strength of mutual local inhibition between alternatives (Route 2) and, thus, the degree to which competitors “suffer” from the support and selection of another alternative.[2]

Convergent thinking would seem to benefit from a strong degree of goal-directedness that is steering and efficiently constraining the search for the right concept or idea. This implies reliance on Route 1 and, hence, on a strong top-down bias of decision-making. Duncan, Emslie, Williams, Johnson, and Freer (1996) have suggested that individuals differ with respect to the degree to which they can provide or at least maintain such a top-down bias. In particular, they have claimed, and provided evidence that Spearman’s g, a measure of fluid

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[2] Some authors have pleaded for what in Figure 1 is indicated as Route 3: the inhibition of unwanted alternatives. We will introduce and further discuss this possibility in Experiment 4.

intelligence, is positively correlated with performance on a task that requires participants to maintain top-down biases over time. This fits with the observation that performance on convergent-thinking tasks is positively correlated with fluid intelligence (Akbari Chermahini & Hommel, 2010).

In contrast, divergent thinking would not seem to benefit from strong top-down control but, if anything, from rather weak and "allowing" top-down guidance. Moreover, efficient divergent thinking would seem to require jumping from one option to another, which suggests that the mutual inhibition between alternative thoughts should be weak. This kind of control state seems to be consistent with a number of previous assumptions and recent findings. For instance, Eysenck (1993) has related the divergent aspect of creativity to schizophrenia and suggested that schizophrenic patients and healthy creative individuals share a certain lack of constraints and inhibition in their thinking. Indeed, several authors since Bleuler (1978) have characterized schizophrenics as showing a kind of "widening of the associative horizon" (Eysenck, 1993). Along the same lines, Ashby, Isen, and Turken (1999) have associated higher dopamine levels (as to be found in schizophrenic patients) with greater cognitive flexibility and less inhibition between alternative thoughts (cf., Cohen & Servan-Schreiber, 1992). In healthy participants, carriers of the DRD2 TAQ IA polymorphism (which results in a 30-40% reduction in DA-D2 receptor density—a receptor that drives inhibitory processes) were shown to perform significantly better in a divergent-thinking task (Reuter, Roth, Holve, & Hennig, 2006).

These considerations suggest that the convergent- and divergent-thinking components of human creativity imply two different, to at least some degree opposite cognitive-control states that facilitate or even generate the respective thinking style. In particular, convergent thinking seems to require either strong top-down control or strong local competition, or both, whereas divergent thinking seems to call for weak top-down control and/or weak local competition. The aim of the present study was to seek for evidence, if possible, for the existence of these two types of control states and for their hypothesized relationship with particular thinking styles. Our general rationale was to characterize the hypothetical control states by studying the way they are affecting (supporting or interfering with) cognitive control in nominally and logically unrelated tasks that are known to require particular types of control.

The rationale underlying our empirical approach was based on the widely shared assumption that control states are inert and therefore changing slowly, especially in the absence of a pressing need for change. From a theoretical perspective, this is suggested by the assumption that control states (or meta-parameters: Doya, 2002) are globally represented and affecting the entire cognitive system (Baars, 1988; James, 1890; Monsell, 1996). Empirical support for this idea has been provided by Memelink and Hommel (2005, 2006), who showed that the attentional relevance of horizontal versus vertical spatial relationships in one task affects the relative weighting of horizontal and vertical stimulus and response codes in a logically unrelated but temporally overlapping stimulus-response compatibility task. In other words, the attentional set in one task automatically affects the attentional set in another. A similar observation has been made by Meiran, Hommel, Bibi, and Lev (2002). They had participants carry out sequences of “ready” responses (to signal that they were optimally prepared) and choice-reaction responses, and consistently found positive (rather than the expected negative) correlations between the latencies for these two types of responses. This suggests that participants’ speed-accuracy settings fluctuate spontaneously during a task and they do so sufficiently slowly to impact temporally close responses in the same way.

If performing a convergent- or divergent-thinking task requires establishing a particular control state, and if this state is relatively inert—so the idea underlying our study—it is likely to spill over to and thus affect other, logically unrelated but temporally close tasks. If so, the characteristics of the control state adopted in the preceding thinking task (the *priming task*, as we will call it) should become visible through the way performance in the following task (the *probe task*) changes as a function of the type of the priming task. If the probe task can be expected to require strong top-down control and/or strong local competition—as many laboratory tasks do—performance thereon should be better if being primed by a convergent-thinking than a divergent-thinking task. In the first three experiments, we applied this reasoning to several tasks that can be assumed to tap different processes in the information-processing chain from perception to action. A fourth experiment tested whether the priming effects obtained in Experiments 1-3 are likely to reflect inhibitory processes. Finally, a fifth experiment included a probe task that is likely to benefit more from a weaker form of top-down control and/or local competition, so that performance thereon was expected to be better if being primed by a divergent-thinking than a convergent-thinking task.

EXPERIMENT 1 (GLOBAL-LOCAL TASK)

The first experiment considered the global-local task developed by Navon (1977) as a probe task. As Navon and others have shown, people can attend different levels of hierarchical stimuli, such as large letters made of smaller letters. Attending to the global aspect of such stimuli is commonly easier and perhaps more natural, as can be seen in faster reaction times and/or more accurate performance in response to global than to local stimulus features (the global-precedence effect; Navon, 1977). Nevertheless, people can be successfully instructed to attend to the local level as well, suggesting that the hierarchical level to which attention is being directed is under cognitive control. Indeed, the cognitive control model of Logan and Gordon (2001) foresees a particular control parameter that is assumed to regulate the currently attended stimulus level.

Maintaining a particular control parameter value or state in the face of stimuli that are open to multiple interpretations can be assumed to rely on, or at least encourage the adoption of a control strategy that relies on strong top-down support of decision-making (Route 1) and/or strong local competition (Route 2) to render the alternative interpretations mutually exclusive. If so, one would expect that a convergent-thinking task as a prime facilitates, or is at least more compatible with the natural mode of operation. In contrast, a divergent-thinking task as a prime would be incompatible with this natural mode and should therefore make it less efficient. If we assume that the difference in performance between responding to the global versus local stimulus level expresses the difficulty to overrule the natural tendency to attend to the global level, we would thus expect that this difference is smaller with a convergent-thinking prime than with a divergent-thinking prime.

Method

Participants

Nineteen young healthy adults served as subjects for partial fulfillment of course credit. Informed consent was obtained from all participants after the nature of the study were explained to them. The protocol was approved by the local ethical committee (Leiden University, Faculty of Social and Behavioral Sciences).

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 2) presented in red on a black screen. Larger (global) rectangles/squares consisted of smaller (local) rectangles or squares. Global stimuli (i.e., squares or rectangles; 93 x 93 pixels or 93 x 189 pixels respectively) were composed of many smaller “local” stimuli (i.e., squares or rectangles; 21 x 21 pixels or 8 x 46 pixels respectively). The space between the local elements of a stimulus was 3 pixels. A global square consisted of 16 small squares or 8 small rectangles; a global rectangle consisted of 32 small squares or 16 small rectangles. The experiment was composed by 3 practice and 3 experimental blocks. Convergent and divergent conditions were created by presenting participants with two paper and pencil creativity tasks (a convergent thinking task and a divergent thinking task).

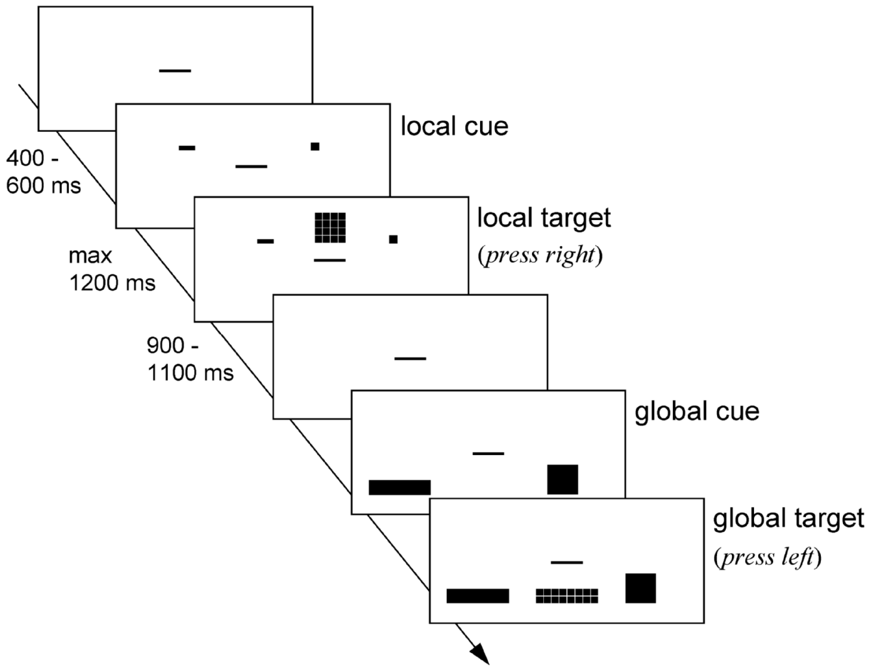

Figure 2: Sequence of events in Experiment 1.

Procedure and Design

Participants served in two 50-min sessions separated by one week. In one session they constantly switched between performing the Remote Association Task (based on Mednick, 1962, and translated into Dutch) for two minutes to induce convergent thinking (the prime task) and completing a block of the global-local taskadopted from Huizinga et al. (2006; see below) as probe task. In the other session they constantly switched between carrying out the Alternative Use Task (Guilford, 1967) for two minutes to induce divergent thinking (the prime task) and performing a block of the global-local probe task. Given that the experiment was composed by three practice and three experimental blocks, participants were to switch between the prime and the probe task six times per session.The order of these two types of sessions was counterbalanced across participants.

Remote Association Task (convergent thinking)

In this task, participants are presented with three unrelated words (such as time, hair, and stretch) and are asked to find a common associate (long). Our Dutch version comprised of 30 items (Cronbach's alpha = .85; see Akbari Chermahini & Hommel, 2011), which were to be responded to within 10 min.

Alternate Uses Task (divergent thinking)

In this task, participants were asked to list as many possible uses for six common household items (brick, shoe, newspaper, pen, towel, bottle) as they can within 10 min. The results can be scored in several ways with flexibility, the number of different categories used, being the most consistent and reliable (Akbari Chermahini & Hommel, 2010).

Global-Local Task

In this task, 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—a condition that increases the global-local effect. In one of the two training blocks, participants responded to the local figures and 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. Cue and target remained on the screen until a response was given or 3500 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 1000 ms. Participants were to respond as fast as possible while avoiding errors.

Results

Performance in the two priming tasks was good and comparable to performance in other studies (e.g., Akbari Chermahini & Hommel, 2010). Participants produced about 15 correct responses on average in the Remote Association Task (*M*=14.8 and *SD*=4.5) and used about 33 different categories in the Alternate Uses Task (*M*=33.3 and *SD*=10.0).

Mean RTs and proportions of errors from the global-local task were analyzed as a function of priming task (convergent vs. divergent thinking), target level (global vs. local), 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). Four-way ANOVAs for dependent measures were run on RTs and error rates.

RTs revealed three reliable main effects: The effect of switch, *F*(1,18)=91.56, p<.0001, MSE = 1531.26, η^2p = 0.84, was due to that repeating the task allowed for faster responding than switching between target levels (346 vs. 389 ms); the effect of target level, *F*(1,18)=85.15, p<.0001, MSE = 1533.82, η^2p = 0.83, reflected the well-known global-precedence effect (Navon, 1977), that is, faster responses to globally than locally defined targets (347 vs. 388 ms); and the congruency effect, *F*(1,18)=36.66, p<.0001, MSE = 1301.12, η^2p = 0.67, indicated interference from the non-target 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 (355 vs. 380 ms).

More important for present purposes, priming task interacted with target level, *F*(1,18)=7.54, p<.05, MSE = 1301.12, η^2p = 0.30. As suggested by Figure 3, the effect of target level was reliable for both convergent and divergent conditions, *F*(1,18)=42.58, p<.0001, MSE = 962.00, η^2p = 0.70, and *F*(1,18)=72.18, p<.0001, MSE = 1320.33, η^2p = 0.80, respectively, but, as predicted, the global preference effect was reduced in the context of convergent thinking.

The error rates revealed no interactions but three main effects only: switch, *F*(1,18)=9.00, $p<.01$, MSE = 54.19, η^2p = 0.33, indicating that repeating the task produced less errors than switching between target levels (8.5% vs. 11.1%); target level, *F*(1,18)=25.30, $p<.0001$, MSE = 89.32, η^2p = 0.53, showing more errors to globally than locally defined targets (12.58% vs. 7.13%); and congruency, *F*(1,18)=70.73, $p<.0001$, MSE = 104.83, η^2p = 0.79, reflecting the interference of the irrelevant target level, as indicated by a smaller proportion of errors on congruent as compared to incongruent trials (4.9% vs. 14.8%).

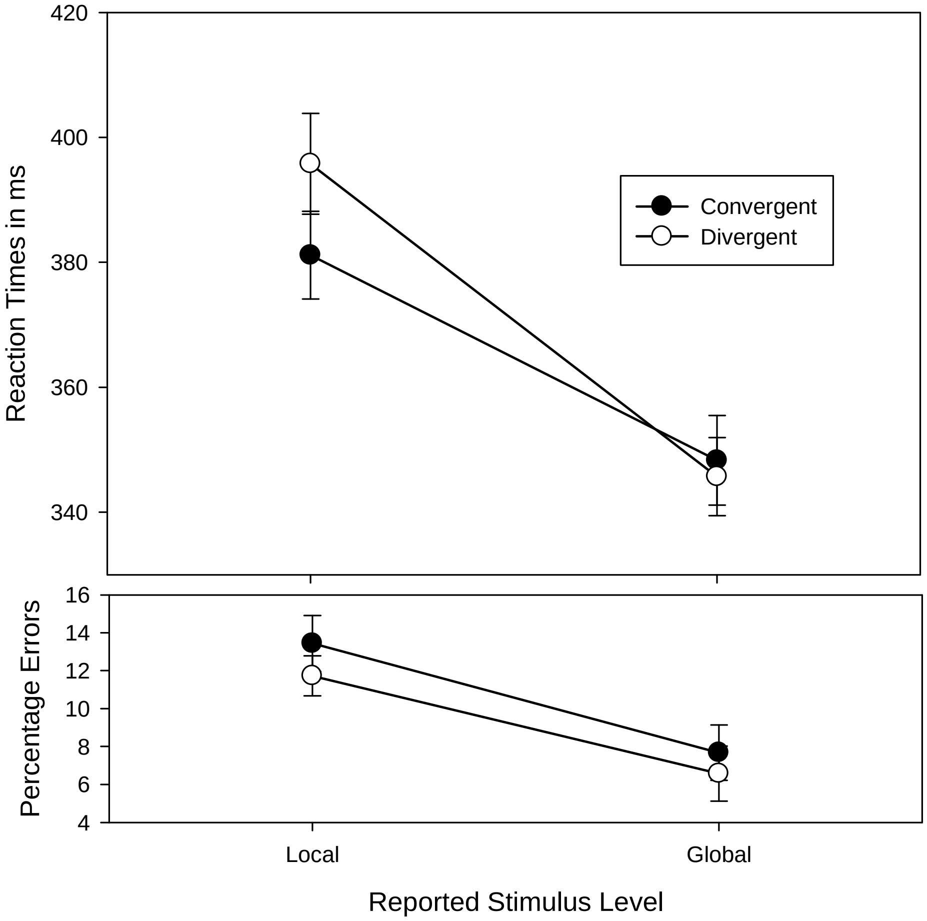

Figure 3: Mean reaction times and error percentages in Experiment 1, as a function of reported stimulus level (global vs. local) and priming task (convergent vs. divergent thinking).

Discussion

We expected that the cognitive-control state required for convergent thinking would be more consistent with maintaining a less dominant attentional set than the state required for divergent thinking. If so, one would expect that the global precedence effect (i.e., the performance benefit associated with responses to global as compared to local stimulus features) is less pronounced after having performed a convergent-thinking task than after a divergent-thinking task. This is exactly what the findings show. As one would expect, performance on the easier and more natural global task is unaffected by the priming task, whereas the more challenging local task, which is more likely to draw and depend on control processes, yields better performance if being primed by the convergent-thinking than by the divergent-thinking task.

A somewhat unexpected outcome is the inverted global-precedence effect in the error rates, suggesting better performance in the local task. Importantly, however, this is a mere main effect that cannot account for the crucial interaction observed in the RTs.

EXPERIMENT 2 (STROOP TASK)

Even though the global-local task draws on cognitive control, it is a task that taps into rather “early” attentional operations on (the outcomes of) perceptual organization processes. Our next step was to see whether interactions between creativity tasks and cognitive control can also be found for attentional control processes operating on somewhat more abstract stimulus representations. A perhaps obvious choice in this context is the Stroop task, which requires participants to respond to the color of colored color words—the less familiar and less overlearned response. Since the seminal study of Stroop (1935) it is known that people perform better in this task if they are presented with congruent stimuli, such as the word BLUE in blue ink, than with incongruent stimuli, such as the word GREEN in blue ink (for an overview, see MacLeod, 1991).

Researchers and available models agree that the Stroop effect is due to some sort of conflict between color- and word-related codes, which calls upon cognitive control to solve it (Cohen et al., 1990). Indeed, given that the stimulus affords different and conflicting types of responding, people need to rely on the representation and top-down impact of the instructed action goal to name the color of the stimuli. However, researchers and models do not agree on which kinds of codes are involved in, and responsible for the conflict: suggestions range from perceptual (e.g., Kornblum, 1994) and semantic codes (Seymour, 1977) to response representations (Dyer, 1973), often driven by the unrealistic assumption that phenomena as complex as the Stroop effect must have no more than one functional locus. To make sure that we are tapping conflict between codes that are fairly abstract, we therefore employed a semantic version of the Stroop task that was developed by Klein (1964).

As Klein demonstrated, color-naming responses are not only delayed if they refer to the ink of incongruent color words but also if they refer to color associates, such as the words “frog” (associated with green), “sun” (associated with yellow), or “fire” (associated with red). Even though this version has the disadvantage of producing a smaller congruency effect than the standard Stroop task, it rules out the possibility that the conflict takes place between perceptual codes—as was the case in Experiment 1. Hence, Experiment 2 was likely to target a different control domain than Experiment 1 did. Nevertheless, our predictions were similar. If successful performance in the Stroop task requires strong top-down guidance from the task goal, this control state should be more compatible with the control state established in a convergent-thinking task If so, the Stroop effect (i.e., the difference between performance on congruent and incongruent Stroop stimuli) should be smaller for convergent-thinking primes than for divergent-thinking primes.

Method

Twenty new young healthy adults served as subjects for partial fulfillment of course credit. They satisfied the same criteria as in Experiment 1. Convergent- and divergent-thinking prime conditions were created as in Experiment 1, the procedure was analogous (except that the global-local task was replaced by the Stroop task), and the apparatus was identical.

In the Stroop task, participants responded to yellow, blue, green, and red words by pressing the “Z”, “X”, “>” or “?” buttons of the QWERTY computer keyboard, respectively.

Eight Dutch color-associates served as (irrelevant) word stimuli: “boom” (tree), “zee” (sea), “zon” (sun), “citroen” (lemon), “gras” (grass), “lucht” (sky), “bloed” (blood), and “vuur” (fire), presented on the black background of the computer screen. The words appeared in either their semantically implied color (50% congruent trials; e.g., the word *bloed* in red ink) or in a semantically unrelated color (50% incongruent trials; e.g., the word *bloed* in green ink). The Stroop task took about 10 min, in which participants were asked to respond to the color of the 144 randomly presented color words while ignoring word meanings. The target remained on the screen until a response was given. During inter stimulus intervals a white fixation cross stayed on the black screen. The interval between presentation of the cue and of the target stimulus was 500 ms. The Stroop task was composed of two experimental blocks, so that participants were to switch between the prime and the probe task two times per session.

Results and Discussion

Performance in the Remote Association Task (*M*=7.4 and *SD*=3.5) and the Alternate Uses Task (*M*=13.2 and *SD*=4.2) was good; the lower absolute scores as compared to Experiment 1 reflected the fact that participants had only 2 instead of 6 2-minute intervals to complete the creativity tasks. Mean RTs and proportions of errors from the Stroop task were analyzed as a function of priming task (convergent vs. divergent thinking) and congruency (congruent vs. incongruent). Two-way ANOVAs were run on RTs and error rates. RTs revealed a reliable main effect for congruency, $F(1,19)=13.23$, $p<0.01$, $MSE = 3923.5$, $\eta^2\text{p} = 0.41$, that is, faster responses to congruent (588 ms) than incongruent stimuli (602 ms). Importantly, this Stroop-like effect was modified by priming task, $F(1,19)= 4.48$, $p<0.05$, $MSE = 1206.6$, $\eta^2 p = 0.19$. As suggested by Figure 4, congruency was reliable for both convergent and divergent conditions but, as predicted, this Stroop-like effect was smaller for the convergent-thinking than for the divergent-thinking prime. The analysis of the error rates revealed no significant effect. This outcome supports our assumption that the control state implemented in the convergent-thinking task was more compatible with the control state that is functional for performing the Stroop task than the control state implemented in the divergent-thinking task was.

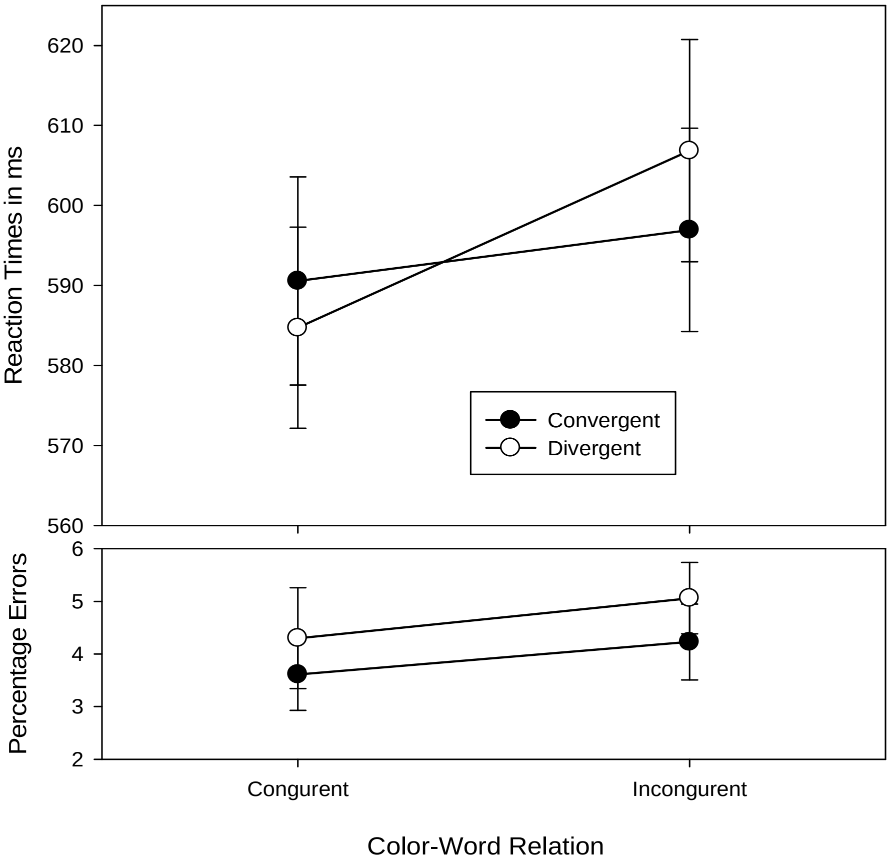

Figure 4: Mean reaction times and error percentages in Experiment 2, as a function of the relationship between named color and the meaning of the stimulus word (congruent vs. incongruent) and priming task (convergent vs. divergent thinking).

EXPERIMENT 3 (SIMON TASK)

The outcome of Experiment 2 suggests that the control-state-compatibility effect observed in a perceptual-conflict task in Experiment 1 generalizes to tasks that are likely to involve semantic conflicts. In Experiment 3 we went on by testing whether the same pattern of results can also be demonstrated in a task that taps into response conflict. The arguably purest assessment of response conflict is represented by the Simon task (cf., Hommel, 2011). In this task, participants respond to a non-spatial feature of commonly visual stimuli by pressing left and right response buttons. Importantly, the location of the stimulus varies randomly and is thus sometimes corresponding with the location of the correct response (the compatible condition) and sometimes not (the incompatible condition). As one might expect, performance is better with compatible than with incompatible relationships between stimulus location and response—the Simon effect (Simon & Small, 1969). Given that this task does not include any congruency or incongruency between the stimulus features (i.e., the non-spatial feature, such as color, and the spatial location), the Simon effect can be taken as a pure measure of response conflict (Hommel, 2011; Kornblum, Hasbroucq & Osman, 1990). Even though the type of conflict is likely to be different from the effects studied in Experiments 1 and 2, it makes sense to assume that the successfully performing the Simon task relies on a similar type of top-down support of the relevant stimulus feature as we have assumed for the global-local task and the Stroop task. Accordingly, we expected that the Simon effect would be smaller if being primed by a convergent-thinking task.

Method

Nineteen new young healthy adults served as subjects for partial fulfillment of course credit. The method was as in Experiment 1 except that the global-local task was replaced by the Simon task.

In the Simon task, a small (.5 x .5 cm) dark-grey fixation square stayed at the center of the screen. The target stimulus was either a green or a blue circle (1.5 cm in diameter) that appeared left or right of fixation. Circle color and location varied randomly but equiprobably. Responses were made by pressing the “Z” or “?” buttons on the computer keyboard with the left or right index finger, respectively.

Participants made speeded discriminative responses to the color of the circle, which stayed on screen until a response was given or 1500 ms had passed. Intervals between subsequent stimuli varied randomly but equiprobably, from 1750-2250 ms in steps of 100 ms. Participants were asked to ignore the location of the stimulus and to react as fast as possible while keeping error rates below 15% on average; feedback was provided at the end of a trial block. The task consisted of 60 practice trials (practice block) and 300 experimental trials (5 experimental blocks), and took about 25 min. to complete. Participants were thus to switch between the prime and the probe task six times per session.

Results and Discussion

Participants showed good performance in the Remote Association Task (*M*=7.7 and *SD*= 2.9) and the Alternate Uses Task (*M*=33 and *SD*=7.04). Mean RTs and proportions of errors from the Simon task were analyzed as a function of priming task (convergent vs. divergent thinking) and compatibility (compatible vs. incompatible). There was reliable main effect of compatibility in RTs, $F(1,18)=227.95$, $p<0.001$, MSE = 23207.49, η^2p = 0.42, showing faster responses in compatible than incompatible conditions (346 vs. 381 ms). Importantly, compatibility interacted with priming task, $F(1, 18)= 8.14$, $p=0.011$, MSE = 145.84, η^2p = 0.31. While the compatibility was reliable for both types of priming, the Simon effect was reduced by the convergent-thinking prime (see Figure 5). The analysis of the error rates revealed no significant effect. We can thus conclude that the control-state-compatibility effect obtained in Experiments 1 and 2 generalizes to a task tapping into response conflict.

EXPERIMENT 4 (STOP-SIGNAL TASK)

The results from Experiments 1-3 suggest that the control states that creativity tasks induce exert specific effects on logically unrelated laboratory tasks in which perceptual, semantic, or response conflicts are to be resolved. According to our theoretical reasoning, these conflicts reflect competition between the cognitive representations of stimulus events and/or actions, which needs to be resolved by biasing the interaction in such a way that goal-compatible representations are strengthened and therefore winning the competition. The role of a suitable control state in this scenario would be to provide a configuration of the cognitive system that maximizes this bias, be it through strengthening the competition bias or local competition or both.

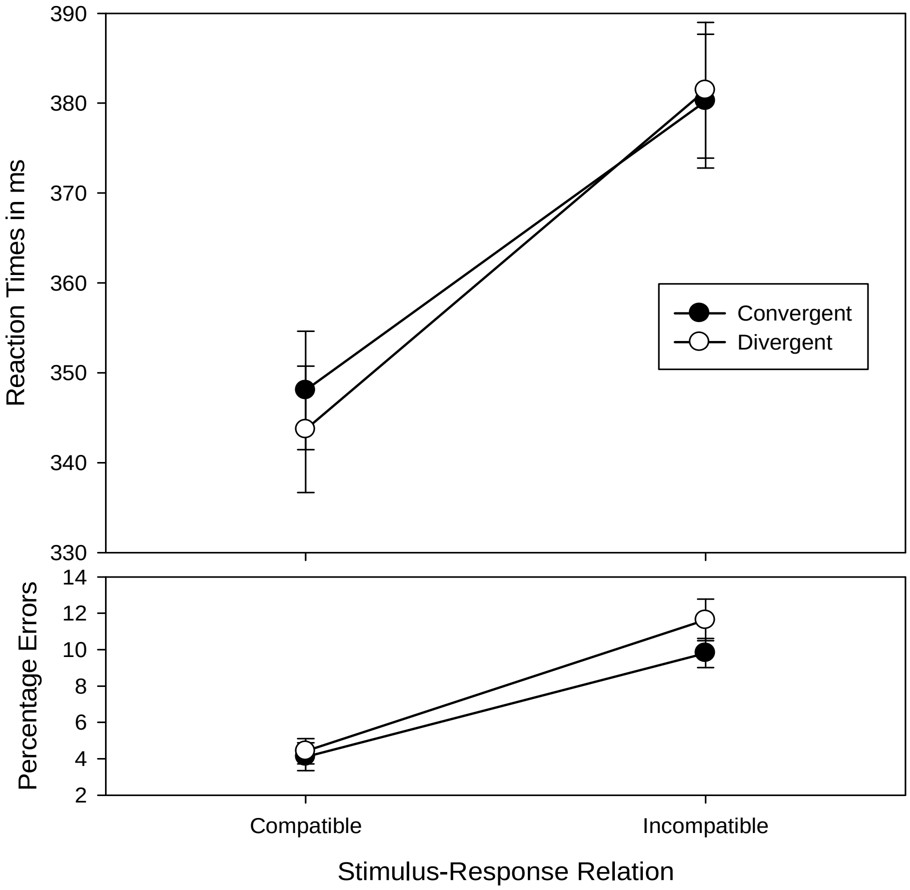

Figure 5: Mean reaction times and error percentages in Experiment 3, as a function of the relationship between stimulus location and response location (compatible vs. incompatible) and priming task (convergent vs. divergent thinking).

An alternative scenario is possible however. Various authors since Freud (1896) have emphasized the importance of inhibitory processes in regulating intentional behavior. In particular, researchers have considered the direct inhibition of response representations as a possible alternative or addition to competition biases (e.g., Harnishfeger, 1995; Ridderinkhof, 2002)—as indicated as Route 3 in Figure 1. With regard to the present Experiments 1-3, one might therefore argue that good performance in the global-local task, the Stroop task, and the

Simon task did not benefit from the convergent-thinking prime task because it had induced stronger competition bias or local competition but, rather, because it had strengthened some sort of inhibitory control. More inhibition might have selectively operated on and weakened global representations in the local task, word representations in the Stroop task, and location representations in the Simon task. It is often difficult to rule out such a possibility because direct inhibition on the one hand and the interplay between competition bias and local competition on the other can mimic each other's effects (Colzato et al., 2008): many effects related to the control of inter-representational conflict can be alternatively modeled by either increasing the impact of Route 3 or by increasing the strength of both Route 1 and Route 2.

In Experiment 4 we tackled this problem by using a probe task that is arguably the most reliable tool to tap into inhibitory control: the stop-signal task developed by Logan and Cowan (1984). In this task, participants are first prompted to execute a response but then, briefly before this response is executed, presented with a stop signal calling for the immediate abortion of that response. Systematically varying the time interval between the go signal and the following stop signal allows one to calculate the so-called stop-signal reaction time (SSRT), which represents an estimation of the processing time needed to stop execution just in time. Several observations have validated the assumption that this task taps into inhibitory control. For instance, SSRTs are elevated in various groups that are known to have difficulties inhibiting motor activity and/or unwanted actions, such as patients suffering from Parkinson’s disease (Gauggel, Rieger & Feghoff, 2004) or diagnosed with ADHD (for a recent review see, Alderson, Rapport & Kofler, 2007), and cocaine users (Colzato, van den Wildenberg & Hommel, 2007). If the task-priming effects obtained in Experiments 1-3 would reflect inhibitory-control processes, we should find comparable priming effects on SSRT in the stop signal task. In particular, SSRTs should be faster (i.e., inhibition more efficient) if being primed by a convergent-thinking task than by a divergent-thinking task. In contrast, no such effect would be expected if the previous priming effects were due to the stronger competition bias and/or local competition induced by the convergent-thinking task.

Method

Twenty new young healthy adults served as subjects for partial fulfillment of course credit. The method was as in Experiment 1 except that the global-local task was replaced by the stop-signal task.In the stop-signal task (adopted from Colzato et al., 2007), responses were made by pressing the “Z” or “?” of the QWERTY computer keyboard with the left and right index finger, respectively. Participants were to react quickly and accurately by pressing the left and right key in response to the direction of a pseudo-randomly left- or right-pointing green arrow (go trials) of about 3.5 X 2.0 cm. Arrows appeared for 1500 ms or until a response was given. Intervals between subsequent go signals varied randomly but equiprobably, from 1250 to 1750 ms in steps of 125 ms. During these interstimulus intervals, a white fixation point (3 mm in diameter) stayed on the screen. The green arrow changed to red on 30 % of the trials, upon which the choice response had to be aborted (stop trials). A staircase-tracking procedure dynamically adjusted the delay between the onset of the go signal and the onset of the stop signal to control inhibition probability (Levitt, 1971). After a successfully inhibited stop trial, the next stop-signal delay increased by 50 ms, whereas the delay decreased by 50 ms after the participant was unable to stop. This algorithm ensured that motor actions were successfully inhibited in about half of the stop trials, which yielded accurate estimates of SSRT and compensates for differences in choice RT between participants (Band, van der Molen &Logan, 2003). The task consisted of five blocks of 104 trials each, the first of which served as a practice block to obtain stable performance, and it took about 30 min. to complete. Participants thus were to switch between the prime and the probe task five times per session.

Results and Discussion

Participants showed good performance in the Remote Association Task (*M*=11.8 and *SD*=2.7) and the Alternate Uses Task (*M*=23.8 and *SD*=6.2). T-tests of mean RTs to go-signals indicated almost identical levels of performance in convergent and divergent sessions (389 vs. 386 ms, respectively), p>.66. More importantly, the same was true for SSRTs (205 vs. 207 ms), p>77.

The outcome does not provide any support for the assumption that inhibitory processes were responsible for the beneficial impact of control states related to convergent thinking on performance in the global-local task, the Stroop task, and the Simon task—at least as far as these processes are captured by the stop-signal task. Even though this conclusion is based on a null effect and needs thus be treated with the necessary caution, it is consistent with the assumption that the task-priming effects observed in the present Experiments 1-3 reflect commonalities between prime and probe tasks in terms of Route-1 and/or Route-2 mechanisms but not Route-3 mechanisms.

EXPERIMEINT 5 (ATTENTIONAL BLINK)

Experiments 1-3 provided evidence that creativity tasks and, as we assume, the control states they require have a systematic impact on subsequent conflict tasks. However, all three demonstrations of such priming effects followed the same pattern in showing better performance after a convergent-thinking task. On the one hand, this makes sense given that most laboratory tasks targeting cognitive control processes were designed to study the impact of goals and intentions on cognitive processing under pressure, that is, under conditions that are challenging the maintenance of goals and intentions or their translation into overt behavior. Accordingly, it is not surprising that performance in these tasks benefits from control states that, as we argue in the case of convergent thinking, make the top-down biasing of cognitive processing and/or the exclusiveness of decision-making more efficient.

On the other hand, however, the observation that convergent thinking turned out to be the better prime in all the conflict tasks we investigated raises the possibility that other, less specific factors might have played a role. Fortunately, Experiment 4 provided evidence that the convergent-thinking task does not improve performance in every possible task or measure, which rules out general factors like motivation, task difficulty, and effort consumption. The same conclusion is suggested by the observation that the priming task failed to produce a main effect on performance in any of the other probe tasks as well. However, it is possible that conflict-related measures, such as the global-local effect, the Stroop and the Simon effect, are more sensitive than is the general performance level, so that it is difficult to rule out that the positive impact of convergent thinking on subsequent performance is less specific than we suggest. This suggestion would gain credibility it the opposite pattern could also be demonstrated, that is, if it could be shown that task performance can also benefit from divergent thinking in principle. Experiment 5 was designed to provide such a demonstration, if possible.

As we have alluded to already, most tasks that are assumed to tap into cognitive control processes follow the strategy suggested by Ach (1905)—presumably the first to investigate the human will experimentally—to put the task goal in opposition to one's habits, such as the tendency to respond to the global shape or locations of visual objects, or to read words rather than naming their color. Only if our will to execute the task goal can overcome these opposing habits, so the idea, can we be sure that performance measures are actually reflecting the operation of the will—or of cognitive control, as we now call it. Accordingly, the degree to which opposing habits can be overcome provides a direct measure of willpower (Ach, 1910) or, in more modern terms, of the efficiency of cognitive control. From this perspective, any increase of top-down control would be expected to improve performance, which makes many laboratory tasks less promising candidates for demonstrating a beneficial priming effect of divergent thinking. And yet, there is one widely used task that has been suspected to suffer from too much cognitive control: the Attentional Blink (AB) task (Raymond, Shapiro & Arnell, 1992).

The AB is observed if two difficult to identify target stimuli appear in close temporal proximity, such as in tasks using rapid serial visual presentation techniques. Whereas the first target (T1) is commonly easy to report accurately, performance on the second target (T2) is often dramatically impaired if it follows T1 within 200-500 ms. Most researchers agree that the AB reflects some sort of attentional bottleneck that prevents the consolidation of T2 while T1 is being processed, so that T2 is registered but forgotten before it can be reported (cf. Hommel et al., 2006; Martens & Wyble, 2010).

The nature of the underlying bottleneck is less well understood, however. There is increasing evidence that the presence and size of the AB depends on the task context (e.g., Di Lollo, Kawahara, Ghorashi & Enns, 2005) and the instructions participants are receiving. For instance, the size of the AB is considerably reduced, and the effect sometimes disappears altogether, if participants are encouraged to assume a more relaxed attitude towards the task (Olivers & Nieuwenhuis, 2005) or are otherwise distracted (Olivers & Nieuwenhuis, 2006).

According to Olivers and Nieuwenhuis (2006), this pattern suggests that the AB is due to an overinvestment of attentional resources into the processing and consolidation of T1, which leaves too little for T2 to perform accurately. This possibility fits well with findings of Shapiro, Schmitz, Martens, Hommel, and Schnitzler (2006), who studied electromagnetic markers of attentional resource allocation in the AB task. As it turned out, participants who showed more evidence of attention-related brain activity while processing T1 were more likely to miss T2 in the blink interval. In other words, people are showing a smaller AB the less they monopolize attentional resources for T1 processing.

Considering the characteristics that we hypothesize to underlie convergent and divergent thinking, it makes sense to assume that the control state driving divergent thinking might be more beneficial for good performance in the AB task than the control state implied by convergent thinking. If divergent thinking weakens the impact of top-down control on the activation of target representations and/or the local competition between them, this would seem to be a good strategy for reducing the size of the AB. Two recent observations support this idea. For one, bilinguals have been shown to produce a larger AB than monolinguals (Colzato et al., 2008). Learning and mastering a second language is often assumed to increase cognitive conflict because it inflates the possibilities to express almost any given concept. To deal with this challenge, bilinguals have been claimed to develop special control strategies to better focus on words from one language to the expense of words from the other (Green, 1998), and there is evidence that these strategies generalize to non-lingual conflict tasks (for an overview, see Bialystok & Craik, 2010). If we thus assume that bilinguals exert more top-down control (i.e., have developed a stronger Route-1 mechanism), the finding that they produce a more pronounced AB suggests that convergent thinking may indeed be associated with a less AB-suitable control state than divergent thinking is.

For another, Calvinists have been shown to produce a larger AB than atheists (Colzato, Hommel & Shapiro, 2010). Following Colzato, Hommel, and colleagues (Colzato, van Beest et al., 2010; Hommel & Colzato, 2010), Calvinists are trained to focus on individual goals and to adopt a particularly “exclusive” control profile, which translates into an emphasis of Route-1 and Route-2 mechanisms. As this emphasis is apparently associated with a larger AB, it makes sense to assume that a divergent-thinking priming task leads to a smaller AB than a convergent-thinking prime.

Method

Twenty new young healthy adults served as subjects for partial fulfillment of course credit. The method was as in Experiment 1 except that the global-local task was replaced by the AB task.

The AB task was adopted from Colzato, Hommel, and Shapiro (2010). Participants were seated at a viewing distance of about 50 cm. The fixation mark ("+") and all target (digit) and distractor (letter) stimuli (16-point Times New Roman font) were presented centrally in black on a gray background. Letters were drawn randomly without replacement from the complete alphabet. Digits were drawn randomly from the set 1-9.

Participants were to identify and report two digits (T1 and T2) presented in a rapid stream of letter distractors. After having read the instructions, which included a slow demonstration of the RSVP, and indicating to have fully understood the task, participants went through 24 training trials, which we re-run if participants made more than 50% errors. The fixation mark was shown for 2000 ms and, after a blank interval of another 250 ms, the presentation of the letter-digit stream commenced. Twenty 20 items appeared with a duration of 70 ms each and an inter-stimulus interval of 30 ms.

The position of T1 in the stimulus stream varied randomly between positions 7, 8, and 9, so to reduce predictability. T2 was presented directly after T1 (lag 1), or after another 2, 4, or 7 distracters (lag 3, 5, and 8 respectively). Both targets were to be reported directly (order of report was not considered) after the last item of the stream was presented by pressing the corresponding digit keys. The task was composed by three blocks (144 experimental trials: 3 temporal locations of T1 x 4 lags x 12 repetitions) and took about 15 min. to complete. Participants werethus to switch between the prime and the probe task three times per session.

Results

Participants showed good performance in the Remote Association Task (*M*=8.8 and *SD*=2.8) and the Alternate Uses Task (*M*=18.4 and *SD*=4.6). T1 and conditional T2 (T2|T1) accuracy data were submitted to separate ANOVAs with lag (1, 3, 5, and 8) as a within-participants factor and prime task as between-participant factor. The T1 analysis produced a main effect of lag, *F*(3,57)=35.57, $p<0.001$, MSE = .001, η^2p = 0.65, due to a dip of performance with the shortest lag (accuracy: 89.2%, 96.5%, 95.8%, and 95.0%, for lags 1, 3, 5, and 8, respectively). This pattern is typical for AB tasks in which presentation rate is fast and the two targets belong to the same category and, thus, satisfy the same selection criteria (Colzato, Hommel & Shapiro, 2010; Hommel & Akyürek, 2005; Potter, Staub & O'Connor, 2002).

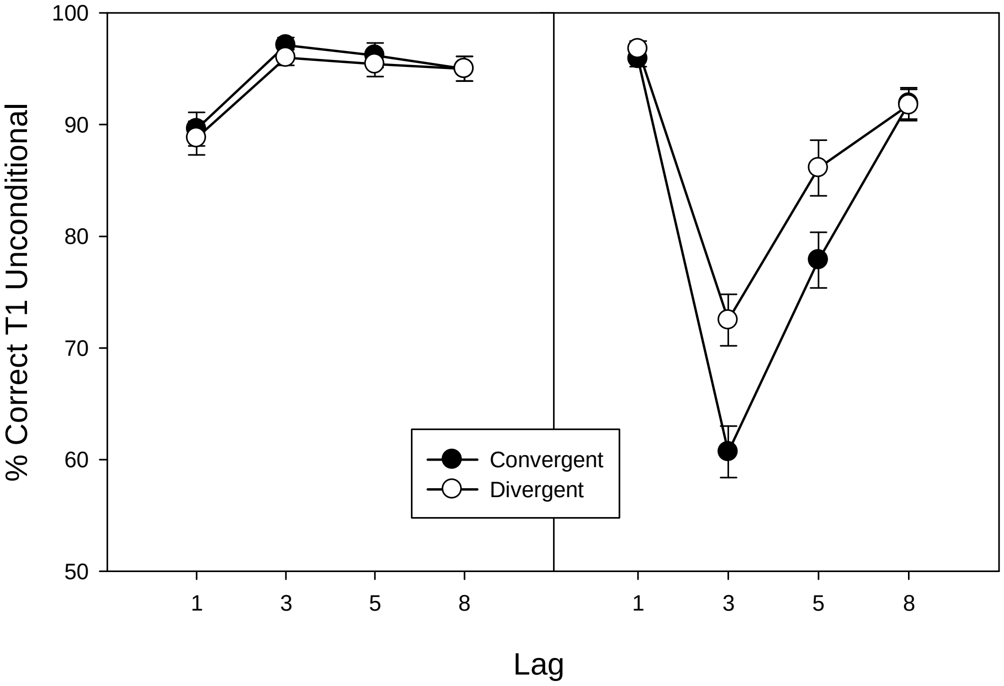

Figure 6: Report accuracy in Experiment 5 for T1 (unconditional) and T2 (given T1correct), as a function of the priming task (convergent vs. divergent thinking).

More importantly, the analysis of conditional T2 accuracy rendered all three effects significant: the main effects of lag, *F*(3,57)=173.88, $p<0.001$, MSE = .004, η^2p = 0.90, and prime task, *F*(1,19)=5.51, $p<0.03$, MSE = .02, η^2p = 0.22, and the interaction, *F*(3,57)=5.42, $p<0.002$, MSE = .006, η^2p = 0.22. The underlying pattern is shown in Figure 6: Whereas the two prime tasks yielded comparable performance at the shortest and longest lag,$F < 1$, a divergent-thinking prime produced better performance than the convergent-thinking prime at lag 3, *F*(1,19)=9.30, $p<0.01$, MSE = .015, η^2p = 0.33, and tended to do so at lag 5, *F*(1,19)=3.95, *p*=0.062, MSE = .017, η^2p = 0.17. In other words, divergent thinking reduced the AB.

The outcome of Experiment 5 was as expected, which suggests that the cognitive control states induced by convergent thinking are beneficial for many but apparently not for all cognitive tasks. Even though it seems clear that some degree of top-down processing must take place in performing an AB task (so to keep the target templates sufficiently active to detect a matching target), this task is likely to suffer from overinvestment of attentional resources (Olivers & Nieuwenhuis, 2006; Shapiro et al., 2006). Our observations confirm that such overinvestment is counteracted to some degree at least by the cognitive set people establish when engaging in brainstorming-like activities. This fits nicely with the previous observations that the AB is reduced if participants assume a more relaxed attitude towards the task (Olivers & Nieuwenhuis, 2005).

GENERAL DISCUSSION

The aim of the present study was to characterize the cognitive-control states that participants establish when carrying out a creativity task by seeking for after-effects of divergent-thinking and convergent-thinking tasks on common, reasonably well understood cognitive tasks. A systematic pattern emerged: convergent thinking benefited performance in the global-local task (Experiment 1), the semantic-Stroop task (Experiment 2), and the Simon task (Experiment 3) more than divergent thinking did. These tasks are suspected to induce conflict between perceptual interpretations, semantic representation, and response codes, respectively, which suggests that the cognitive-control state underlying convergent thinking is well-suited to reduce various sorts of cognitive conflict. As we have suggested, this might be because this control state is characterized by a relatively strong top-down support of task-relevant information and/or by relatively strong local competition between representations of relevant and irrelevant information (Routes 1 and 2). In contrast, the two prime tasks had no specific impact on the ability of participants to inhibit strong response tendencies (Experiment 4). This is inconsistent with any role of inhibitory processes in regulating convergent and divergent thinking (Route 3), at least as far as they are needed for and assessed by the stop-signal task. Finally, we were able to show that the control state induced by convergent thinking is not advantageous for all cognitive tasks. In particular, tasks that can be assumed to benefit from a relaxation of top-down control, such as the AB task, gain more from the control state induced by divergent thinking (Experiment 5).

Taken together, our findings suggest a relatively clear-cut picture, according to which convergent and divergent thinking are associated with specific control states that people can apparently establish on-the-fly. On the one hand, this does not rule out the possibility that some individuals are more able, proficient, or practiced in establishing one or another of these states. In that sense, our findings do not rule out the possibility that some individuals are, or at least can be more creative than others—the trait account of creativity. On the other hand, however, our findings do suggest that creativity is also a matter of inter-individual variability. In other words, the same person can be more or less creative—the state account of creativity.

One important aspect of the pattern we obtained is that human creativity is not a unitary concept. Even though creativity studies have been using versions of our divergent-thinking and convergent-thinking tasks for decades, our findings provide strong evidence that these two types of tasks do not measure the same thing. This also fits with Akbari Chermahini and Hommel's (2010) observation that both types of tasks are related to dopamine but in very different ways and with the conclusion of Baas, De Dreu, and Nijstad (2008) that creativity tasks differ substantially in their sensitivity for particular aspects of creative performance. It may very well be that both convergent and divergent thinking is needed for truly creative activities: divergent thinking presumably more in the leading brainstorming phase that considers all possible options and convergent thinking more in the following phase in which the preferred option is further thought through and worked out. Nevertheless, it seems to make little sense of speaking about creativity as such without referring to specific cognitive or computational functions. Only if these functions can be properly isolated, a realistic functional and neural model of creative performance can be developed.

One limitation of our experimental approach is that it did not provide a neutral baseline, so that it is impossible to say whether better performance after one type of thinking was due to a benefit associated with this thinking style or interference associated with the other style or both. However, this consideration is based on the questionable assumption that a given participant's control state is neutral before entering a psychological laboratory. Note that our experimental rationale could only work because control states are apparently inert and tend to outlive the task for which they were created (Allport et al., 1994; Memelink & Hommel, 2006). This implies that every experimental subject brings mixtures of various control states to the lab—states that were originally created to master the exam the subject was coming from, to overcomethe participant's tendency to smoke after lunch, to avoid distractions on his or her way to the testing room, and so forth. Research on the so-called resting-state activity (Smith et al., 2010) provides strong evidence that even having a participant to do nothing at all creates very specific types of interactions within and between neural networks—control states that is. All we could thus hope for was that our experimental manipulations were pushing the control states of our participants in one or another direction without getting even near to any perfect experimental control. Even though this does not allow addressing all the questions that may remain, it was sufficient to demonstrate that the control states induced by the two types of creativity tasks are different and more compatible with some tasks but not with others.

Considering that convergent and divergent thinking apparently induce different control states and, thus, are supporting performance in different types of tasks, it might be tempting to assume that these control states are opposites, mirror images of each other. In fact, the scenarios we developed in the introduction might suggest that the two critical control routes (1 and 2) are correlated in such a way that cognitive control may alternatively engage in either a strict control style involving strong top-down bias and local competition or in a loose control style involving weak top-down guidance and local competition. Even though such an approach would certainly be attractive in its parsimony, we at this point hesitate to adopt it for at least three reasons implied by the observations of Akbari Chermahini and Hommel (2010). One is that individual performance in convergent thinking and divergent thinking was not correlated, which does not fit with the negative correlation that the unidimensional account would suggest. Second, convergent thinking was more reliably correlated with fluid intelligence than divergent thinking was but, if anything, the two correlations tended to go into the same direction with better convergent and divergent thinking performance with individuals higher in intelligence. Again, a unidimensional account would rather seem to suggest correlations of different signs. And, as mentioned already, both convergent and divergent thinking performance was related to a physiological marker of dopamine production but the two functions obtained cannot be described as the opposites of each other: whereas convergent thinking was linearly related to dopamine (better performance the lower the dopamine level), divergent thinking related to dopamine in an inverted-U shape (best performance with medium levels). Even though it is true that psychological functions might be related to neurochemistry in complicated ways, these different profiles do not provide support for the idea that the control states underlying convergent and divergent thinking are mere mirror images of each other. In any case, more research on this issue is urgently needed.

Our study aimed at characterizing the two arguably most relevant and most often investigated types of creative activity. However, we do not mean to imply that convergent and divergent thinking cover the whole range of human creativity, nor do we think that the two types of control states that we focused on are the only aspects of controlling creative behavior. For instance, Dietrich (2004) made a distinction between deliberate and spontaneous creative processes and between cognitive and emotional knowledge domains within which these processes operate. Considering the nature of our tasks, the present study could thus be characterized as targeting deliberate creative processes operating in a mainly cognitive knowledge domain. Even though Dietrich’s framework is post hoc and has not yet been empirically tested, it is thus possible that our conclusions do not, or not fully, generalize to spontaneous creativity and/or knowledge with a stronger emotional flavor.

Another interesting distinction that has been made with respect to creative processes is that between solutions that are associated with a conscious “Aha!” or insight experience and those that are not (for an overview, see Kounios & Jung-Beeman, in press). Jung-Beeman and colleagues have provided evidence that insight-associated solutions are mediated by different brain areas and that these areas are differentially sensitive to experimental manipulations, such as solution priming (e.g., Bowden & Jung-Beeman, 2003; Jung-Beeman et al., 2004). Given the relatively long-lasting after-effects of creativity tasks in the present study, it makes sense to assume that participants in such insight studies do not switch between different control configurations on a trial-to-trial basis. This suggests that the same control configuration can generate different types of experience and, presumably, allow for different ways to find a creative solution. Which way is chosen in a given trial might be the result of competition between alternative solutions and the differential top-down support they receive. Note that providing strong Route-1 support for one alternative only biases, but does not determine, the ultimate decision, so that sometimes a non-supported alternative might win the competition. If one considers top-down support a kind of expectation, a winning non-supported alternative might be more surprising and more likely to trigger an “Aha!” experience. In any case, it seems clear that future research does not only need to differentiate between different types of processes underlying creative behavior and different types of control states driving these processes, but it also needs to study the manner in which control states exert their control and constrain cognitive competition for the most creative solution.

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