

Convergent and divergent operations in cognitive search

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The phylogenetic development of humans and many other species is characterized by a transition from reactivity to proactivity. In contrast to the dominating experimental paradigm in behavioral and neuroscientific research—where the presentation of experimenter-controlled stimuli are marking the start of theoretical and empirical analysis—humans rarely await environmental triggers to get on their feet but, rather, are driven by internal needs, goals, and passions. Proactive behavior guided by internal anticipations and predictions requires executive functions that operate off-line rather than in real-time. Indeed, planning an action only after having encountered its execution conditions often makes little sense, which is why goalkeepers prepare themselves for jumping, catching, and pushing the ball long before they even see it coming.

Planning an action in the absence of the object and situational cues it relates to requires means to represent and stimulate them in advance (i.e., off-line). This calls for cognitive abilities that go beyond what our basic sensorimotor online systems have to offer—that is, the systems that translate stimulus input into motor output more or less in real-time and that we share to some degree with almost all living organisms. In humans and perhaps in other primates, this reliance of planning ahead on longer-term internal representation has propagated the development of a dual-system architecture. For instance, in humans, manual actions emerge from the interaction between a stimulus-driven sensorimotor online system (mediated by the dorsal pathway; e.g., Milner & Goodale, 1995) and a slower-working (ventral) control system that relates highly processed perceptual information to the construction of goal-related action plans (Glover, 2004; Hommel, Müsseler, Aschersleben & Prinz, 2001a, 2001b). That is, the emergence of off-line systems did not lead to the replacement of online systems, which provides the opportunity to restrict off-line action planning to the specification of the

goal-relevant features of an action but to leave the filling-in of the less important motoric details to the sensorimotor online system (Turvey, 1977).

This distribution of labor requires the acquisition of enduring action representations, that is, of memory traces that capture the main characteristics of successful actions and their consequences. As I will argue, these traces provide the building blocks for off-line action planning, which renders the search through stored action representations an essential part of action control. In other words, action planning requires cognitive search (through possible options) and might have led to the evolution of cognitive search routines that we now can also employ for other purposes, such as searching for perceptual events and through memory. That is, what is commonly considered to represent different types of search operations may all have evolved from action planning, suggesting that they might share the same characteristics (FOOTNOTE 1). In the following, I will indeed argue that all types of cognitive search (be it in searching for perceptual events, for suitable actions, or through memory) share the characteristic of following a fixed sequence of cognitive operations.

Searching for suitable actions

Evolution does not care so much about the deep insights and interesting memories an organism may or may not have but selects for appropriate actions. So how do we identify and select appropriate actions and how do we tailor them flexibly to the situational requirements? In view of the dominating stimulus-response paradigm in the experimental analysis of action control and other cognitive processes, it is not surprising that many theoretical approaches to action selection attribute the greatest responsibility in the selection process to the stimulus. Preparing for an action is viewed as the activation of task-relevant stimulus-response rules or associations, which make sure that processing a task-relevant stimulus leads to the spreading of activation to the associated

response code, so that this code is likely to win the internal competition for controlling the output (e.g., Anderson, 1993; Cohen, Dunbar & McClelland, 1990; Kornblum, Hasbroucq & Osman, 1990). Obviously, this approach presupposes either extensive experience of the agent with the task at hand or some sort of instruction describing which rules are acceptable in a given situation—much like in the standard experimental setup. How people choose actions under less constrained conditions and how they can ever act in the absence of stimuli remains unclear (Hommel et al., 2001a).

=== FIGURE 1 ===

Carrying out an action presupposes the existence of a goal (FOOTNOTE 2), the intention to create a particular outcome by definition. This requires some sort of anticipation regarding the action's outcome, some expectation that the action will be producing particular effects and some motivation to produce them. The question of how these anticipations are created and how they guide the eventual selection of one concrete action has been addressed by two different approaches: the ideomotor approach, which focuses on the perceptual aspects of action outcomes, and the motivational approach, which emphasizes their affective implications.

The ideomotor approach to goal-directed action (James, 1890; for an overview, see Shin, Proctor & Capaldi, 2010) assumes that agents automatically register the perceptual consequences of their movements and integrate the motor patterns underlying the movements with the representations of the consequences they produce (see Figure 1, left panel). Hence, moving in one's environment is assumed to lead to the acquisition of bidirectional associations between movement patterns and codes of their perceptual outcomes. Given this bidirectionality, agents can then use the associations in either direction and thus intentionally reactivate a particular motor pattern by anticipating (“thinking of”) its sensory consequences. The ideomotor approach has

received ample empirical support: Novel action-produced perceptual effects are indeed spontaneously acquired and integrated with the corresponding action in adults, children, and infants, so that effect-related stimuli become effective primes of that action (for an overview, see Hommel, 2009). Brain-imaging studies suggest that the hippocampus provides the bidirectional link between action plans stored in and/or generated by the supplementary motor area and the perceptual representations of action effects in the respective sensory cortices (Elsner et al., 2002; Melcher et al., 2008).

According to the ideomotor approach, translating an intended goal into actual action requires the cognitive representation of the wanted sensory consequences or, more precisely, of the sensory implications of the wanted effect. Once this representation has been formed or activated, the first step of action selection can be considered a kind of feature match: the wanted outcome's sensory consequences (i.e., the description of the action goal) can be matched against the sensory consequences of all the actions in the agent's repertoire (see Figure 1, left panel). The result of this matching operation is the activation of all candidate actions that would be suited to create the intended effect in principle, or at least an effect that is perceptually similar.

Identifying action opportunities is commonly not part of experimental analyses, where the options are almost always specified by the task and/or arbitrarily defined by the experimenter. Accordingly, it is not surprising that this aspect of action selection is not very well understood while much more is known about selection of actions from pre-specified response sets. Apart from the above-mentioned stimulus-centered accounts, which assume some sort of translation of stimulus information into response activation, research on this topic has emphasized two (related) motivational criteria that underlie action selection: reward and efficiency. Generations of learning theorists have pointed out that carrying out some actions provides more reward than carrying out

others, and that this is likely to affect the probability with which an action is selected. Recent neuroscientific findings have provided strong support for the idea that action selection is systematically biased by the anticipation of reward or punishment (Schultz, 2006) and/or the related affective states (Damasio, 1996). Another line of research that has focused on the impact of efficiency on action selection showed that agents prefer action variants that imply less cognitive effort (e.g., Kool, McGuire, Rosen & Botvinick, 2010) and metabolic cost (e.g., Chapman, Weiss & Rosenbaum, 2010). If one considers that both factors represent something like chronic goals and that they are likely to be correlated with specific affective states, these findings seem to fit with the assumption that the anticipation of reward and/or positive affect biases decision-making towards the associated action (see Figure 1, right panel).

Ideomotor and motivational approaches capture important aspects of the internal search for the action that is best suited to reach an intended goal. Interestingly, the purposes that ideomotor and motivational processes seem to serve are complementary (de Wit & Dickinson, 2009): defining which actions would be suited to reach a particular goal (the purpose of ideomotor mechanisms) does not yet provide sufficient criteria for making the eventual selection, while comparing candidate goals with respect to the reward they may provide or the effort they require (the purpose of motivational mechanisms) presupposes some rather limited set of action alternatives that are all suitable in principle. This suggests that ideomotor and motivational mechanisms operate in a sequence, as indicated in Figure 1, with motivational mechanisms selecting from the set provided by ideomotor mechanisms.

In the present context, it is important to note that this suggested sequence of operations implies a succession of two rather different search modes. Ideomotor mechanisms are starting with one representation, the description of the goal, and try to

diverge and activate as many perceptually related representations as possible. In contrast, motivational mechanisms are starting with a limited number of representations and then try to converge onto one optimal solution. In the following, I will discuss evidence suggesting that:

(1) convergent and divergent search operations can be found and distinguished in various types of cognitive search, including the search for perceptual targets and the search through memory for problem solutions;

(2) all these types of search are likely to consist of a fixed sequence of divergent search operations followed by convergent search; and that

(3) convergent and divergent search are likely to require different configurations of cognitive control.

To substantiate these claims, I will proceed by discussing evidence for convergent and divergent search operations in the context of searching for to-be-perceived objects, such as in visual search, and in the context of searching through memorized objects and events, such as with problem solving. I will conclude by suggesting a rudimentary control architecture that may underlie convergent and divergent search and present some evidence supporting this suggestion.

Searching for perceived targets

People tend to spend a great deal of their time on searching for objects and other people, just think of parents looking for their kids or scientists looking for a particular paper that they would swear was on their desk a few minutes ago. Searching for external events has been mostly studied in the visual modality and there is consensus that at least two different types of visual search exist: feature search, such as looking for a red target among green distractors, and conjunction search, such as looking for a green X (i.e., the conjunction of the color green and the shape X) among red Xs and green Os (Wolfe,

1994). These two types of search differ in ease and efficiency: searching for a feature goes fast and is not much affected by the number of distractors, whereas searching for a feature conjunction is slow and highly sensitive to the number of distractors. These different characteristics have motivated the assumption that feature search can proceed in parallel and in a more or less bottom-up fashion, while conjunction search requires serial operations that are under top-down control.

Perceptual search processes are commonly studied and theoretically addressed under complete neglect of action-related processes. The underlying idea is that the control of perceptual search is devoted to input control while action-related processes deal with output control—two types of control that most researchers consider independent and unrelated (Johnston, McCann & Remington, 1995). And yet, recent observations tend to undermine this implicit conviction. As summarized elsewhere (Hommel, 2010), a number of findings suggest that the efficiency of searching for a particular feature depends on the action carried out to signal the presence of the target or of actions that are being planned in the context of the search operation. For instance, searching for shape-defined targets is more efficient after preparing a grasping action, whereas searching for location- or intensity-defined targets is more efficient after preparing a pointing action (Fagioli, Hommel & Schubotz, 2007; Wykowska, Schubö & Hommel, 2009). Hence, visual search is modulated by, and can thus not be independent of action planning.

=== FIGURE 2 ===

The reason why action planning and search are related may have to do with the distribution of labor between the off-line perception-action system and the online sensorimotor system discussed above (Hommel, 2010). While this distribution makes action planning and execution more flexible, it also raises a number of serious control

problems. For instance, how does the sensorimotor system know which information is relevant for steering the motor activity selected by the perception-action system? As Wykowska et al. (2009) and Hommel (2010) have suggested, this problem might be solved by the perception-action system through increasing the gain of feature information coming from action-relevant feature dimensions (see Figure 2). For instance, when preparing for a grasp, the perception-action system might increase the weight given to feature values coming from feature maps coding for shape and orientation, whereas preparing for a pointing action might lead to stronger weighting of feature values coded on location maps. Interestingly, the stronger weighting of stimulus attributes coded on feature maps that provide task-related information has been assumed to represent the mechanism underlying the attentional control of search processes (e.g., Found & Müller, 1996; Wolfe, Butcher, Lee & Hyle, 2003). If the functionality attributed to this mechanism is what action control provides, it makes sense to assume that what we call visual attention is a phylogenetic derivative of action control (Hommel, 2010), which again would render observations of interactions between action control and attention less surprising than it might seem.

If visual attention is really an evolutionary byproduct of improving action control mechanisms, one would expect that perceptual search processes are showing the same characteristics as action control. If thus the search for the right action proceeds through a sequence of divergent and convergent search operations, one would expect the same sequence for perceptual search. That seems to be far-fetched at first sight, especially if we consider the classical paradigms employed to study feature and conjunction search. Take, for instance, a display in a typical feature-search task: in which sense would searching for a red circle surrounded by twenty green circles require any sequence of divergent and convergent processes?

And yet, single-cell recordings in monkeys provide considerable evidence for such a sequence (Lamme & Roelfsema, 2000). Facing a number of stimuli is assumed to trigger a nonselective (i.e., not yet attentionally modulated) spread of neural activation throughout the visual cortex all the way up to frontal areas—the so-called “fast feedforward sweep”. It is so fast that after about 100 ms even the highest levels of visual coding (i.e., brain systems coding for complex stimulus characteristics and stimulus identities) have responded to a presented stimulus. Neuroscientific methods allowed for following the spread of stimulus-induced activation throughout the entire brain and revealed that the speed of spreading is mainly determined by the brain's hierarchical structural and functional architecture—with each layer adding about 10 ms (Lamme & Roelfsema, 2000; Tovee, 1994). Neurally speaking, the fast feedforward sweep can be considered decidedly divergent, as it activates as many stimulus-related representations as possible, presumably including various alternative interpretations of a given stimulus (Marcel, 1983), and it activates representations of currently relevant, attended stimuli and stimulus features no more than representations of irrelevant stimuli and features. Even so, this nonselective spread of information might well be sufficient for performing a number of tasks, such as the detection of the presence of a particular feature (Treisman & Gelade, 1980).

The visual fast feedforward sweep is reliably followed by a second phase of neural activation with entirely different characteristics. This so-called “re-current” processing wave works its way back to early visual areas and it differentiates between relevant and irrelevant (attended and unattended) information by selectively enhancing that part of the sweep-induced activation that relates to the relevant stimulus (features) (e.g., Chelazzi, Miller, Duncan & Desimone, 1993; Lamme & Spekreijse, 1999). This re-current wave is apparently necessary for the emergence of conscious representations

(Lamme, 2003) and for the segregation and integration of stimulus features (Lamme, 2003; Lamme & Roelfsema, 2000). This implies that the fast feedforward sweep may often be sufficient to detect particular features but that searching for feature conjunctions requires re-current processing. If we consider that the latter serves to integrate stimulus features, this scenario perfectly fits with the feature-integration theory (FIT) suggested by Treisman and Gelade (1980). As FIT implies, searching for a feature may be mastered by monitoring the activation level of dedicated feature maps. If the monitored level increases during the feedforward sweep the participant does not need to await the re-current processing wave to give a response. This can explain why the search for simple features is often fast and insensitive to the number of distractors. When searching for conjunctions of features, however, detecting the presence of a particular feature is insufficient. Rather, the features making up the conjunction would need to be integrated, which according to FIT is a serial process—so that search time increases with the number of visible objects being considered. If we consider that the re-current processing wave is selective and converging onto one given object, conjunction search may indeed require a whole sequence of convergence operations, that is, a sequence of re-current waves targeting alternative objects.

As we can see, at least conjunction search can be characterized as a sequence of divergent processing (the fast feedforward sweep) followed by a convergent processing (the re-current wave). But what about feature search? It is interesting to note that this kind of search does not really capture the ecological essence of everyday search performance. People are commonly looking for objects or people that in some cases may have features with a particular pop-out quality but are not selectively defined by them. Hence, we rarely search for single features. And yet, if we have to serially process a visual scene in order to locate a conjunctively defined target, we do not scan the scene

randomly but are guided by features that are part of the conjunction (Wolfe, 1994). This suggests that the main function of the divergent feedforward sweep is to determine the feature database that the following convergent operations can use to home in onto possible targets. We can thus conclude that at least the bulk of everyday visual search can be aptly characterized as a sequence of a divergent, stimulus-driven spread of activation—an operation that seems to serve the purpose of identifying as many candidate targets as possible—followed by a convergent, goal-driven selection of one specific event representation. Exactly as in the case of searching for appropriate actions.

Searching for solutions

Even though the ultimate purpose of selecting to-be-perceived targets and to-be-produced actions relates to external, environmental states of affairs, the search operations involved are without exception targeting internal representations. As we have seen, some characteristics seem to be shared by search operations aiming at representations of currently perceived events, as in visual search, and search operations aiming at representations of future events, as in action planning. Given that the representations are likely to differ in various ways, this commonality is remarkable and suggests that the characteristics we can identify are not restricted to direct interactions with our environment.

Indeed, divergent and convergent operations can also be found in problem solving and similar, entirely internal search processes. Particularly obvious is their existence in the domain of creative thinking. Even though the importance of human creativity cannot be overestimated, the processes underlying it are understudied and poorly understood (Sternberg, Kaufman & Pretz, 2002). In part, this is due to strong traditions in this field that either focus on creativity as a personal trait—hence, as a characteristic that a given person does or does not have, or emphasize the product, rather than the functional

characteristics, of the creative process (see Brown, 1989; Runco, 2007). Only more recently, authors tend to agree that truly creative acts do not reflect the operation of just one process, brain area, or intellectual faculty but, rather, the interplay of multiple cognitive processes and neural networks (e.g., Dietrich, 2004; Eysenck, 1993; Heilman, 2005). And yet, there is no agreement as to what these processes and networks might be and how they are to be identified.

Guilford (1967) was one of the first to distinguish between two basic types of thinking that might underlie creative acts. For one, divergent thinking serves the purpose of producing as many possible solutions to one given problem as possible and, for another, convergent thinking serves to find the one with the most optimal solution to problems that require the satisfaction of multiple constraints. Two classical tasks provide good examples: The Alternate Uses Task (Guilford, 1967) requires participants to name as many appropriate uses of a simple object, such as a pen, as possible, which calls for a literal “brainstorm” through memory; in contrast, the Remote Associations Task (Mednick, 1962) presents participants with three concepts (e.g., time, hair, and stretch) per trial, who are then to identify the one concept that is related to all three (long).

Unfortunately, the distinction between divergent and convergent thinking is not often heeded in creativity studies, which often employ divergent tasks (for overviews and discussion, see Baas, De Dreu & Nijstad, 2008; Davis, 2009), but sometimes also convergent tasks (e.g., Isen, Daubman & Nowicki, 1987) or ad-hoc developed and difficult-to-categorize tasks to study “the creativity” (for an overview, see Plucker & Makel, 2010). This seems particularly problematic as divergent and convergent thinking not only differ with respect to their computational goals but also seem to rely on different functional and neural mechanisms (cf., Dietrich, 2004). A first hint is provided

by the observation that individual convergent-thinking performance is not correlated with divergent-thinking performance (Akbari Chermahini & Hommel, 2010) and that performing convergent- and divergent-thinking tasks induce opposite mood states (Akbari Chermahini & Hommel, 2011). Moreover, there is evidence that divergent-thinking performance relates to the individual dopamine level of participants in the form of an inverted U-shape, with medium levels allowing for the best performance, whereas convergent-thinking performance shows a linear, negative relationship with dopamine levels (Akbari Chermahini & Hommel, 2010).

Even though many researchers have focused on one type of creative thinking or the other, entire creative acts like the invention of a new tool or the conception of a new painting are likely to require both: a first phase of brainstorming that identifies as many options as possible and a subsequent phase of zooming into one option and thinking it through. Indeed, Wallas (1926)—as various authors since—suggested that creative acts run through four stages including (1) preparation, where the problem is investigated; (2) incubation, where the problem is thought about unconsciously; (3) illumination, where ideas come together to form a possible solution; and (4) verification, the stage in which the chosen option is evaluated and confirmed. Even if more processes are likely to contribute to a creative act, it makes sense to characterize the first two stages as emphasizing divergent processes and the final two stages as emphasizing convergent processes.

Control states underlying convergent and divergent search

Summarizing the discussion so far, there is increasing evidence that convergent and divergent search operations can be observed in a broad range of cognitive activities, including the search for perceptual events, the search through problem-solving solutions, and the search through representations of possible actions. We have also seen

that these two types of operations seem to come as a fixed sequence with divergent search being followed by convergent search—a sequence that may sometimes be cycled through repeatedly, such as when the sought-for target, action alternative, or memory is not found and/or when goals are changing. Moreover, there are reasons to assume that the two types of search operations are controlled by different cognitive-control states. Let us now consider how these states may be characterized.

=== FIGURE 3 ===

Figure 3 sketches the basic idea underlying many biological models of decision-making (for a review, see Bogacz, 2007). Most models assume that representations of alternatives, such as A and B in the figure, are competing with each other. As alternative decisions are commonly mutually exclusive, collecting more evidence for, or increasing the tendency towards one alternative increases the activation of the corresponding representation (e.g., of A), which again leads to the suppression of other alternatives (such as B). If the evidence is clear-cut, decision-making might run off automatically: at some point, sufficient evidence is collected for one of the alternatives and/or the competing alternatives have received sufficient suppression, so that the winner can be determined. However, biological systems are noisy and evidence is not always as clear-cut as one might wish, so that many authors have assumed contributions from top-down processes that bias decision-making towards goal-consistent solutions (e.g., Duncan, Humphreys & Ward, 1997).

This scenario suggests that different control states might be created by modulating the strength of the top-down bias (control route 1) and/or local competition (control route 2; see Colzato et al., 2008). Strengthening top-down bias and/or increasing local competition would establish a relatively “convergent” control mode that goes for singular targets and “exclusive” decision-making. In contrast, relaxing top-down control

and/or decreasing local competition would establish a relatively “divergent”, integrative control mode that is able to tolerate the selection of multiple targets. Such focused and relaxed control modes may underlie convergent and divergent processing in perceptual search, creative thinking, and action selection, and thus represent general control states of the human cognitive system.

Interestingly, similar pairs of states have been claimed to exist in other cognitive domains as well. For instance, both functional (Dreisbach & Goschke, 2004) and neuroscientific (Cools, 2008; Cools & d’Esposito, 2009) considerations suggest that executive control seeks for a balance between two extreme control states: one mode that guarantees the stability of goal representations in the face of obstacles and resistance and another mode that allows for giving up and trading the present goal for a more reasonable or promising alternative. Cools and d’Esposito (2009) suggest that the stability part of this delicate balance might be mediated by the prefrontal dopaminergic pathway, whereas the flexibility part is mediated by the striatal dopaminergic pathway. It is interesting to note that the prefrontal mechanisms that Cools and d’Esposito consider relevant for maintaining stability has also been assumed to provide the top-down bias in competitive decision-making (Desimone & Duncan, 1995), which might suggest that there is a tight relationship between the control modes responsible for stability and for convergent thinking. Indeed, the individual efficiency of both top-down control (Duncan, Emslie, Williams, Johnson & Freer, 1996) and convergent thinking (Akbari Chermahini & Hommel, 2010) has been reported to correlate with intelligence. Reversely, a behavioral genetics study revealed that individuals with the DRD2 TAQ IA polymorphism (which results in a 30-40% reduction in DA-D2 receptor density—the receptor type mainly found in the striatal dopaminergic pathway) show significantly better performance in divergent thinking (Reuter, Roth, Holve, & Hennig, 2006). This

fits with the fact that antipsychotic D2-antagonistic drugs affect the so-called “positive symptoms” of schizophrenia, which have been described as a kind of “widening of the associative horizon” (Eysenck, 1993). It thus seems that the functional dialectic between convergent and divergent operations is mirrored to at least some degree in the relationship between stability and flexibility, and this seems to imply some overlap of the underlying neural substrate. Nevertheless, until now the logic of the stability-flexibility concept has been applied to action goals only, whereas the convergent-divergent concept can potentially be applied to any type of decision-making—be it between to-be-attended targets, memory traces, representations of alternative actions, or goals. However, given that the search for a target, memory item, or action needs to be goal-directed, decisions between goals need to precede, and selected goals need to outlive, more specific decisions—which requires at least some sort of temporal hierarchy of decision-making (cf., Hommel, 2009).

A similar, possibly related pair of control states has been referred to as exploitation and exploration modes (e.g., Cohen, McClure & Yu, 2007; Daw et al., 2006). The concepts of exploitation and exploration are almost identical to what other authors have referred to as stability and flexibility, but exploitation-exploration approaches have focused more on the strategies driving control towards one or the other pole of this dimension and the information and neural signals informing such strategies. Moreover, while dopamine has been assumed to control the balance between stability and flexibility (Cools & d’Esposito, 2009), the control of the balance between exploitation and exploration has been attributed to norepinephrine (Aston-Jones & Cohen, 2005). It is assumed that expectations and uncertainty are important parameters, with moderate degrees of certainty and expected uncertainty propagating exploitation, and perfect certainty and unexpected uncertainty propagating exploration (Cohen et al.,

2007). Future research would need to test the interesting hypothesis that the same information that propagates exploitation also induces a convergent operation style, while information that propagates exploration induces a divergent operation style.

If we assume that comparable convergent and divergent search modes exist in perceptual search, memory search, and action selection, and that in all these cases the search modes are controlled by the same cognitive-control states, one would expect specific interactions between all sorts of tasks that are likely to require the establishment of such control states. In particular, one would expect that interleaving or quickly switching between any two tasks would yield better performance if they call for the same (focused or relaxed) control state than if they imply different states. Two recent studies suggest that this is indeed the case.

Hills, Todd, and Goldstone (2008) demonstrated that participants who in a visual foraging task searched through clumpier distributions in space spent more time on constructing possible words from a set of letters in a Scrabble task. A possible interpretation is that a clumpier environment is more likely to propagate a convergent control style than a more diffuse distribution of possible targets, and that a convergent style would lead to more endurance when working on a Scrabble problem. Along similar lines, Hommel, Akbari Chermahini, van den Wildenberg, and Colzato (2011) had participants switch between blocks of convergent- and divergent-thinking tasks and other tasks that are commonly taken to tap into cognitive-control processes. Tasks that can be suspected to require rather strong top-down control—like Navon's (1977) global-local task, the Stroop task, and the Simon task—yielded better performance if being mixed with a convergent-thinking than with a divergent-thinking task. This fits with the prediction that both types of tasks rely on a rather focused control mode and therefore benefit more if being mixed with each other than with a task that calls for a

relaxed mode, such as the divergent-thinking task. Hommel et al. also employed the Attentional Blink task, which has been suspected to benefit from lesser top-down control (Olivers & Nieuwenhuis, 2006; Shapiro et al., 2006). As predicted, this task yielded better performance if being mixed with a divergent-thinking task.

Conclusion

The evolutionary emergence of a cognitive off-line system that allows for both the anticipation and the generation of external events has made perceivers/agents more or less independent from the current situational circumstances and rendered them proactive rather than reactive. Proactive processes require choices, however, and choices imply the search for a suitable or, ideally, even the best option. Accordingly, humans have developed search strategies that, as I have argued, follow two different goals. Divergent search operations identify useful and feasible options without necessarily relating them, whereas convergent search operations try to pick the best (i.e., most rewarding and/or least demanding) option from this restricted set. There is evidence that these two types of operations can be found in perceptual and memory search, as well as in action selection—hence, in all sorts of searching through cognitive representations. Moreover, there is evidence that these two operations differ with respect to the neural underpinnings and that they are controlled by dissociable control states.

The observed similarities across various sorts of search processes are suggestive of a common phylogenetic source and I have speculated that the emergence of the ability to plan actions prospectively (i.e., off-line, in the absence of response-triggering external cues) was the driving force. If planning involves decision-making between alternative stored action representations, it can be considered a process of cognitive search, and it is possible that it represented the prototype for the development of other types of cognitive search (Hommel, 2010). What I did not discuss was how the ability to

plan ahead evolved. An interesting possibility is discussed in the chapter of Hills and Dukas (2011). They suggest that cognitive search—the internal matching of a number of representations against some goal-relevant representation—might represent the internalization of the ability to overtly search the environment (Hills et al., 2008). In other words, cognitive search through object and event representations might in some sense simulate overt, active search for external objects and events. This view is consistent with my suggestion that action control is the prime mover in the evolution of cognitive search (and other attentional operations: Hommel, 2010), and it may help generalizing the present discussion to the analysis of cognitive skills and processes in general.

Moreover, Hills and Dukas' (2011) perspective points to a possible origin of the divergent-convergent sequence in cognitive search operations that I have considered. Overt search, as in food foraging behavior, logically and empirically alternates between (overt) exploration (looking around for possible food) and exploitation (collecting and/or eating the food). The cognitive control of overt exploration behavior is likely to require a more divergent decision-making style, as discussed above, while the control of overt exploitation calls for a convergent style. This implies a systematic sequence of action-control styles over time, commonly beginning with the divergent control style, followed up by convergent control. If so, seeing the same sequence in various versions of cognitive search seems to be a logical consequence of the internalization of overt search behavior into a cognitive skill.

Footnote

1. From the perspective of a cognitive system, there is indeed no logical difference between, say, searching for a visual target, searching for (i.e., retrieving) one's memory of one's last birthday present, searching for (i.e., selecting) an action alternative suitable to produce a particular song by means of a keyboard, searching for a particular metaphor, or searching for the possible uses of a pen. In all these cases, the searcher consults internal representation of past and/or present events and matches their content against some sort of search template, which represents the target or intended outcome, until some reasonable match is obtained. In that sense, there is no logical reason to believe that the cognitive operations underlying visual search, memory search, action selection, the production of options in verbal planning and creativity or problem-solving tasks differ in principle, and I know of no empirical evidence enforcing this assumption either.

2. In this article, I will make the uncontroversial assumption that all sorts of cognitive search, including perceptual search and action selection, are under the control of goals. How, according to which principles, and by what kind of mechanism goals are searched for and identified will not be discussed. However, it may well be that what I consider a goal is no more than the next level of what is actually a multi-layered decision-making hierarchy. Accordingly, goals might be selected according to the same principles, and by means of the same mechanisms, that are involved in selecting a visual target or a manual action.

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Captions

Figure 1: The distribution of labor between (A) the pre-selection of actions (from motor patterns m_1 - m_9) that are associated with goal-related action effects (B in this example) and (B) the weighting of the pre-selected actions according to the affect the state they are expected to produce, with chronic goals biasing this process towards alternatives satisfying them (with m_5 being the most likely candidate for execution in this example).

Figure 2: A process model of action-induced attention, taken from Hommel (2010). Feature maps provide information for off-line perception and action planning and for online specification of open action parameters. Note that the output gain is modulated by the perception-action system, so that information from goal-relevant feature maps has more impact on sensorimotor processing.

Figure 3. Possible mechanisms involved in decision-making. The goal-relevant alternative A is supported by the goal representation (1) but competes with choice alternative B through mutual inhibition (2). In addition to the competition bias is provided by the goal (1).





