V.4 Metacontrol

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Abstract

This chapter introduces the concept of metacontrol, the ability to balance one's cognitive-control style between persistence and flexibility. It is explained how the metacontrol concept differs from the traditional idea of cognitive control, which captures persistence, but not flexibility. Recent findings are discussed that show how metacontrol and metacontrol adjustments to the current task and context affects information processing in general, in addition to findings that suggest particular neurophysiological underpinnings and mechanisms of metacontrol. Finally, the chapter discusses how binding and retrieval might be specifically affected by metacontrol biases towards persistence or flexibility.

V.4.1 Control and metacontrol—a conceptual clarification

In Chapter V.1, the concept of cognitive control was introduced to explain how specific cognitive processes can be tailored to meet particular task demands. Humans possess a wide variety of cognitive processes and skills, but each task requires a unique combination of these, as well as a specific way of applying them to process information efficiently, achieve goals, and adapt optimally to environmental circumstances.

Traditional models of cognitive control, however, are limited in scope. They often emphasize only one type of control challenge, a focus largely inherited from the theoretical construct of attention. Research on attention typically begins with the observation that humans encounter far more information than they can possibly process. Our physical and social environments provide an overwhelming amount of potential input, so we must selectively attend to the information most relevant to our current goals. Because humans are goal-directed beings, it follows that information selection should be guided by our goals and intentions. This view has led to the influential idea of attention as a filter, prioritizing goal-related information while suppressing irrelevant input.

While attention can thus be understood as governing information selection, the broader concept of cognitive control extends this logic to both information processing and action selection. Just as we cannot process all available information, we also have many potential responses to any given situation. Cognitive control imposes the necessary constraints to guide response selection (Norman & Shallice, 1986), increasing the likelihood that we choose actions best suited to current demands. Moreover, cognitive control coordinates the processes that bridge stimulus processing and response selection—such as attention, memory, elaboration of stimuli, evaluation of possible responses in light of norms or risks, and even affective processes like emotion regulation.

Yet, the traditional view of cognitive control is narrow, with a strong emphasis on constraints and restrictions in processing. Such constraints are indeed often beneficial. For example, when preparing for an exam in a noisy library or during a dormitory party, it is advantageous to focus on what is strictly necessary and relevant, and to suppress distractions unrelated to studying. However, in other contexts, restricting information flow may be counterproductive. Imagine a flight struck by a hurricane, forcing the pilot to land in a desert. Rigidly adhering to prior goals or routine problem-solving strategies would be maladaptive under these circumstances; instead, novel strategies and flexibility are essential. The same holds true for everyday situations like brainstorming or managing unforeseen challenges. Thus, the traditional model of cognitive control captures only one side of the coin: conditions where persistence, focus, and suppression of irrelevant input are useful. It neglects contexts where flexibility, openness, and exploration are crucial.

In recent years, various scholars have emphasized the need for a more comprehensive approach to cognitive control. Friedman, Miyake, and colleagues (2000; Friedman & Miyake, 2004) expanded the construct to include distinct components: inhibition (suppressing incorrect responses), updating (maintaining current working memory contents), and shifting (switching between task sets). Goschke (2003) highlighted so-called cognitive-control dilemmas, where traditional control strategies can be counterproductive. Similarly, Cools (2006, 2008; Cools & D'Esposito, 2011) proposed that cognitive control depends on contributions from two separable dopaminergic pathways: the mesofrontal pathway (ventral tegmental area → prefrontal cortex) and the nigrostriatal pathway (substantia nigra → striatum). Durstewitz and Seamans (2008) reached similar conclusions from a computational neuroscience perspective.

Building on these insights, Hommel and colleagues (Hommel, 2015; Hommel & Colzato, 2017; Hommel & Wiers, 2017) developed the Metacontrol State Model (MSM). According to this model, people can adapt their style of cognitive control to current circumstances by adjusting how control operates. The traditional concept of cognitive control can be understood as one extreme of a broader continuum—a metacontrol bias toward persistence. At the opposite pole lies cognitive flexibility. The term *metacontrol* emphasizes that it refers to regulating the mode in which control is applied—literally, "control of control." Importantly, metacontrol does not replace cognitive control itself; rather, it modulates the style in which cognitive control shapes processing and behavior. The MSM thus situates the traditional model as one end of a persistence–flexibility spectrum, providing a more complete account of human adaptability.

Before we have a look at the available research on how individuals navigate from metacontrol persistence to flexibility, and back, let us first consider when and under which circumstances one would expect persistence or flexibility to dominate. On the one hand, many tasks and challenges in cognitive, motivational, and clinical research require individuals to focus on relevant, and to ignore irrelevant information and other kinds of distraction, to stick with their current intentions and to resist external temptation, to keep digging into an important problem that needs to be solved, or to maintain their plans over some time. Under all these circumstances, individuals would be well-served by biasing their processing style towards persistence, even if they may not be willing to give up all flexibility altogether. Hence, under such circumstances, one would expect people to bias their metacontrol towards persistence and people with a natural bias towards persistence to perform particularly well. On the other hand, however, other tasks and challenges suggest a much greater portion of flexibility. Think of individuals facing unsurmountable problems, people in dysfunctional relationships or with unrealistic plans for the future, inventors interested in out-of-the-box solutions and innovation, or those suffering from endless ruminations. Individuals under such conditions would be well-served by biasing their metacontrol towards flexibility, which helps them to “let go”, and those with a natural bias towards flexibility should deal more effectively with such problems and issues.

V.4.2 Functional mechanisms of metacontrol

The key to understanding how metacontrol shapes the operation of cognitive control lies in its relation to content. Cognitive control must account for which stimuli are available in a given situation, which responses are appropriate, and which intermediate processes are needed to link stimuli and responses. In other words, cognitive control depends on content-specific representations—of events to be processed and events to be generated.

Metacontrol, however, operates differently. If, as several authors have argued, metacontrol is mediated by neurotransmitters such as dopamine, it is important to note that these substances diffuse broadly throughout the brain and affect many processing components. This makes it unlikely that metacontrol can be localized in a specific brain region or that it operates on particular representations. Instead, metacontrol influences the overall style of information processing across the system.

Hommel and Colzato (2017) suggested one possible mechanism, building on Bogacz’s (2007) review of biologically plausible neural models of decision-making. According to Bogacz, all such models rest on two principles. First, decision-making is competitive: Neural representations of alternatives inhibit one another, and the ultimate choice emerges from this mutual suppression. Second, decision-making is goal-sensitive: Alternatives consistent with current goals receive additional support, making them more likely to prevail. Hommel and Colzato proposed that metacontrol moderates the degree to which these two principles shape decisions. Under extreme persistence, both goal-biasing and competition are maximized, enabling strong suppression of irrelevant information and tight focus on goal-relevant options. Under extreme flexibility, both are minimized, allowing unselected alternatives to remain active and enabling rapid switching from one option to another (see Figure 1).

*** FIGURE 1 ***

Support for the Metacontrol State Model (MSM) comes from evidence of both intra-individual and inter-individual differences in metacontrol biases. For example, individuals with a genetic predisposition favoring information processing in prefrontal regions perform especially well on persistence-heavy tasks, whereas those with a predisposition favoring striatal processing excel at flexibility-heavy tasks (for review, see Hommel & Colzato, 2017). Culture also plays a role: Individuals from more individualistic societies or with more individualistic religious backgrounds tend to perform better on persistence-heavy tasks, while those from collectivistic cultures or religious traditions tend to excel in flexibility-heavy tasks (for review, see Hommel & Colzato, 2017). These findings suggest that people differ in their default metacontrol bias—some leaning toward persistence, others toward flexibility.

At the same time, people can dynamically adjust their metacontrol bias in response to situational demands. For instance, positive mood has been shown to bias individuals toward flexibility (e.g., Dreisbach & Goschke, 2004; van Steenbergen et al., 2009, 2010), consistent with evidence that positive affect increases striatal dopamine levels. Similarly, different forms of meditation bias metacontrol differently: Focused-attention meditation improves performance on persistence-reliant tasks (Lutz et al., 2008), whereas open-monitoring meditation enhances performance on flexibility-reliant tasks (Lippelt et al., 2014). In addition, priming individualistic versus collectivistic orientations—for example, by having participants process personal versus relational pronouns—induces context-insensitive, focused processing and reduces the likelihood of integrating bystanders into self-representations (Kühnen & Oyserman, 2002; Colzato et al., 2012). Furthermore, as will be discussed in the next section, neurophysiological analyses indicate that persistence-demanding and flexibility-demanding tasks elicit distinct patterns of neural activity.

Together, these findings suggest that people can shift their metacontrol bias toward persistence or flexibility within seconds—or even milliseconds—depending on task requirements. At the same time, individuals differ in their default positions on the persistence–flexibility continuum. How these intra-individual adaptations and inter-individual defaults interact remains an open question. A study by Mekern et al. (2019) suggests that, if personal defaults play a role, they can be rapidly overridden by task-specific demands. In this study, individual tendencies to cluster or switch responses across multiple tasks did not correlate across tasks, indicating that situational task demands exert a stronger influence than stable personal preferences. On the other hand, there are also findings that suggest a stronger role of inter-individual differences. For instance, Akbari Chermahini and Hommel (2010) found that performance in a divergent thinking task (which should rely on flexibility) relates to the spontaneous eye blink rate (a marker of striatal dopamine, see next section) in an inverted U-shaped manner. That is, individuals with medium blink rates outperformed those with low or particularly high blink rates. This suggests that some people might benefit more from particular interventions, like mood induction dopaminergic medication, than others. Indeed, inducing positive mood improved performance in low, but not in high blinkers in the Akbari Chermahini and Hommel (2010) study.

It is important to note that other authors have suggested additional functional mechanisms that may underlie metacontrol. For instance, biases towards persistence might increase the updating threshold for information sent to working memory, whereas biases towards flexibility might lower this threshold (Eppinger et al., 2021). Also, whether and when shifts of the bias are initiated may not only depend on the present stimulus but also on contextual learning (Siqi-Liu & Egner, 2020) and expected reward (Dreisbach & Fröber, 2019). Finally, some have argued that metacontrol might not vary on one single dimension (from persistence to flexibility), but that persistence and flexibility might operate independently (Egner, 2023; but see Hommel et al., 2024).

V.4.3 Neural mechanisms of metacontrol

So far, we have seen evidence that a bias toward metacontrol persistence corresponds to stronger mutual competition between alternative representations and greater support for goal-compatible options, whereas a bias toward metacontrol flexibility corresponds to weaker competition and reduced goal support. But how are these functional characteristics implemented in the human brain? Two sets of findings provide initial insights into the possible neural mechanisms underlying metacontrol.

The first set of findings concerns the widely held assumption that metacontrol emerges from the contributions of, or interactions between, two systems: a prefrontal system, driven by the dopaminergic pathway originating in the ventral tegmental area, and a striatal system, driven by the dopaminergic pathway originating in the substantia nigra (Cools, 2006, 2008; Durstewitz & Seamans, 2008; Hommel & Colzato, 2017). As noted earlier, studies on genetic predispositions and task performance are consistent with this framework: Predispositions favoring prefrontal processing benefit persistence-heavy tasks but impair flexibility-heavy ones, whereas predispositions favoring striatal processing show the opposite pattern (for a review, see Hommel & Colzato, 2017). This is further supported by findings that spontaneous eyeblink rate—an indicator of striatal dopamine levels (Karson, 1983)—predicts divergent thinking (flexibility-heavy) but not convergent thinking (persistence-heavy; Akbari Chermahini & Hommel, 2010). Moreover, engaging in divergent-thinking tasks increases positive mood (Akbari Chermahini & Hommel, 2012a), and inducing positive mood increases spontaneous eyeblink rate (Akbari Chermahini & Hommel, 2012b). Together, these findings are consistent with claims of a mechanistic overlap between striatal dopamine levels, positive mood, metacontrol flexibility, and performance in flexibility-dependent tasks—even though the underlying neurochemistry is likely to be extremely complex, especially because dopamine interacts with serotonin.

The second set of findings relates to recent research on neural noise. Electrophysiological studies on the neural basis of cognitive processes, including cognitive control, have traditionally focused on periodic activity. Neural communication is assumed to rely on rhythmic oscillations that synchronize activity across systems, with different frequency bands (e.g., alpha, beta, gamma) supporting different forms of communication (Fries, 2005). By contrast, aperiodic activity was long dismissed as noise—something to be ignored or filtered out. However, recent work in physics has suggested that neural noise, or aperiodic activity, may play an important functional role in regulating brain activity. The development of a mathematical index—the aperiodic exponent—has made it possible to quantify this activity. A high exponent reflects lower levels of broadband neural activity (i.e., less cortical noise), whereas a low exponent reflects higher levels of such activity. Importantly, the aperiodic exponent has been shown to track the brain's excitation–inhibition balance: Higher exponents reflect stronger inhibition, while lower exponents reflect stronger excitation.

This perspective has direct implications for metacontrol (as also acknowledged by Musslick & Cohen, 2021; Musslick et al., 2025). Under persistence-biased processing (Figure 1A), with strong goal support and stiff competition between alternatives, we would expect relatively low neural noise (=high exponent), because neural activities are strongly focused on just one or only a few alternatives, which quickly outcompete other candidates. Under flexibility-biased processing (Figure 1B), with weaker support and competition, we would expect greater neural noise (=low exponent), because mutual inhibition is weak, so that many competitors are active at the same time. Recent studies support this prediction. For example, Zhang et al. (2023) found that persistence-demanding task conditions were associated with a higher aperiodic exponent, indicating less cortical noise. Moreover, Pi et al. (2024) showed that task-induced adjustments of the exponent were more pronounced in individuals with lower resting-state exponents, suggesting that stimuli are especially effective at driving task adaptation when baseline cortical noise is less optimal.

Additional evidence comes from pharmacological and stimulation studies. Dopaminergic drugs and brain-stimulation techniques known to increase the brain's signal-to-noise ratio have been found to enhance adjustments of the aperiodic exponent to persistence demands (Gao et al., 2024, 2025). This supports the idea that dopaminergic pathways regulate metacontrol by modulating the balance between signal and noise. Developmental studies also provide converging evidence: Pi et al. (2025) observed a systematic decrease in aperiodic activity from childhood to adulthood, likely reflecting maturation of the prefrontal cortex. At the same time, the ability to flexibly adjust cortical noise to task demands increased with age. Adults did not lose the ability to shift noise levels but instead used it more strategically. While most studies report stimulus-induced increases in the aperiodic exponent during persistence-demanding tasks, reductions have also been observed in flexibility-heavy contexts such as task-switching (Yan et al., 2024).

Taken together, the evidence suggests that metacontrol depends on the interaction of dopamine-driven prefrontal and striatal systems and on the brain’s ability to adjust cortical noise, as indexed by the aperiodic exponent, to match task demands.

V.4.4 The impact of metacontrol on binding and retrieval

We have seen that metacontrol varies both within and between individuals, that it can be characterized as a bias toward persistence or flexibility, that it depends on prefrontal and striatal systems targeted by dopaminergic pathways, and that it likely operates through task-specific adjustments in cortical noise. The key question now is whether, and how, metacontrol influences the binding of elements into event files—that is, bindings of stimulus, context, and/or action features (Hommel, 2004)—and their subsequent retrieval. This question can be divided into two parts: (1) whether the handling of event files is influenced by metacontrol biases, and (2) whether such effects arise during binding, retrieval, or both. Let us begin with the first question: Is there evidence that metacontrol affects the handling of event files?

Addressing this requires evidence that the creation or retrieval of event files is systematically shaped by task or context conditions linked to metacontrol biases. Crucially, metacontrol operates in a content-independent fashion, unlike cognitive control, which operates on specific content. For example, the intentional-weighting mechanism of the Theory of Event Coding (TEC; Hommel et al., 2001; Memelink & Hommel, 2013) assumes that task-relevant feature codes receive higher weights than task-irrelevant ones. From the very first studies of event-file construction (Hommel, 1998), effects of repeating or alternating task-relevant features have been consistently stronger and more reliable than those for irrelevant features. For example, if participants respond to stimulus shape with a left or right key, repetition or alternation of shape interacts with response repetition or alternation, while stimulus color—if irrelevant—has considerably smaller and less reliable effects of this kind. Hence, the strength and probability of these effects clearly depend on context (e.g., task relevance of stimulus features; Memelink & Hommel, 2013). While they may be modulated by metacontrol, they do not themselves constitute metacontrol effects, which are expected to alter processing style rather than the processing of particular content.

Some initial evidence for metacontrol influencing event-file creation comes from studies on the attentional blink (Akyürek et al., 2007, 2008). In these tasks, rapidly presented visual streams require participants to identify one or two target stimuli among distractors. The authors proposed that successful performance requires event-file creation to distinguish targets from distractors, and that participants can control the temporal scope of these files. By manipulating stimulus duration and inter-stimulus intervals, they induced either smaller or larger integration windows. Longer stimuli with shorter blanks increased cases in which both targets were reported but without order information—suggesting that both were integrated into a single event file. EEG data further showed that shorter integration windows were associated with neural markers of opening a new event file, absent under larger-window conditions. These findings indicate that feature integration can be modulated by metacontrol. Supporting evidence also comes from event-segmentation tasks, in which participants divide movies into meaningful units. Children tend to create larger units than adults (Ghorbani et al., 2024), consistent with higher aperiodic activity (greater cortical noise) observed in younger participants (Pi et al., 2025). Adults, however, can flexibly adopt coarse or fine segmentation strategies when instructed (Zhou et al., 2025), and clear instructions can shift children's performance toward an adult-like pattern (Zhou et al., 2024).

Metacontrol also appears to be sensitive to conflict. Yan et al. (2025) showed that partial-feature repetitions (e.g., repeating the relevant stimulus feature while alternating the response) increase the aperiodic exponent, suggesting that feature-code conflict reduces aperiodic activity and decreases cortical noise. Such conflict-induced changes in metacontrol and neural activity take time to implement, which likely explains why effects emerge not in the current trial but in the subsequent one (Jia et al., 2024). In any case, there seems to be a tight relationship between binding, retrieval, and metacontrol, which in some sense may operate both ways.

Further evidence comes from Hommel et al. (2011), who studied stimulus–response binding in 9–10-year-old children, young adults, and older adults. Partial-repetition costs were much larger in children and older adults than in young adults (but see Giesen, Eberhard, et al., 2015; Giesen, Weissman, et al., 2018). Given the protracted maturation of the prefrontal cortex and its decline in aging, these findings suggest that an efficient prefrontal cortex enables processing to remain focused on current stimuli and responses, whereas a less efficient prefrontal cortex allows retrieval of event files from prior trials. This pattern parallels results from attentional-blink and event-segmentation studies: the most efficient brains form the smallest event units, unless task demands encourage otherwise.

Turning to the second question—does metacontrol affect binding, retrieval, or both?—segmentation findings strongly suggest an influence on binding, as metacontrol biases alter the size of integration windows used to consolidate features into event files. Smaller windows, however, are effortful and benefit from a fully matured prefrontal cortex and explicit instructions. Beyond this, there is little evidence for other binding-related effects. This becomes clear when considering standard event-file paradigms (Hommel, 1998): Participants respond to two consecutive stimuli, with stimulus features and responses being repeated or alternated. The hallmark binding effect is that complete repetitions or complete alternations produce better performance than partial repetitions (e.g., repeating the stimulus but alternating the response). Critically, the presence of such an effect indicates binding and retrieval; its absence, however, is ambiguous, as it could reflect a lack of binding, a lack of retrieval, or both.

For example, Hommel et al. (2011) observed stronger repetition effects in children and older adults. This could reflect changes in binding, retrieval, or both. But given that both groups are typically impaired in binding (due to immature or declining neural systems), interpreting the results as superior binding is implausible. A more reasonable interpretation is that these groups have reduced ability to prevent retrieval of bindings from prior trials. Similarly, Zmigrod et al. (2013) found larger repetition effects in children with autism spectrum disorder compared to controls. Since autism is associated with impaired feature integration, stronger binding is unlikely; rather, reduced control over retrieval provides a better explanation. In all such cases, deficits in prefrontal functioning—immature, deteriorated, or impaired—likely reduce the ability to shield current performance from past bindings (i.e., from bindings that are unrelated to the present goal), thereby revealing the impact of metacontrol on retrieval (Hommel, 2022).

To summarize, there is evidence that metacontrol influences how continuous experience is segmented into meaningful units. A bias toward persistence, typical in young adults, seems to promote smaller temporal windows during event-file integration. Effects of metacontrol on retrieval are most evident in conflict-inducing conditions and in populations with weaker prefrontal control systems, where previous events more strongly affect current performance. In short, persistence biases reduce the impact of past experiences on the present, while flexibility biases increase it—suggesting that metacontrol shapes how strongly we relate current experiences to prior ones.

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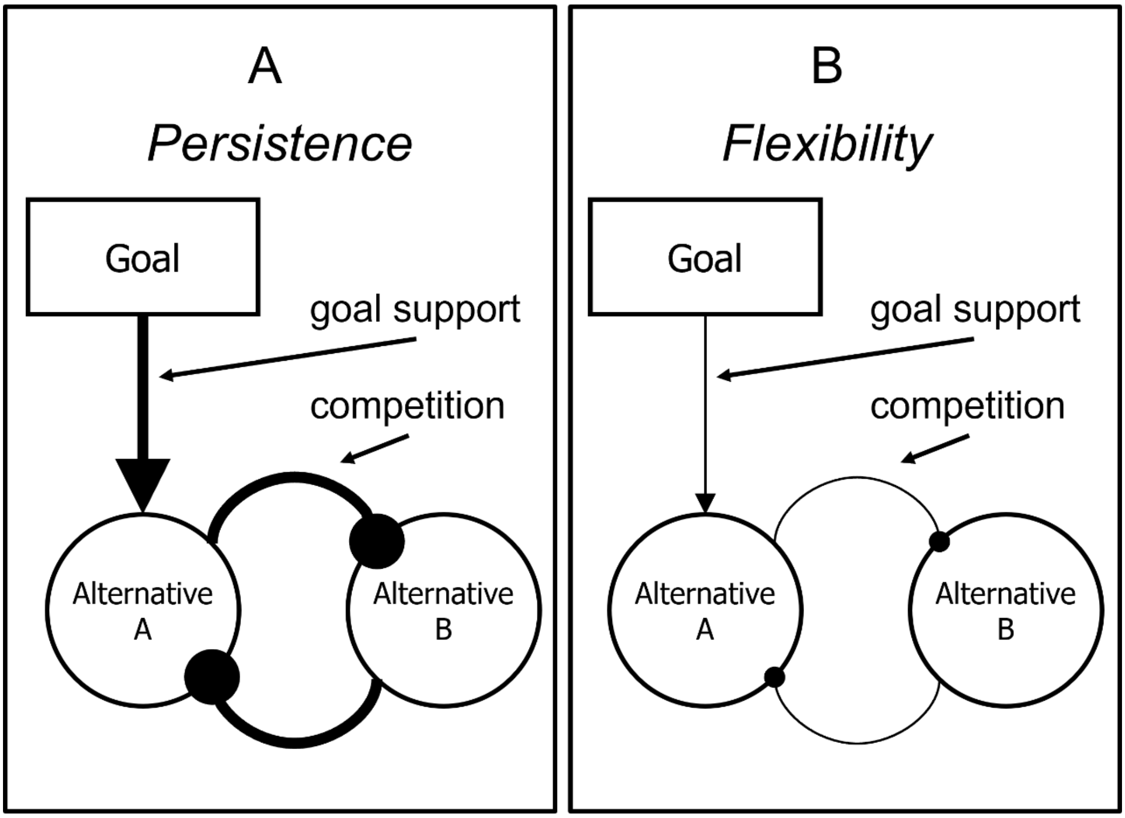
Figure 1

The functional mechanism of metacontrol. Metacontrol is assumed to vary on a bipolar scale between persistence and flexibility. Decision-making is assumed to result from the competition between alternatives (A and B in this example), which is indicated by the mutual inhibition between A and B, and from selective support for alternatives that are more compatible with the current goal(s). Extreme persistence is assumed to be characterized by particularly strong goal support and stiff competition, whereas extreme flexibility is assumed to be characterized by only weak goal support and minor competition.



Glossary

Event file

Integrated representation of the components of an experience event, commonly comprising of codes of stimulus features, response features, contextual features, the task representation, possible affective codes, and more (Hommel, 2004).