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REVIEW

Cognitive flexibility and stability at the task-set level: A dual-dimension framework

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Metacontrol coordinates goal-directed information processing, giving rise to cognitive flexibility and stability. However, the structure of flexibility and stability in metacontrol has long been subject to an overlooked assumption that these states vary on a single spectrum. This unidimensional structure gives rise to an obligatory flexibility-stability tradeoff: Becoming more flexible must come at the cost of lower stability. Although a "unidimensional" framework such as this has intuitive appeal, a great deal of recent work reveals that flexibility and stability can vary independently. Here, we review evidence that is challenging for the unidimensional framework to account for. As an alternative, we propose a dual-dimension framework (DDF) whereby flexibility and stability are assigned to separate dimensions, each ranging from low to high and capable of varying independently. In addition, we describe processes by which people shift along both dimensions. Theoretical benefits of adopting the DDF include a more fine-grained explanation of observed variability in behavior. Possible applications include strategies for better aligning metacontrol states with situational demands. In light of these implications, combined with the available data, we propose that the DDF might offer a better way to describe the structure of flexibility-stability metacontrol.

Keywords: task switching, congruency effect, flexibility-stability tradeoff, cognitive control, persistence

1. INTRODUCTION

Cognitive control is the capacity to direct cognition and behavior towards desired objectives (Miller & Cohen, 2001). Cognitive control promotes success when “prepotent” behaviors (well-established or otherwise more powerful), such as checking one's phone upon receiving a notification, interfere with goal attainment, such as paying attention during a classroom lecture. For example, during a midday class, a student might frequently get text messages from friends about lunch plans. With similar repeated experience, the midday class becomes an automatic "contextual cue," triggering heightened control and discouraging phone-checking before any buzz. The example illustrates how control can be triggered by contextual cues, including the broader environment where cognitive control is required. Empirical evidence supporting this contextual regulation of control has been extensively documented lately (Abrahamse et al., 2016; Braem et al., 2019; Braem & Egner, 2018; Bugg & Egner, 2021; Chiu & Egner, 2019; Egner, 2014). Following this recognition, “metacontrol” has been coined to differentiate contextual regulation of cognitive control from cognitive control per se, specifically referring to the strategic adjustment of cognitive control based on the given context (Goschke, 2013; Hommel, 2015).

Because task demands can vary widely, many different *metacontrol* states are possible. Here, we focus on two commonly discussed metacontrol states: *flexibility* and *stability*. Flexibility is defined as prioritization of multiple goals and fluent transitions among these goals; for example, switching between reading words on lecture slides and jotting notes. Stability is defined as shielding goals from distraction or interference; for example, tuning out distractions like buzzing phones in class.

Flexibility and stability defined in this way have traditionally been viewed as opposing ends of a single spectrum, representing an unavoidable tradeoff (Cools, 2016; Dreisbach, 2012; Dreisbach & Fröber, 2019; Goschke, 2003, 2013; Hommel, 2015; Paul et al., 2021). We refer to this conceptualization as the unidimensional framework of metacontrol. According to the unidimensional framework, flexibility and stability are considered antagonistic, always varying inversely. However, when relating the unidimensional framework to real-world scenarios, the framework would suggest that a student switching smoothly between the two goal-relevant, beneficial tasks (listening to the lecture and taking notes) cannot effectively shield against the goal-irrelevant task of checking their phone. Treating flexibility and stability as a zero-sum tradeoff does not reflect how daily life often requires both simultaneously.

To allow flexibility and stability to vary independently, we propose an alternative conceptualization dubbed the dual-dimension framework (DDF; see also Geddert and Egner, 2022; Egner, 2023 for similar proposals). However, this is not a fully elaborated model, but rather a conceptual framework for organizing findings already covered by the unidimensional framework and those beyond its scope. Therefore, the rest for this paper adheres to the following structure: (1) a review of the rationale and evidence for the unidimensional framework; (2) a review of the evidence that is inconsistent with the unidimensional framework; (3) an in-depth description of the DDF; and (4) a discussion of the implications and benefits should the DDF be supported by future evidence.

2. THE UNIDIMENSIONAL FRAMEWORK OF FLEXIBILITY AND STABILITY

In this section, we elaborate on the unidimensional perspective. We first summarize the key ideas and rationale. We then describe common experimental paradigms for evaluating flexibility and stability, followed by the body of evidence supporting the unidimensional framework. Throughout this section, we also occasionally highlight the limitations of the evidence supporting the unidimensional approach, paving the way for the next section, titled *Challenges to the Unidimensional Framework.*

2.1 Overview and Rationale

The rationale for the unidimensional framework is best understood through the lens of task-sets, defined as a collection of mental representations of stimuli, rules, and responses needed to produce goal-appropriate behavior. A task-set therefore focuses attention on task-relevant stimuli features and away from irrelevant features. (Dreisbach & Haider 2008, 2009; Dreisbach & Wenke 2011). A task set can be instantiated strongly, making it "shielded" against other task-irrelevant stimuli or distractions, or less strongly, making it less shielded. Strong shielding is synonymous with cognitive stability. However, if one's goal suddenly changes, strong shielding becomes detrimental, synonymous with impaired flexibility. The difference between stability and impaired flexibility is merely a semantic value judgment: The terms denote identical information processing strategies for the task-set. The key is that high shielding produces stability and, consequently, reduced flexibility. This description is a central feature of the unidimensional account: a single parameter—the degree of task-set shielding—determines both flexibility and stability such that they are locked in a tradeoff.[1]

2.2 Operationalizing Flexibility and Stability

Flexibility/stability as broad and general descriptors has been the subject of much psychological research (e.g., for reviews, see Braem & Egner, 2018; Eppinger et al., 2021; Goschke, 2013; Hommel & Colzato, 2017). Due to this diversity of research, flexibility and stability are conceptualized and operationalized in many different ways, creating ambiguity and confusion when interpreting research findings (e.g., Ionescu, 2012). To avoid this problem, we narrow our focus to examine flexibility and stability at the level of the "task-set." Accordingly, we primarily focus on paradigms that are designed to examine control over task-sets, especially in "cued task switching paradigms" where participants are cued on which task to perform for each trial. Task switches typically incur longer response times and more errors compared to task repeats, indicating the involvement of cognitive control processes. These processes include activating new task-sets in working memory and overcoming lingering activations from previous task-sets (Allport et al., 1994; Meiran, 1996b; Rogers & Monsell, 1995). When these processes are upregulated to promote better switching among task-sets, switch costs are reduced. Within our circumscribed definition of flexibility, decreases in switch costs serve as the operational definition of heightened flexibility.

Based on this definition, a common manipulation used to shift flexibility is adjusting the number of switch trials: Switch costs are reduced when switches are frequent versus rare (e.g., Dreisbach et al., 2002; Dreisbach & Haider, 2006; Kang & Chiu, 2021; Liu & Yeung, 2020; Monsell & Mizon, 2006; Schneider, 2016; Schneider & Logan, 2006). This has been demonstrated, for example, when spatial locations or stimulus identity are used as contextual cues associated with biased switch probabilities (Chiu, 2019; Crump & Logan, 2010; Leboe et al., 2008). The effect has also been demonstrated using lists (blocks of trials) with frequent vs. rare switches (e.g., Dreisbach et al., 2002; Dreisbach & Haider, 2006; Kang & Chiu, 2021; Liu & Yeung, 2020; Monsell & Mizon, 2006; Schneider, 2016; Schneider & Logan, 2006; Yu-Chin, 2022). This effect, known as the list-wide

[1]It is important to note that this tradeoff is typically conceptualized within a single level of cognition, such as goal or task-set instantiation, rather than across multiple levels of processing. We acknowledge that it is equally important to consider the flexibility-stability tradeoff when multiple levels of processing are involved, c.f., Fröber and Dreisbach (2023).

switch probability effect, reflects increased flexibility as participants become more adept at switching between tasks. Lists serve as contextual cues that modulate the efficiency of control over task-sets.

The same task-switching paradigms can also be used to assess stability, so long as the paradigm utilizes bivalent stimuli. Bivalent stimuli afford two different tasks with overlapping responses. For example, the digit "3" can be classified as “odd” in an odd/even task and “small” in a larger/smaller-than-5 task. When one task is relevant and the other is irrelevant, bivalent stimuli can be either congruent (producing the same response in both tasks) or incongruent (producing different responses). These congruency differences lead to differences in performance, known as the congruency effect (Sudevan & Taylor, 1987). This effect arises either from interference caused by past experiences of different responses to the same stimulus (Logan, 1988, 2002; Yamaguchi & Proctor, 2011) or from categorizing every stimulus based on both task rules (Schneider, 2015, 2018). Regardless of the source, the performance cost observed on incongruent trials reflects the interference of irrelevant and detrimental information in goal-relevant processing. Cognitive control is needed to suppress irrelevant information and shield the relevant task-set. When these processes are upregulated, congruency effects are reduced. Decreases in congruency effects are commonly used to operationalize heightened stability.

Stability is also commonly modulated by manipulating the proportion of incongruent trials in a paradigm (e.g., Bejjani et al., 2022; Botvinick et al., 2001; Dreisbach & Fröber, 2019; Geddert & Egner, 2022; van Steenbergen, 2015). Mirroring list-wide switch probability effects for switch costs, differences in congruency effects between frequent vs. rare incongruent lists are referred to as list-wide proportion congruent effects. These effects are often researched in Stroop paradigms (Bugg et al., 2011; Bugg & Hutchison, 2013; Chiu et al., 2017; Jacoby et al., 2003; for reviews see Bugg, 2017; Bugg & Crump, 2012), but have also been demonstrated in the congruency effects of task-switching paradigms (e.g., Bejjani et al., 2022; Botvinick et al., 2001; Braem, 2017; Dreisbach & Fröber, 2019; Geddert & Egner, 2022; van Steenbergen, 2015). Together, list-wide switch probability and list-wide proportion congruent manipulations are commonly used to alter metacontrol and provide working illustrations of the context-dependent changes that we use to operationalize metacontrol.

However, researchers differ on how they interpret congruency effects as metacontrol indices. In accordance with the unidimensional framework, some researchers consider congruency effects to reflect both flexibility and stability. This idea assumes that the unidimensional framework is correct: Any increases in congruency effects must indicate a decrease in flexibility. To illustrate, this tradeoff is analogous to how movement on one end of a see-saw must unavoidably be compensated on the other end. While this is an efficient approach from within the unidimensional framework, it is not suitable for testing the veracity of the unidimensional framework itself; the result could only be circular. To avoid this problem, others have suggested that flexibility and stability must be indexed separately. In this approach, context-dependent changes in congruency effects are used to measure stability only, while changes in switch costs measure flexibility only (Geddert & Egner, 2022). In this paper, we adopt the latter approach and advocate for the separate assessment of flexibility and stability as distinct constructs. This separation allows for an unbiased examination of the relationship between flexibility and stability. In the next subsection, we review relevant findings that satisfy this criterion, enabling an exploration of the relationship between the two metacontrol states.

2.3 Empirical Evidence for the Unidimensional Account

The unidimensional framework has intuitive appeal and, without a doubt, is supported by several lines of behavioral evidence. A particularly recent example comes from a line of research demonstrating the susceptibility of metacontrol to operant conditioning. Braem (2017) frequently rewarded one group of participants immediately following successful task switches during cued task switching, while the other group was instead rewarded frequently after task repeats. In a later part of the experiment, both groups were asked to freely choose either to switch or to repeat tasks. The results revealed that participants frequently rewarded for task switches earlier had a higher voluntary switch rate compared to those frequently rewarded for task repeats. Moreover, Braem (2017) also found an increased congruency effect in the group that had been conditioned for flexibility, indicating a flexibility-stability tradeoff. Similar conditioning effects have been shown in the opposite direction as well: Held et al. (2023) rewarded participants frequently on incongruent trials and rarely on congruent trials. Participants who had been conditioned for stability then showed reduced congruency effects as well as an increase in switch costs, indicating a flexibility-stability tradeoff once more. Merging these two conditioning procedures, Bartossek et al. (2023) replicated both Braem's (2017) and Held et al.'s (2023) findings and furthermore revealed that the loss in stability (or flexibility) was proportional to the volitional increase in stability (or flexibility).

As previously mentioned, a very common metacontrol manipulation is to manipulate the frequency of task switches or incongruent trials. This method occasionally offers support for the unidimensional account. Particularly strong support can be found in a recent study by Qiao et al. (2023), who manipulated the frequency of incongruent trials by including task-irrelevant distractors to evaluate its impact on the flexibility-stability tradeoff. They reported, and subsequently replicated, that an increase in the frequency of distractors resulted in both decreased distractor effects and increased switch costs. Moreover, the authors modeled participants' control learning and found that the best-fitting model assigned both flexibility and stability to a single parameter—guaranteeing a tradeoff. Together, these recent studies provide support for the unidimensional account.

Above, we have described instances where changes in external context led to changes in cognitive control settings. Changes in internal context, such as affect, can also modulate cognitive control. Among the most often cited when discussing a flexibility-stability tradeoff, Dreisbach and Goschke (2004) directed participants to perform a single categorization task on a target stimulus indicated by a pre-defined ink color while ignoring a differently colored distractor. The mappings between ink color and target/distractor changed mid-way through the experiment: In one condition, the novel color designated the target, but the previous target color became the distractor color after the switch. This setup was intended to measure perseveration, or the degree to which participants continue to pay attention to the previous, but now irrelevant, target color. In the other condition, the new color designated the distractor, and the old distractor color became the new target color. This setup was intended to measure distractibility, or the degree to which one is inappropriately attracted to the novel distractor color. The results confirmed that each condition produced perseveration or distractibility, respectively. Armed with these diverging conditions, positive affect was induced among participants in Experiment 2. Affect had been selected as an established means of shifting metacontrol towards flexibility. The affect manipulation had opposite impacts in the two conditions: reducing perseveration in the first but increasing distractibility in the second condition (Dreisbach & Goschke, 2004). This is among the earlier studies finding that facilitated switching comes at the cost of intrusions from unwanted task-sets – i.e., a flexibility-stability tradeoff.

Besides these findings, many additional studies documented a flexibility-stability tradeoff (Brown et al., 2007; Chiew & Braver, 2014; Cools et al., 2010; Dreisbach et al., 2005; Dreisbach, 2006; Fischer & Hommel, 2012; Goschke, 2000; Goschke & Bolte, 2014; Hefer & Dreisbach, 2016, 2017; Locke & Braver, 2008; Stoet & Snyder, 2003, 2007b; Tharp & Pickering, 2011; Watzek et al., 2019; Yahya & Özkan Ceylan, 2022). In each of these studies, a manipulation or individual difference which impacts flexibility had an inverse impact on stability, suggesting that the two constructs traded off. All of the evidence cited above in support of the unidimensional framework *does* satisfy the requirement for separate measurement of flexibility and stability. However, as we elaborate next, a considerable body of research that also satisfies the separation requirement did not align well with the unidimensional framework.

3. CHALLENGES TO THE UNIDIMENSIONAL FRAMEWORK

In this section, we highlight literature that is inconsistent with the unidimensional framework. We divide our review of these findings into two broad categories: within individuals versus between individuals. It is important to consider both within-individual and between-individual tradeoffs (and the lack thereof) because separate patterns could conceivably emerge (e.g., Mekern et al., 2019). These within-individual studies include, in order: (1) flexibility manipulations failing to impact congruency effects; (2) flexibility manipulations failing to impact attentional capture; and (3) flexibility and stability often loading onto separate latent factors. The between-individual studies include: (1) individual differences in flexibility failing to predict stability measures; and (2) neuropsychological double dissociations between flexibility and stability.

3.1 Within Individuals

3.1.1 Flexibility Manipulations do not Influence Task-Rule Congruency Effects

Based on the unidimensional framework, changes in flexibility should always be offset by opposite changes in stability. However, this assumption was challenged by Geddert and Egner (2022)'s recent study. The authors independently manipulated both the probability of task switches and the proportion of task-rule incongruent trials *within-subjects*—two manipulations that have produced robust behavioral effects, i.e., the list-wide switch probability effect indexing flexibility, and the list-wide proportion congruent effect indexing stability, respectively. Thus, the study allowed measurement of both (1) changes in task-rule congruency effects as switches became more frequent and (2) changes in switch costs as incongruent trials became more prevalent. According to the unidimensional framework, there should be an interaction between the two manipulations and specifically a tradeoff relationship: A larger congruency effect in the frequent switch condition than in the rare one, and a larger switch cost in the frequent incongruent condition than in the rare one. Unexpectedly, neither effect was observed— (1) adaptation to the higher switch probability did not increase congruency effects, and (2) adaptation to the higher proportion incongruence did not increase switch costs. When compared to a model including an interaction term, Bayesian statistics indicated evidence 7 times greater supporting a model with no interaction. This finding of no interaction was replicated using different kinds of task-rule congruency. These findings revealed instances where flexibility and stability varied independently.

Switch probability manipulations' lack of impact on congruency effects have also been documented in earlier studies (Chiu & Egner, 2017; Kang & Chiu, 2021; Siqi-Liu & Egner, 2020). While shifting flexibility (not stability) was the primary focus, stability could still be indexed by congruency effects because bivalent stimuli were used. From our own lab, we consistently found smaller switch costs in the frequent switch condition than in the rare one, but have never found a significant difference in the congruency effect between the two conditions (Chiu & Egner, 2017; Kang & Chiu, 2021). Taken together, there is consistent evidence that individuals adapt to situations requiring cognitive flexibility without relaxing stability. Regarding the lack of modulation of congruency effects in these studies, a straightforward explanation is that there was no demand for changing stability across different switch probability conditions. This explanation fits with the idea of demand avoidance (e.g., Kool et al., 2010; Schouppe et al., 2014; Shenhav et al., 2013) whereby cognitive effort is a key determinant for engaging cognitive control and metacontrol.

Because these acute experiences with frequent switching can induce shifts towards flexible metacontrol states, more chronic exposure may be expected to similarly reduce switch costs. Indeed, Zhao et al. (2020) revealed significantly diminished switch costs after 21 days of task-switching training. This benefit was observed both on the trained tasks and a transfer task with different stimuli and response rules. This transfer means that participants became better at switching in general, perhaps by associating the laboratory with the demand for a flexible metacontrol state and retrieving it in the transfer task. Critically, this flexible state did not come at the cost of decreased stability: Training had no impact on stability indices derived from the Stroop or Flanker paradigms. A similar pattern was demonstrated among children (Zhao et al. 2018). Intensive training can also cause a shift towards greater stability but no complimentary shift away from flexibility. Talanow and Ettinger (2018) reported improved Stroop performance over 8 training sessions, but there was no change in (untrained) switch costs. In the absence of training or a biased switch probability manipulation, flexibility can also be increased by inducing positive affect (Tae et al., 2021, Experiment 2) without modulating stability.

3.1.2 Flexibility Manipulations do not Increase Attentional Capture.

In addition to task-rule congruency effects, stability can be operationalized as the extent of shielding against task-irrelevant distractors. Inconsistent with the unidimensional framework, studies have shown that increasing flexibility does not invariably increase bottom-up attentional capture by these distractors. For instance, in a recent study by Sali and Key (2021), participants switched between two categorization tasks, and the probability of switches was varied across blocks in order to modulate switch costs, similar to previous studies. Unlike others, the target stimulus for the categorization task was inside a pre-defined target shape in an array with other shapes (e.g., a circle among diamonds). Thus, before performing the categorization task, participants had to locate the target stimulus first. Critically, in half of the trials, both target and distractors were in the same color (i.e., a distractor absent condition), while in the other half, one of the distractors was in a unique color (i.e., a distractor present condition). This distractor present condition has been shown to capture attention and slow responses to the target (e.g., Theeuwes, 1992). Thus, comparing distractor absent versus present conditions provides an index of stability. In two experiments, the switch probability manipulation modulated switch costs with frequent switches incurring smaller switch costs, as expected. However, the performance cost due to distractors was not significantly different when switches were frequent versus when they were rare. These results showed that increased flexibility did not come with decreased stability as indexed by attentional capture.

3.1.3 Flexibility and Stability Load Onto two Separate Factors

Besides considering the direct effects of flexibility manipulations like switch probability on stability indices, we can also examine the factor structure of these constructs. Factors can be derived from behavioral paradigms such as those using list-wide switch probability/list-wide proportion congruent manipulations, or from self-report data. After each are discussed in turn, both types of data will point to a similar factor structure: flexibility and stability represent distinct—albeit positively correlated—latent variables.

Bejjani et al. (2022) recently investigated whether flexible and stable metacontrol states can be explained by one versus two factors. Participants performed two separate paradigms: One paradigm featured a list-wide switch probability manipulation and the other featured a list-wide proportion congruent manipulation. The authors examined correlations across participants between the list-wide switch probability effect and the list-wide proportion congruent effect. A structural equation modeling analysis was performed to find out whether individual performance differences in both tasks could be explained by (1) a single-factor structure, (2) a two, negatively correlated factor structure, or (3) a two, positively correlated factor structure. The first and second structures would be consistent with the unidimensional framework, while the third would not. Challenging the unidimensional framework, Bejjani et al. (2022) found that the list-wide switch probability and list-wide proportion congruent effects are best explained by a two, positively correlated factor structure. Namely, flexibility and stability in metacontrol are separate constructs, and it is possible for the same individuals to be proficient or deficient at both.

Self-report studies offer a separate line of converging evidence challenging the unidimensional framework by measuring individuals' perceptions of their own cognitive flexibility and stability. In particular, Derryberry and Reed (2002) measured self-report flexibility and stability in terms of shifting versus focusing of attention. Earlier, Derryberry and Rothbart (1988) noticed that people tend to self-identify themselves as skilled in both shifting and focusing, or unskilled in both; but rarely as prioritizing one in such a way that requires tradeoff. To formally test this, Derryberry and Reed (2002) later developed an Attentional Control Scale, asking participants to report their agreement with a series of statements related to shifting, such as, "It is easy for me to alternate between two different tasks" as well as statements related to focusing, such as, "When concentrating, I can focus my attention so that I become unaware of what's going on in the room around me." A confirmatory factor analysis revealed two factors (Chiorri & Vannucci, 2019), supporting the proposal that flexibility and stability in attentional control are dissociable states of an individual. Such findings would be unexpected based on the unidimensional framework. Notably, in subsequent studies using the Attentional Control Scale, the two subscales were positively correlated across individuals (Carriere et al., 2013; Chiorri & Vannucci, 2019; Jessup et al., 2021; Ralph et al., 2014, 2017; Sansevere & Ward, 2021; Qiao & Liu, 2020). Like much of the behavioral data, psychometric data suggest that flexibility and stability are not locked in a tradeoff.

3.2 Between Individuals

3.2.1 Individual Difference Variables Modulating Flexibility do not Trade off With Stability

Inter-individual relationships between flexibility and stability provide another way to evaluate metacontrol. That is, the unidimensional framework predicts a negative correlation between individual differences in flexibility and stability. Recall that flexibility and stability are metacontrol states, indexed via "changes" in cognitive control. Therefore, evidence presented in this section will relate to individual difference factors which produce "changes" in cognitive control indices, rather than the direct correlation between the indices themselves. However, if any, we did find several documented instances of nonsignificant or positive correlations between switch costs and Stroop interference (e.g., Sánchez-Cubillo et al., 2009; Ward et al., 2001; Zhao et al., 2021). While not speaking directly to metacontrol as we have defined it here, these findings do suggest that there are at least separable cognitive control mechanisms engaged in overcoming Stroop interference and in switch costs. Such distinct mechanisms at the control level are likely necessary for independent modulation at the metacontrol level, serving as an assumption check lending additional credence to the individual difference studies considered next.

At the level of metacontrol, several quasi-experimental studies provide additional evidence challenging the unidimensional framework. Such studies can reveal whether individual differences in flexibility also have an impact on stability in the same group of participants. In some studies, the individual difference variable of interest might be considered flexibility per se. For example, Wiradhany et al. (2020) found no relationship between self-reported media multitasking (flexibility) and distractor suppression (stability). However, it may be argued that self-report media multitasking taps different constructs than differences in switch costs, and including a separate index of flexibility (other than the individual difference variable of interest) would allow for stronger conclusions. Accordingly, all following papers in this section report the impacts of individual difference variables on common indices of both flexibility and stability. Although the impacts of media multitasking on cognitive measures are strongly contested and directionally inconsistent (e.g., Luo et al., 2021, 2022; Murphy & Shin, 2022; Parry & Le Roux, 2021; Schneider & Chun, 2021; Wiradhany & Nieuwenstein, 2017), when reported, such effects tend to selectively impact switch costs and not laboratory stability indexes (e.g., Alzahabi & Becker, 2013; Ophir et al., 2009; Wiradhany & Nieuwenstein, 2017). A similar pattern appears when using self-report flexibility and stability as opposed to task-based measures: Reported flexibility, but not stability, differs based on media multitasking (Luo et al., 2022).

Another individual difference factor with bearing on flexibility and stability is reappraisal ability, defined as the capacity to adaptively change one's interpretation of negative information. Higher reappraisal ability predicted increased switch costs, but no change in Stroop effects (McRae et al., 2012). In a similar vein, school classes taught in two languages predicted decreased switch costs, but no change on congruency effects (Christoffels et al., 2015). Although cognitive advantages of bilingualism are inconsistent and contested (Dick et al., 2019; Mas-Herrero et al., 2021; Paap et al., 2017; Sanchez-Azanza et al., 2017), in this particular study, students enrolled in bilingual classes produced smaller switch costs compared to those instructed in only one language. While switch costs differed as a function of bilingual education, the congruency effect did not. Similarly, Dong and Liu (2016) investigated the impacts of a semester-long class on language interpreting. Upon post-test of cognitive abilities, students in this class showed reductions in switch costs, but no change in Stroop effects. In other words, reappraisal ability and language training selectively influenced flexibility without impacting stability. There are also examples of independence in the opposite direction: Stroop interference increased with age, but switch costs showed no changes (Hirsch et al., 2016, *Experiment 1*; Hutchison et al., 2010; Reimers & Maylor, 2005; Wasylyshyn et al., 2011, but see Georgiou-Karistianis et al., 2006, who used a different paradigm). While the individual differences studies in this section did not involve direct experimental manipulation of flexibility or stability, they follow the same pattern as the within-subject studies: Certain individual difference variables appear to increase or decrease one metacontrol state across individuals without causing opposite changes in the other metacontrol state in those same individuals. The unidimensional framework is not well suited to explain this selectivity of modulation.

3.2.2 Flexibility and Stability can be Doubly Dissociated

Double dissociations are a direct means of demonstrating that two different cognitive capabilities are subserved by separate neural systems. Indeed, Stuss et al. (2000) showed that lesions in distinct parts of the human frontal cortex are linked to distinct flexibility/stability impairments as measured in the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948; Milner, 1963). Like cued task-switching, participants occasionally switched between different categorization rules to apply to multivalent stimuli; but unlike cued task-switching, the appropriate task was not explicitly instructed and instead needed to be inferred by performance feedback. Participants had to continuously adapt in a context-sensitive manner. We reason that this is similar to experimental manipulations of switch probability (or proportion congruency): The WCST should also prompt flexibility-stability metacontrol. With this premise in mind, flexibility and stability (or the lack thereof) in the WCST are operationalized by two different kinds of errors. Perseverative errors occur when participants do not adapt to changes and continue using a sorting rule after performance feedback indicates the rule is no longer relevant—an intuitive index of inflexibility. Set-loss errors, on the other hand, occur when participants apply new sorting rules in the absence of feedback indicating a change—a failure of task-set maintenance indicating inadequate stability. Lesions limited to the inferior medial frontal cortex were associated with no changes in perseverative errors but increased set-loss errors (Stuss et al., 2000, replicated also in monkeys by Dias et al., 1997), while lesions in the superior medial frontal cortex were instead associated with greatly increased perseverative errors but relatively small increases in set-loss errors (Stuss et al., 2000).

Although less localized than the lesions studies by Stuss et al. (2000), other neurological conditions also reveal dissociations between flexibility and stability. We summarize some of them in Table 1. For example, impaired flexibility but preserved stability are seen in conditions such as amyotrophic lateral sclerosis (Abrahams et al., 1997; Lange, et al., 2016d; Lange et al., 2016a; Seer et al., 2015) and schizophrenia (Manoach et al., 2002; Sullivan et al., 1993). Whereas, conditions associated with impaired stability but preserved flexibility include dyslexia (Kapoula et al., 2010; Protopapas et al., 2007; Stoet et al., 2007b), alcoholism (Sullivan et al., 1993) and sleep-related hypermotor epilepsy (Licchetta et al., 2018). Double dissociations are of neuropsychological value for localizing brain areas and systems responsible for behaviors. Unfortunately, the studies presented here provide neither consistent nor converging neuroanatomical loci of flexibility and stability, but instead, a diverse set of brain changes. This is unsurprising, given that flexibility and stability are higher-level metacontrol states emerging from recruitment of other basic processing abilities, not freestanding functions (c.f., Ionescu, 2012; Schneider & Logan, 2009). Metacontrol likely involves distributed and overlapping brain networks (e.g., Barbey et al., 2013; Collette & Van der Linden, 2002). While the localization of flexibility and stability is

Table 1
Selective Impairment of Flexibility or Stability

Flexibility	Stability	Condition
Impaired	Preserved	Superior medial frontal cortex lesion (Stuss et al., 2000) ALS (Abrahams et al., 1997; Lange et al., 2016a; d; Seer et al., 2015) Age-related cognitive impairment (Zhang et al., 2007) Schizophrenia (Kieffaber et al., 2006; Manoach et al., 2002; Sullivan et al., 1993) DAT1 polymorphisms (den Ouden et al., 2013)
Preserved	Impaired	Inferior medial frontal cortex lesion (Stuss et al., 2000) Dyslexia (Kapoula et al., 2010; Protopapas et al., 2007; Stoet et al., 2007b) Sleep-related hypermotor epilepsy (Licchetta et al., 2018) Healthy aging (Davidson et al., 2003; Hutchison et al., 2010) Primary dystonia (Lange, et al., 2016b; c) Alcoholism (Lannoy et al., 2019; Sullivan et al., 1993) SERT polymorphisms (den Ouden et al., 2013)

ambiguous, the separation of their neural mechanisms is anything but: These double dissociations provide support for an alternative framework that allows flexibility and stability to vary independently across individuals.

Pivoting away from studies of brain disorders, den Ouden et al. (2013) observed a flexibility-stability dissociation by examining gene polymorphisms related to the dopamine versus serotonin neurotransmitter systems. Two versions of the DAT1 dopamine transporter gene were compared against each other. Likewise, two versions of the SERT serotonin transporter gene were compared. This study used a reversal learning task like the WCST in that the task provided an index of flexibility with the measure of perseverative errors and an index of stability with the measure of set-loss errors. People with different versions of the DAT1 gene showed systematic differences in the number of perseverative errors, but no difference in set-loss errors. Meanwhile, people with different versions of the SERT gene showed no differences in the number of perseverative errors but differed systematically in terms of set-loss errors.

Furthermore, a flexibility-stability dissociation was documented within the dopamine system alone. To examine the effects of dopamine, Furman et al. (2020) compared the impacts of impairing primarily DA1 versus primarily DA2 receptors in human participants performing a modified task-switching paradigm. In this paradigm, distractor congruency effects indexed stability and switch costs indexed flexibility. A double dissociation was revealed after accounting for individual differences in baseline dopamine: For high-dopamine participants, pharmacologically disrupting DA1 receptors primarily located in the prefrontal cortex impaired distractor suppression (stability) but had no impact on task-switching (flexibility). In contrast, for low-dopamine participants, pharmacologically disrupting DA2 receptors primarily located in the striatum impaired task-switching (flexibility) but had no impact on distractor suppression (stability). The remaining 2 conditions (i.e., high-dopamine/disrupted DA2 and low-dopamine/disrupted DA1) impacted neither switching nor distractor suppression.

This points to dissociable neural mechanisms that contribute to flexibility and stability within the dopamine system.[2] Combining these findings with the role of serotonin (den Ouden et al., 2013), neurotransmitter-level double dissociations indicate that flexibility can be determined independently from stability. In summary, the neuropsychological data presented here, along with the individual differences and within-subjects evidence discussed in the preceding sections, underscores the need for an alternative framework of metacontrol's structure.

4. THE ALTERNATIVE DUAL-DIMENSION FRAMEWORK (DDF)

We now delve into a more detailed description of the alternative DDF. First, we will offer *a priori* justification for the independence between flexibility and stability by highlighting a biologically plausible computational model. This will provide one means by which the DDF could be grounded in theory. Second, we will describe what issues the DFF mainly addresses and what new value it adds. This entails describing the theoretical benefits of the DDF, and the two metacontrol states unique to the DDF—low in both flexibility and stability and high in both. Lastly, we re-examine some of the existing data through the lens of the DDF.

4.1 An Example Computational Model Compatible With the DDF

Up to this point, our focus has been to evaluate the compatibility of existing data with either framework. However, it is crucial to evaluate whether the DDF's key feature can be derived from a broader theory of how the brain processes information. To this end, we highlight one computational model and explain how it enables the independent regulation of stability and flexibility in a context-dependent manner. The Prefrontal cortex/Basal ganglia Working Memory (PBWM) model is a computational model of working memory (O'Reilly & Frank, 2006). The model accommodates multiple concurrent mental representations within separate functional buffers known as 'stripes' in the prefrontal cortex. While sensory inputs and motor outputs are processed and mapped in posterior cortices, the prefrontal cortex contextualizes these mappings with relevant prior information and goals. A basal ganglia gating mechanism, modulated by the dopaminergic reinforcement learning system, determines the degree of shielding or updating at each stripe. The model also includes a learning parameter in the basal ganglia which allows the gate to selectively open for goal-appropriate working memory updates but remain closed to unneeded information. Based on these features, the PBWM allows for independence between flexibility and stability in two ways. First, employing separate stripes for distinct working memory representations, along with prefrontal cortex contextualization, the model facilitates flexibility in specific representations while maintaining stability in others (Frank et al., 2001). This is akin to a chef smoothly switching between washing and chopping vegetables while remaining vigilant against a pot boiling over. Second, within a single stripe, the basal ganglia gate (modulated by learning) allows representations associated with goal success through while blocking those linked to failure. This is similar to the example of the classroom context effectively cueing a student to switch smoothly between listening and note-taking, all while resisting the temptation to check their phone. However, despite the apparent alignment of PBWM with the DDF, other approaches may also be applied to instantiate the DDF, and future work is needed to fully model the DDF explicitly.

[2] It should be noted that the authors interpreted these findings in terms of an inverted-U shape regarding the impact of dopamine amount on performance: The key is to have the proper amount of dopamine (neither too high nor too low). When DA1 activity was disrupted (too high or too low), stability suffered while flexibility was unchanged. On the other hand, when DA2 activity was disrupted, flexibility suffered while stability remained unchanged.

4.2 Benefits of the DDF

4.2.1 Explaining More Variance

As illustrated in **Figure 1**, the DDF provides a framework for more fine-grained analysis of metacontrol, capable of capturing more variance in behavior (c.f. Braver et al., 2021; Gonthier et al., 2016). Flattening this variance to different locations on a single spectrum means useful signal may be misidentified as noise. For example, positive affect sometimes increases flexibility and decreases stability concurrently (Goschke & Bolte, 2014; Isen, 2001; van Steenbergen, 2015) while in other cases, positive affect has no impact on stability (Bruyneel et al., 2013) or even increases stability (Chiew & Braver, 2014). The changing impact of positive affect presents an inconsistency in need of explanation.

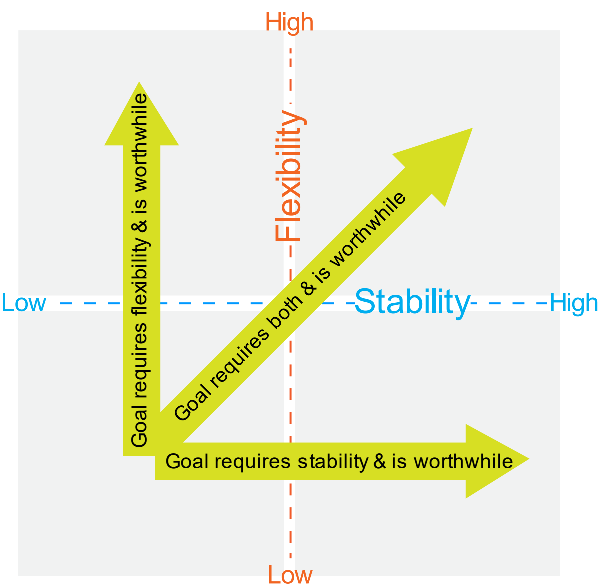

Figure 1. The Dual-Dimension Framework of Flexibility and Stability. The framework puts flexibility and stability on separate axes. Consequently, it allows each to vary independently based on motivation, goal requirements and the bottom-up emphasis of demand. While tradeoffs may occur in some situations, they are reflections of the interplay among these factors rather than inherent default outcomes.

Although the figure appears to show the dimensions as perpendicular to each other, we do not intend to claim that flexibility and stability must always be uncorrelated. Furthermore, although the unidimensional framework makes a strong prediction that flexibility *always* trades off with stability, we do not make the equally strong prediction that flexibility *never* trades off with stability. In fact, random sampling from a dual-dimension structure will give rise to cases where flexibility and stability are positively correlated, as well as cases where they are negatively correlated. Next, we discuss the processes by which individuals shift among the four quadrants.

4.2.2 Adding two More Metacontrol States

One's current metacontrol state depends on motivation, goal requirements, and bottom-up emphasis of metacontrol demand. Concerning motivation, both flexibility and stability are perceived as effortful and are avoided when not worthwhile (Kool et al., 2010; Schouppe et al., 2014; for a review, see Cools, 2016). However, motivation alone will not increase flexibility in tasks that require no switching: Goal requirements also dictate which form of metacontrol is engaged. Finally, bottom-up emphasis of these requirements further fine-tunes metacontrol states, often implicitly signaled by task structure. Commonly, only the value of flexibility or stability is emphasized in a single experiment. By considering these three forces, the DDF also captures the central observation in the unidimensional account: tradeoffs. If paradigms alternate between emphasizing only one metacontrol state at a time, a tradeoff should emerge (see Geddert & Egner, 2022, for discussion). However, this tradeoff would be caused by participants' unwillingness to 'waste' effort. Next, we describe the two DDF-unique metacontrol states.

The 'low-in-both' combination corresponds to a metacontrol state that is not adaptive to changes in goal-relevant information but is highly susceptible to interference from goal-irrelevant information (distractible). Despite its central tradeoff, the unidimensional framework does not deny the existence of this metacontrol state—yet it also does not explain it. The DDF explicitly accounts for simultaneously low flexibility and low stability seen in many situations, both severe and mundane. Starting with severe, Goschke (2003) in fact noted several paradoxical impairments in both flexibility and stability. For example, some prefrontal lesions are linked to low flexibility as indexed by failure to learn and apply new task rules (perseverative errors) on the WCST, and also low stability as indexed by "utilization behavior" such as automatically grabbing and using someone else's toothbrush any time it is visible in the middle of another task (Braver et al., 1999; Engle et al., 1999; Iaccarino et al., 2014; Lhermitte, 1983; Owen et al., 1991). Conditions such as Parkinson's disease have been known to impair both flexibility and stability (Lange et al., 2017; Pollux, 2004, but see Cools et al., 2010). Furthermore, attention-deficit/hyperactivity disorder (ADHD) is characterized by both low flexibility and low stability (e.g., Atalar et al., 2016; Barkley, 1997; King et al., 2007; Roshani et al., 2020). Aside from neuropsychological reasons, low flexibility and stability can occur among otherwise healthy individuals due to acute sleep deprivation (Aidman et al., 2019; Cheng et al., 2017).

Less intuitive is the 'high in both' combination. An example of a daily-life situation requiring concurrently high flexibility and stability might be the notetaking scenario from the beginning of the article—the rewarding outcome of a good grade requires both fluent task-switching between attending to the lecture and writing notes but also successful stability against a phone's alert triggering a switch to the task of checking the phone. Suppressing the habitual response of phone-checking should also not cause suppressed switching to other tasks; overall success requires both high flexibility and high stability. This hypothetical is demonstrated concretely by one of Geddert and Egner's (2022) experimental conditions: The frequent switch/frequent incongruent condition reduced both switch costs and congruency effects concurrently. As another example, anxiety deriving from desire to succeed in class can decrease both switch costs and Stroop effects concurrently (Kofman et al., 2006).

4.3 Applying the DDF to Previous Findings of Flexibility-Stability Tradeoff

Equipped with these metacontrol-shifting forces and the resultant metacontrol states, we now apply these tools to some of the studies reviewed above, discussing how the DDF would account for instances of flexibility-stability tradeoff. Consider the finding that incongruent stimuli on one trial (trial n) sometimes trigger larger switch costs on the subsequent trial (trial n+1; Brown et al., 2007; Goschke, 2000; Meiran, 1996a; Monsell et al., 2003; Rogers & Monsell, 1995). According to the DDF explanation of this sequential effect, encountering the conflict on trial n reminds participants about the value of stability. Participants enter trial n+1 with a refreshed emphasis on the demand for stability. However, if trial n was a repeat, n+1 will receive no such reminder of the demand for flexibility. The DDF holds that, if properly reminded and motivated, it is possible for participants to exhibit simultaneous flexibility and stability, thereby showing no flexibility-reduction on trial n+1. However, the DDF predicts that such a scenario will only occur when— (1) success is deemed valuable, (2) success requires both flexibility and stability, and (3) the task environment makes these requirements readily apparent. Absent these conditions, flexibility should trade off with stability because of demand avoidance. This demonstrates a way in which the DDF can explain at least as much as the unidimensional account.

As another example, consider the metacontrol conditioning literature (Braem, 2017; Held et al., 2023). When rewards follow switch trials, participants may learn that stability is not necessary to maximize earnings and choose to sacrifice it. Along similar lines, participants may have begun the task with a general desire to perform well (depending on the person), and then lose the intrinsic motivation upon receipt of targeted, external rewards (Deci, 1971; Deci & Ryan, 1985). The result would be a maximization of reward-producing efforts only, and a loss of motivation for all efforts unrelated to producing rewards. According to the DDF, this sacrifice is strategic, and not structural. Moreover, under the DDF, a well-designed reward structure should be able to promote both flexibility and stability simultaneously.

5. DISCUSSION

Having laid out our dual-dimension framework, we turn to discussing future directions. First, we provide some considerations for future research, including (1) better articulation for both unidimensional and dual-dimensional frameworks, (2) the possibility of additional frameworks, and (3) strategies for falsifying the DDF. Second, we consider some broad implications should the DDF be supported by future evidence. These include reframing of metacontrol interventions, as well as consideration about what is considered "ideal" metacontrol.

5.1 Directions for Future Research

It should be noted that both unidimensional and dual-dimensional frameworks make the claim that flexibility and stability take place at the same point in the information-processing hierarchy. This means that care must be taken regarding the level of processing at which flexibility and stability are operationalized. As described in the lion's share of the literature reviewed above, the findings consistent with a flexibility-stability trade-off typically occur at a single level of processing. However, this is not always explicitly articulated in the unidimensional framework. In contrast, we emphasize that the DDF aims to describe flexibility and stability variations within a single level. We suggest that proponents of either framework should make this 'same level' assumption more explicit in both conceptual descriptions and operationalizations.

Although it is beyond the scope of the present review, an interesting third framework would be to consider flexibility and stability at different levels of processing, such as considering stability at a lower sensory/motor processing level and flexibility at a higher task-set level, or by considering flexibility to occur temporally before beginning a new task while stability occurs only after beginning the task. It has occasionally been argued that such a multi-level framework is the true way to conceptualize the unidimensional framework, such that the unidimensional framework actually makes no "same level" claim (c.f., Fröber et al., 2022). On the one hand, we believe this to be inconsistent with the face-value interpretation of descriptions of the flexibility-stability tradeoff as we have encountered in the literature (e.g., flexibility and stability are determined at the single level by a top-down bias parameter in Hommel's (2015) metacontrol state model[3]). If this is to be the route for future versions of the unidimensional account, we recommend that this be explicitly pinned down and captured in future models. On the other hand, such a multi-level conceptualization may prove promising as an alternative to both unidimensional and dual-dimensional frameworks, and merits future investigation (c.f., Fröber & Dreisbach, 2023). In that case, an additional step is needed to first demonstrate that flexibility and stability are being measured at different levels. In sum, we recommend future research proceed with increased attention to the implicit assumptions inherent in conceptualizations of flexibility and stability.

[3] As a caveat, this model includes a second parameter which also determines flexibility/stability (called mutual inhibition), but neither parameter can be said to assign flexibility solely to one level of the information processing process while assigning stability to another.

Regarding this future research, a central focus will undoubtedly be adjudicating between the two (possible three) competing accounts. In pursuit of this goal, we suggest some conditions required for falsifying the DDF. First, independent measures of flexibility and stability must have high construct validly, and the mappings between measures and constructs must not be ambiguous. Given that some may question the use of response congruency effects to index stability, future work may be needed to develop better measures. Second, flexibility and stability must be operationalized at the same level of processing. Third, flexibility and stability must be equally emphasized by the design, and success in both must be considered valuable to the participant. Falsification of the DDF can occur if these procedures produce a tradeoff, despite the steps taken to promote both high flexibility and stability.

5.2 Broader Impacts of the DDF

Should the DDF be supported under this rigorous attempt at falsification, the DDF may produce benefits regarding practical applications. It may also help to reframe our conceptualizations of "optimal" metacontrol. Each possibility is now discussed in turn.

Regarding the practical applications, a more fine-grained analysis afforded by the DDF might be harnessed to help explain the seemingly paradoxical combination of inappropriate flexibility and inappropriate stability in ADHD (Atalar et al., 2016; Barkley, 1997; King et al., 2007; Roshani et al., 2020). Along these same lines, the DDF can help explain another condition characterized by engagement of neither flexible nor stable goal-directed action: learned helplessness (Hiroto & Seligman, 1975; Overmier & Leaf, 1965; Seligman & Maier, 1967). Learned helplessness occurs when insufficient reinforcement prompts individuals to cease goal seeking altogether, regardless of whether the goal requires flexibility (Bukowski et al., 2019) or stability (Henderson et al., 2012; Jostmann & Koole, 2007; Mikulincer, 1989). Even in the absence of ADHD or learned helplessness, people may avoid flexibility and stability due to common demand avoidance (Brosowsky & Egner, 2021; Kool et al., 2010; Kool & Botvinick, 2013, 2018; Niebaum et al., 2019; Van Dessel et al., 2020; Vermeylen et al., 2019). In sum, meaningful ways of improving flexibility and stability would be valuable in a variety of contexts.

In the past, researchers have attempted to remediate deficient flexibility or stability by directly targeting and increasing people's capacity for these two metacontrol states. However, such efforts, especially in the form of computerized training, show little success (Simons et al., 2016). To partly explain this result, we speculate that deficiencies in flexibility or stability lie with incorrect selection of metacontrol states rather than insufficient *capacity*. According to the DDF, all three 'low-in-both' situations (ADHD, learned helplessness, and demand avoidance) reveal metacontrol states that are low in both flexibility and stability. When the current metacontrol state is inappropriate, one or more of the following three determinants of metacontrol states are the cause—lack of motivation for goal attainment, incorrectly matching metacontrol states to goal requirements, or inaccurate perception of the goal's metacontrol demands. Therefore, rather than attempting to increase the capability for flexibility or stability, we posit that it may be more effective to focus on these three determinants. For instance, when metacontrol remains in the 'low-in-both' state, it is worth asking three questions: (1) Are flexibility and stability sufficiently rewarding? (2) Are flexibility and stability required to attain rewards? (3) Does the environment sufficiently induce bottom-up processing of such requirements? Answering these questions may lead to novel ways of addressing context-inappropriate metacontrol states.

In addition to these practical applications, the DDF may speak to how we conceptualize "optimal" metacontrol. Along with problems caused by the 'low-in-both' metacontrol state, an intriguing possibility is that the 'high-in-both' state can also be detrimental. The Expected Value of Control framework (Shenhav et al., 2013) predicts that movement between metacontrol states should be efficient such that effort never exceeds task requirements. However, a DDF-unique violation of the Expected Value of Control framework could be caused by dysregulations among the three metacontrol state determinants: Applying both flexibility and stability when only one is required can be just as inefficient as applying neither. In other words, there may be inappropriate over expressions of metacontrol. Under certain circumstances, for example, providing participants with explicit but false instructions regarding the likelihood of a task switch (despite a 50% switch rate; e.g., Liu & Yeung, 2020) may hurt overall performance on a switching paradigm. The DDF allows for investigation of such phenomena along two lines: whether some people do indeed violate the Expected Value of Control framework; and how to correct such inefficiencies. This possibility aligns with recent perspectives that *more* cognitive control is not necessarily better, but that proper daily function lies with correctly aligning control strategies to situational demands (e.g., Dreisbach & Fröber, 2019). Whether addressing 'too little' or 'too much' metacontrol, future work is needed to translate these ideas into applicable interventions.

6. CONCLUSION

Here, we have pointed out that the unidimensional framework is unable to account for the full range of behavioral and neuropsychological data concerning flexibility and stability primarily at the level of task-set control. Therefore, we suggest that an independence between flexibility and stability should be considered. While several pieces of evidence supporting the DDF come from null findings—such as indicating a lack of effects or correlations—we believe that this compilation of evidence serves as a foundational resource for the field, encouraging a reconsideration of the widely assumed tradeoff. We emphasize that a tradeoff can still happen in some circumstances, but this is a function of motivation and demand for a given metacontrol state rather than a default result. We propose that adopting the DDF will help to provide a clearer, more elaborated picture of the flexibility-stability relationship that can account for a wider range of goal-directed behavior.

7. CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

8. ACKNOWLEDGEMENTS

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