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Review

Does cognitive control have a general stability/flexibility tradeoff problem?
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The claim that cognitive control is constrained by a *general* stability–flexibility tradeoff dimension has inspired research, ranging from modeling of basic control phenomena to cognitive implications for psychiatric conditions. Yet, the results with variants of the task-switching paradigm show (1) evidence of 'anti-tradeoff' patterns (co-occurrence of stability and flexibility), (2) that when tradeoffs do exist, they are often directly tied to highly specific memory representations, and (3) that there is little conclusive evidence of tradeoffs for naturally occurring variability within or between individuals. Instead of a general tradeoff dimension, we suggest conceptualizing cognitive task control in terms of navigating a cognitive map that represents competing states (tasks) with varying degrees of resolution (depending on top-down control), and where high-resolution encoding supports both stability and flexibility.

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Introduction
Positive mood appears to make us flexible but also susceptible to distractions [1–3]. Maintaining openness to multiple tasks comes at the cost of efficient performance within each individual activity [4]. And certain neurological or psychiatric disorder may represent opposite extremes of a dimension ranging from either highly perseverative to unconstrained patterns of thought or action (e.g. Parkinson's disease vs positive symptoms in Schizophrenia [5–9]).

These and related phenomena are often understood as manifestations of a fundamental stability–flexibility dilemma [10–12], an idea that initially arose from attempts to model cognitive control problems through simple connectionist networks [4,11,13–15]. In such networks, the activation pattern across nodes creates an 'attractor landscape' that allows *either* stable attractor states that resist interference *or* flexibility at the cost of increased interference (see Figure 1a). Furthermore, if our cognitive system can be either flexible or stable, but not both [4], it needs strategies for biasing itself in a context-adequate manner in either direction — a type of regulation that is now often referred to as 'meta-control' [16,17].
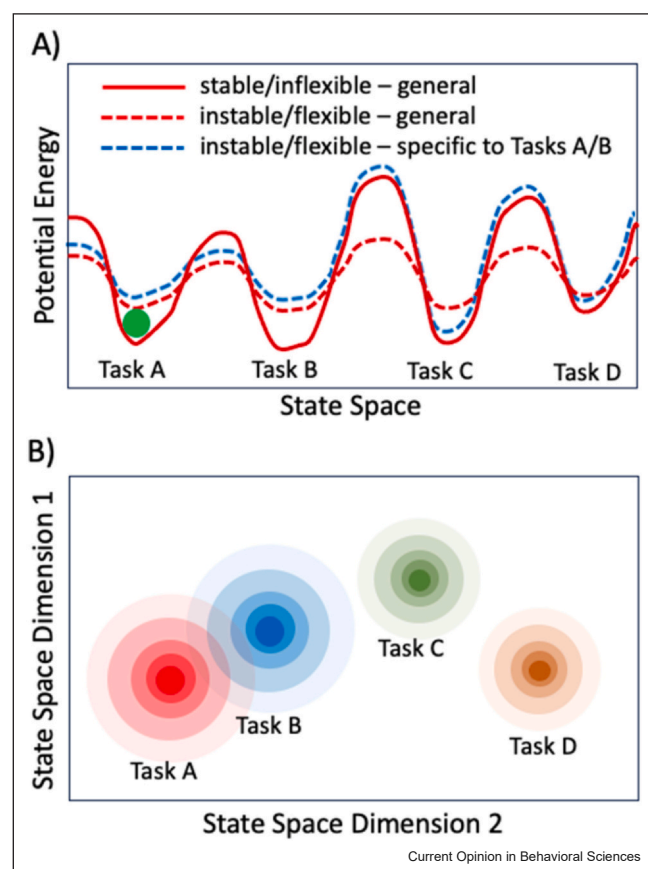
The stability/flexibility tradeoff idea is attractive because of its potential, theoretical, and pragmatic reach: It has been used to explain phenomena from trial-to-trial information processing dynamics [13] to the effects of mood on cognitive control or how cultures might shape cognition [18]. Yet, while the underlying attractor landscape model provides a causal explanation for potential tradeoffs, it comes with no specification or constraints regarding the generality of tradeoff phenomena. In principle, tradeoffs could arise either in a highly representation-specific or a 'system-wide' manner (Figure 1a), and as result from experimental manipulations, as well as from within-individual or between-individual, natural variations cognitive control (see Figure 3). Therefore, we focus here on evidence from the task-switching paradigm [19,20] as a model situation for probing the generality of tradeoff patterns (Figure 3 [21]).

Stability/flexibility in task switching
A foundational result is that task switch costs are larger following trials with response conflict (i.e. Figures 2a and 3a [11,22–24]): Supposedly, to counter conflict from the irrelevant task, current task control is strengthened, thus creating stability at the cost of flexibility. A conceptually

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The attractor landscape model and the cognitive map model of task control. **(a)** Attractor landscape model of task control. The topology of the landscape is created through the connectivity parameters of a neural network (e.g. the degree of lateral inhibition between nodes representing competing tasks). Each task is represented by attractors (i.e. basins) with varying depths. The stronger the task control, the deeper the basin, but also the more energy is required to move to an alternative basin. In principle, the depth of basins can be modulated for the entire state space (dashed red line) or in a representation-specific manner (e.g. between Tasks A and B; blue dashed line); also, variations in the depth of basins could result from control-relevant events (e.g. following conflict), from endogenous variations in control capacity, or due to individual differences (Figure 3). **(b)** The cognitive map depiction of task control. Tasks are represented as locations within a multidimensional task space encoded in LTM. The stronger the task control, the higher the resolution of the encoded representation. Higher resolution (Tasks C and D) reduces interference from competing tasks (stability) and makes tasks more easily findable (flexibility) than low-resolution encoding (Tasks A and B).

related result is that switch costs are often larger when switching from a harder, nondominant (e.g. Stroop color naming) to an easier, dominant task (e.g. Stroop word naming). Again, this 'paradoxical' switch cost asymmetry [25,26] can be explained by assuming that shielding nondominant tasks from dominant task conflict requires stronger top-down control input than the other way round. This control setting then carries over into the next trial, resulting in an activation landscape that makes switching to the dominant task particularly difficult [27,28].

Within-individual dynamics

Arguably, a unidimensional stability/flexibility continuum should also govern the naturally occurring trial-by-trial dynamics within-individual subjects. To test this prediction, Mayr et al. assessed fixations to targets (stimuli relevant to the current task) and distractors (stimuli related to the competing task) within a cued task-switching paradigm [29]. This allowed tracking the within-individual waxing and waning of interference control (stability) by identifying high-control trials (no alternate task fixations) versus low-control trials (with alternate task fixations). Interestingly, results showed the *opposite* of a tradeoff pattern (Figure 3b), indicating that endogenous variations in control had concordant effects on interference resolution and switching ability.
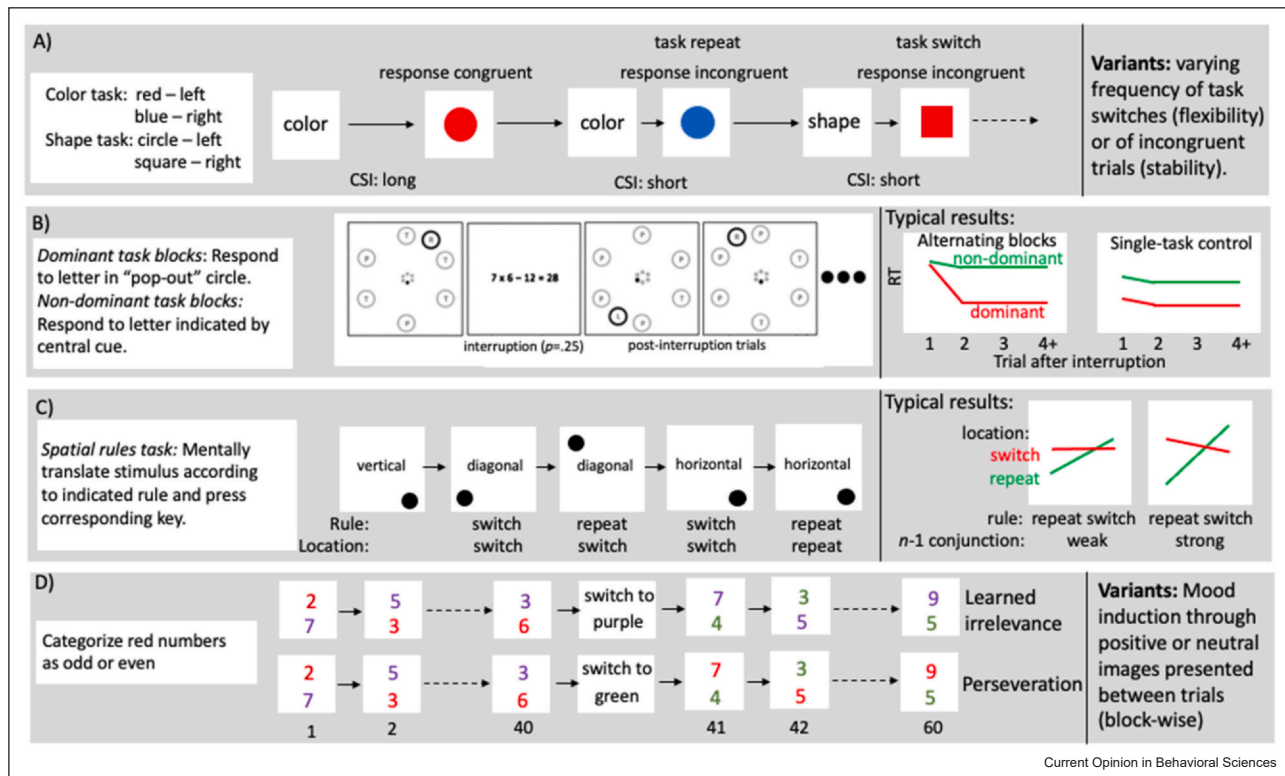
Switch cost asymmetry without switching

According to the attractor landscape model, a specific control setting should have the strongest effects on immediately following control events [22,27]. In one study from our laboratory (Figure 2b), we tested explicitly the importance of direct carry-over of activation patterns for the emergence of the switch cost asymmetry [30]. Participants performed dominant and nondominant tasks in alternating, *single-task blocks*, which were occasionally interrupted by completely unrelated math problems. The return to the primary tasks elicited postinterruption costs that were considerably larger for the dominant than for the nondominant task, even though no immediate carry-over could occur. Furthermore, this cost asymmetry disappeared in a group of participants who had never experienced the nondominant task, showing that the asymmetry arose from interfering long-term memory (LTM) traces that encoded previous encounters of the competing task (Figure 2b). Thus, instead of constrained by temporal contiguity, the tradeoff pattern was mediated through highly specific representations coded in LTM (for related results, see Refs. [31–36]). Mayr et al. [30] argued that while performing the dominant task, such LTM representations interfere when events such as interruptions or long intertrial intervals [37] trigger an opening on the working memory (WM) input gate [38,39]. The principle of parsimony implies that even regular task switches are only a special case of this category of 'WM opening' events and require no additional explanations, such as special status of carry-over from the previous trial.

Conjunctive representations

Another recent series of experiments probes the basis of representations that mediate tradeoff phenomena. The focus here was on 'partial overlap costs' [40,41], a phenomenon that is particularly prominent in task switching
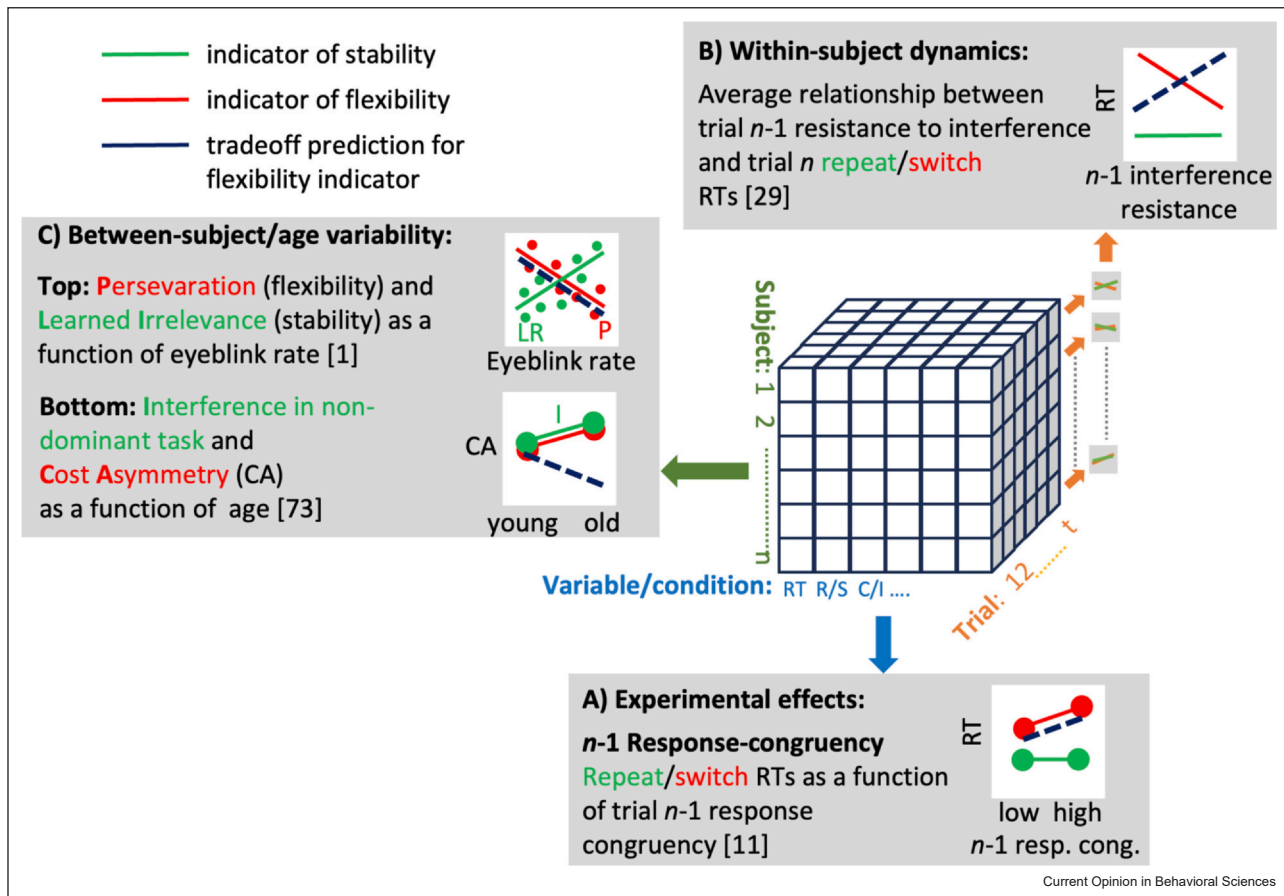
Figure 2

Variants of the task-switching paradigm to assess stability/flexibility dynamics. **(a)** Cued task-switching paradigm. In each trial, one of two or more simple stimulus-response rules is randomly cued and needs to be applied to the presented bivalent stimulus. Switch costs, the difference in performance between switch and no-switch trials serves as indicator of flexibility. Trial-by-trial variations in response–congruency (whether competing rules lead to the same or different responses) manipulate the need for interference control [11]; response–congruency effects have also been used as measure of stability [56]. Manipulations of switch frequency [29] or frequency of incongruent trials [56]) allow the independent manipulation of flexibility and stability. **(b)** Cost asymmetry without switching [31]. Participants alternate between single-task blocks of performing either a dominant task, in which attention to the target object is guided in a bottom-up manner or in a nondominant task, in which attention is guided through a central cue. Following interruptions through simple math problems, subjects show a strong cost asymmetry (i.e. larger cost for the exogenous than the endogenous task) that is limited to the first postinterruption trial (even though no actual switches between competing tasks occur here). Furthermore, the cost pattern is eliminated when participants experience only a single task throughout the entire session (single-task control). **(c)** Partial overlap costs in the rule-selection paradigm [43]. The partial overlap cost is expressed in a cross-over interaction between rule repeats/switches and position repeats/switches and supposedly reflects interference from a conjunctive representation of action-relevant aspects formed on the previous trial. On the right: EEG decoding of the trial-to-trial strength of conjunctive representations suggests that strong conjunctions on trial n − 1 lead to greater partial overlap costs [43]. **(d)** Dreisbach & Goschke stability/flexibility paradigm. Subjects begin with one attentional set (e.g. focus on red color) that is changed after 40 trials; dependent variable is the average RT across all postchange trials [1]. Changes either require switching to a color that was previously ignored (purple), while now a new color needs to be ignored (learned irrelevance) or switching to a new color (green), while ignoring the previously relevant color (perseveration). Positive mood or high eye blink rate are associated with performance benefits in the perseveration condition but with costs in the learned irrelevance condition. EEG, electroencephalogram.

situations [42]. It reflects a cross-over interaction in the form of benefits when both the rule/task and the stimulus/response either repeat or change but costs when the rule changes and the stimulus/response repeats, or vice versa (Figure 2c). This pattern has been attributed to the non-linear *integration* of all relevant action aspects for trial $n − 1$ into a conjunctive, 'event-file' representation, thought to be essential for action selection [41]. Using electroencephalogram decoding, Kikumoto and Mayr [43] directly measured the strength of conjunctive and basic-level representations in individual trials (see also Refs. [44,45]).

Importantly, trial-by-trial conjunction strength predicted same-trial response speed (RTs) — an indication of stability. Moreover, stronger trial-n conjunctions also led to larger partial overlap costs on trial $n + 1$. Follow-up work combined this paradigm with a stop signal task [46]. Here, the strength of the conjunctions at the time of the stop signal was inversely predictive of the ability to successfully stop the associated action — arguably an important aspect of flexibility [47]. Thus, the strength of conjunctions/event files indeed modulates the stability/flexibility tradeoff. Yet, the observed pattern is also highly specific: While the strength of the

Figure 3

Potential sources of variation within which tradeoff patterns can arise. The logically unrelated sources of variability are presented in the form of 'Cattell's data cube', along with representative examples of idealized data patterns (tradeoff predictions are expressed in the dark blue, dashed line). **(a)** *Experimental contrasts* (the most frequent approach) require averaging performance in a condition-specific manner while ignoring within-subject and between-subject sources of variability. **(b)** *Within-subject dynamics* can be analyzed, for example, by examining trial-to-trial relationships between performance indicators through hierarchical linear modeling. **(c)** *Interindividual differences analyses* typically use parameters extracted from experimental conditions (e.g. switch costs) but ignore trial-to-trial dynamics. Individual differences analyses can be based either on parameters from directly competing tasks (e.g. switch costs and response–congruency effects) or from independently assessed tasks (e.g. switch costs and WM).

more general rule/task representation predicted current trial RTs independently of conjunctive representations, it did not affect trial $n + 1$ flexibility [43,46].

Flexibility settings

The notion of meta-control along the stability/flexibility dimension implies that people can assume different 'flexibility control settings' depending on the context [12]. Indeed, block-wise manipulations of the switch rate show a strong reduction of switch costs when switch rate increases [24,48,49]. The earlier-mentioned study (*Within-Individual Dynamics*) in which we had used eye-tracking to directly measure between-task interference had included a switch rate manipulation and also found reduced switch costs with increasing switch rate [29]. Consistent with a stability/flexibility tradeoff, between-task interference was largest when switch costs were reduced (for high switch rate). Yet, follow-

up work with three different tasks [50] also suggested that frequency-specific adaptations reflect our cognitive system's ability to adapt to likely transitions within a given task space [51] rather than the unspecific adjustment of a 'flexibility' parameter (see also Ref. [52]). This conclusion is consistent with other findings, indicating that switch frequency manipulations are highly specific to experienced task transitions [48,53]. While there are some reports of counteracting experimental effects on switch costs and response–congruency costs [54,55], manipulations of switch frequency manipulations usually do *not* affect response–congruency effects between competing tasks [53,56]. Thus, switch frequency manipulations and response–congruency effects may occur on different levels of the control hierarchy (between-task vs within-task control), and therefore allow independent adjustments of stability or flexibility [56,57]. More generally, the tradeoffs produced by the meta-control

of flexibility settings seem to be specific to the involved representations and levels of selection.

Individual and age differences

The idea that individuals operate on different positions along the stability/flexibility tradeoff function predicts negative correlations between measures of stability and flexibility. This would constitute a remarkable deviation from the ubiquitous 'positive manifold' of correlations among any set of cognitive measures [58–61]. Probably, the strongest such evidence comes from studies showing that eye blink rate (as an indicator of striatal Dopamine levels) using the perseveration/learned irrelevance paradigm (see Figure 2b, Figure 3c, [62–64]). Arguably though, the measures used here may reflect the same underlying tendency, namely, the bias toward novel information (Figure 2d), rather than differentiable indices of stability and flexibility. Most other studies have examined relationships between separate tasks representing stability and flexibility and usually found positive or nonsignificant correlations [65–68]. However, usually these studies did not pursue process-pure measures of either aspect. Considering the strong prior expectation of a positive manifold, it is possible that without adequate experimental or statistical controls, a potential negative relationship may have to express itself against a positive 'baseline' relationship.

A recent study with the earlier-mentioned interruption paradigm [30] explicitly tested the tradeoff model prediction that individuals with weak top-down control (such as old adults and low-WM individuals) should show a reduced cost asymmetry [27]. While both groups showed clear evidence of weakened control, low-WM individuals exhibited no reduction of the cost asymmetry (controlling for age), and old adults exhibited an 'anti-tradeoff' pattern in the form of increased rather than a reduced asymmetry (controlling for WM, Figure 3c).

Caveat regarding the empirical evidence

Strong conclusions regarding the nature of stability/flexibility tradeoffs need to be conditioned on the fact that existing work has rarely considered RTs and accuracy together, such as through drift-diffusion modeling (but see Ref. [69]). This is potentially problematic, as strategic variations along the stability/flexibility dimension may easily also affect speed–accuracy tradeoffs (or vice versa), thereby potentially occluding or mimicking stability/flexibility-related effects.

Conclusions

The attractor landscape model has been highly impactful in conveying the idea of a unidimensional stability–flexibility dimension as a parsimonious explanation of variations in control across experimental conditions [11], within individuals, across individuals [64], and even cultures or differences in religious upbringing [18]. Yet, as reviewed here, relative to the assumed generality, evidence in favor of such tradeoffs appears surprisingly brittle.

Representational, not temporal constraints

A common thread through most examples discussed here is that tradeoffs are typically mediated through the very representations between which selection occurs [43,70]. Furthermore, strong endorsement of a task-relevant representation can impair later selection of a competing representation, not because of immediate carry-over, but because that event is stored in LTM and can therefore interfere anytime in the future [30,31]. Similarly, transition probabilities between specific representations appear to become part of the LTM knowledge base and subsequently modulate patterns of interference in a tradeoff-like manner [29,53] but show little sign of transfer across representations or levels of selection [56].

These results do not rule out the existence of unspecific tradeoffs or control modes. There is, for example, considerable evidence that mild positive mood facilitates a broadening of attention and favors novel information [1,71]. One interesting possibility is that evidence in favor of more general control modes is more likely obtained in paradigms that capture preferences for novelty (Figure 2d), rather than the ability to flexibly move back and forth between highly familiar representations, as assessed in the task-switching paradigm [72]. This also serves as a reminder that the stability/flexibility control dilemma is just one of several optimization problems proposed in the literature (e.g. exploration/exploration, novelty/familiarity, selection/orientation, speed/accuracy). While they all share some family resemblance, the degree of representation-level and implementation-level overlap is currently an open question — a situation that is likely to add to empirical inconsistencies.

Conjunctive representations as commitment device

The detailed analysis of the dynamics of conjunctive representations/event files suggests that these may be selectively involved in mediating specific stability/flexibility tradeoffs. One interesting hypothesis is that conjunctive representations serve as a 'commitment mechanism' that makes represented actions highly efficient but also difficult to change. A crucial next question is whether conjunctive representations are the first step toward LTM representations of action episodes [42,73] and thereby also mediate longer-term tradeoff phenomena [30]. One recent study using the electro-encephalogram decoding approach showed that the flexibility costs of strong conjunctions 'jump' across intermittent trials — a first important step toward probing the longer-term dynamics of such representations [74].

Sources of variability

While most tradeoff-consistent evidence comes from experimental manipulations within individuals (Figure 3a), many of the more interesting generalizations of the tradeoff idea are related to natural variations in control between or within individuals (Figure 3b, c). Yet, evidence regarding individual differences in relationships is rare and, in general, provides either indications of positive relationships or the absence of a tradeoff. And except for the evidence reviewed above that shows a positive stability/flexibility relationship [29], we are not aware of other examinations of within-individual control dynamics. There is no logical connection between the different sources of variability [75], making it particularly important to formulate level-specific models and test them appropriately.

Landscape or map?

From the perspective of the attractor landscape framework, stability/flexibility tradeoffs are inevitable. Yet, as mentioned earlier, the absence of such stability/flexibility tradeoffs can be explained by a model that assumes independent adjustments on different levels of control [56,57]. Prompted by the cited instances of a co-occurrence of stability and flexibility [29,76], we propose as another alternative, or complementary conceptualization that the LTM representation of the task/state space has map-like qualities (Figure 1b, [76–79]). Depending on the degree of top-down control, task sets are encoded with varying degrees of distinctiveness [76,80–82]. High distinctiveness prevents interference from nearby states and leads to memory traces that themselves produce less subsequent interference. Higher-resolution encoding also makes alternative states more findable, thereby facilitating flexible switching between states. As a downside, high distinctiveness may come with its own optimization problem as it probably also constrains generalization and transfer across contexts [83,84]. The map/distinctiveness perspective can explain why older adults who typically encode less distinct LTM traces than young adults [85,86] exhibit both greater interference *and* a greater switch cost asymmetry, instead of the predicted tradeoff. More generally, there is now an emerging set of competing models that make specific, testable predictions. Ultimately, this should lead to a more realistic, although likely also more complex characterization of the relationship between stability and flexibility.

Declaration of Competing Interest

No conflicts of interest.

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- •• of outstanding interest

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