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Review

Measuring Adaptive Control in Conflict Tasks

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The past two decades have witnessed an explosion of interest in the cognitive and neural mechanisms of adaptive control processes that operate in selective attention tasks. This has spawned not only a large empirical literature and several theories but also the recurring identification of potential confounds and corresponding adjustments in task design to create confound-minimized metrics of adaptive control. The resulting complexity of this literature can be difficult to navigate for new researchers entering the field, leading to suboptimal study designs. To remediate this problem, we present here a consensus view among opposing theorists that specifies how researchers can measure four hallmark indices of adaptive control (the congruency sequence effect, and list-wide, context-specific, and item-specific proportion congruency effects) while minimizing easy-to-overlook confounds.

Highlights

Early putative indices of adaptive control in conflict tasks have spurred not only a great deal of research but also numerous discussions on what these indices actually measure.

Recent studies have shown that adaptive control effects can be observed after controlling for low-level confounds. However, many canonical findings in the literature, for instance concerning the functional neuroanatomy of adaptive control, are based on older, confounded designs, and may thus be subject to revision.

This research field is now starting to experience a second wave of studies on adaptive control in conflict tasks employing improved designs that allow us to (re)address old and new questions.

The Quest for Pure Measures of Adaptive Control

Cognitive control (see Glossary) allows people to act in ways that are consistent with their internal goals [1]. To investigate such control, psychologists often use selective attention tasks that create **conflict** by pitting instructed task goals against incompatible stimulus information and automatic action tendencies (i.e., conflict tasks). For example, in the seminal Stroop task [2], researchers study how the ability to identify the color of a printed word varies with whether the word cues a different semantic representation and response than the color (e.g., the word BLUE in red ink; incongruent trials) or whether these are the same (e.g., the word RED in red ink; congruent trials). Participants typically respond more slowly and less accurately on incongruent versus congruent trials. Researchers commonly consider the size of this 'congruency effect' as being indicative of the signal strength of the irrelevant dimension relative to the relevant dimension, as well as of the level of cognitive control applied – when congruency effects are relatively small, researchers infer that there is greater recruitment of cognitive control.

Importantly, conflict tasks also allow psychologists to study modulations of congruency effects that are thought to reflect adjustments of cognitive control; we refer to this as **adaptive control** (sometimes also called 'control learning' [3]). These dynamic adjustments of control are particularly important to measure because it is the matching of processing modes (e.g., a narrow vs a wide focus of attention) to changing environmental demands, and/or in response to performance monitoring signals (e.g., conflict), that characterizes adaptive behavior [4]. In other words, instead of conceptualizing control as a static, time-invariant process (e.g., by assessing mean congruency effects over an entire experiment), adaptive control research is concerned with how control is regulated in a dynamic and time-varying manner. This captures both the need to deal with a changing environment as well as the notion that control is costly and should be imposed only as much as necessary [5]. Research on adaptive control has already led to many important insights and influential theories [5–9], and continues to inspire an increasing number of studies. Moreover, beyond the basic research domain, adaptive control has been the topic of many studies and theories on developmental changes [10–12] and on various clinical disorders [13–19].

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However, numerous metrics of adaptive control have been put forth, criticized, and revised several times. Therefore, it can be difficult for new (or applied) researchers in this domain to infer what represents current best practices for studying adaptive control. In fact, many studies continue to use task designs or analysis strategies that researchers in the basic research community no longer consider to effectively measure adaptive control [20,21]. For example, a recent review on adaptive control in schizophrenia concluded that 'there are very few clearly interpretable studies on behavioral adaptation to conflict in the literature on schizophrenia' ([13], p. 209). Crucially, systematic comparisons between older, confound-prone, and newer, confound-minimized measures of adaptive control have shown differential behavioral effects [22] and patterns of brain activity [23,24]. Therefore, the aim of the present paper is to promote best practices for investigating adaptive control, based on a current consensus view shared by different researchers in this field.

The Need for 'Inducer' and 'Diagnostic' Items when Studying Adaptive Control

When employing conflict tasks, the goal of the researcher is typically to isolate changes in behavior that reflect adjustments to relatively abstract attentional settings or task representations (e.g., 'pay more attention to the target' or 'be cautious in selecting the response') as opposed to concrete settings (e.g., 'look at the green square' or 'press the left response key'). For example, in the Stroop task, abstract adjustments of control could involve paying more attention to the task-relevant color dimension or trying to inhibit the response cued by the task-irrelevant word dimension. Such adjustments are abstract in the sense that they should lead to generalizable performance benefits that are independent of specific stimulus features or actions [25]. For instance, increased attention to the task-relevant color dimension should lead to reduced interference from the task-irrelevant word dimension, regardless of the exact color and word that appears.

However, several researchers have pointed out that classic purported indices of adaptive control in conflict tasks can often be re-explained in terms of more basic stimulus–stimulus or stimulus–response learning processes ([21] for review). These considerations have led to various theoretical discussions about how such forms of lower-level learning relate to cognitive control (Box 1). However, experts in this domain generally agree that manipulations that promote learning at this concrete level are relatively easy to avoid. Therefore, if researchers want to study adaptive control independently of low-level learning, our recommendation is that they should employ paradigms that are designed to minimize opportunities for exploiting stimulus–response or stimulus–stimulus associations. We will refer to these design features in the remainder of this paper as 'confounds' (but see the section When Low-Level Learning Is Not a 'Confound').

To explain how to accomplish this goal, we brought together different researchers in this field (with different theoretical backgrounds, Box 1) to summarize an emerging consensus view on how to design conflict tasks to study adaptive control. It quickly became apparent that the best way to summarize our view is to emphasize one key experimental design principle that enables researchers to investigate adaptive control in a confound-minimized fashion. Specifically, the principle is to distinguish between **inducer items** that trigger adaptive control and **diagnostic items** that measure the effects of adaptive control on performance.

Without going into the intricacies of the different confounds when investigating adaptive control, which have been extensively discussed in other papers [21,26,27], we describe here how to create tasks that avoid these confounds. We focus on four common markers of adaptive control (Box 2 and Figure 1): the congruency sequence effect (CSE), the list-wide proportion congruency effect (LWPCE), the context-specific proportion congruency effect (CSPCE), and the item-specific proportion congruency effect (ISPCE). Specifically, we discuss how the inclusion of inducer and diagnostic items minimizes confounds that often prevent researchers from

Glossary

Adaptive control: refers here to control processes or executive functions that dynamically adjust processing selectivity in response to changes in the environment or to internal (performance) monitoring signals (e.g., conflicts).
Cognitive control: the term (also 'executive functions') is generally used to describe a set of (not always well-defined) higher-order processes that are thought to direct, correct, and redirect behavior in line with internal goals and current context.
(Cognitive) Conflict: conflict in information processing is thought to occur when two or more mutually incompatible stimulus representations and/or response tendencies are triggered by a stimulus, such as an incongruent stimulus in the Stroop task (invoking e.g., both 'blue' and 'red').
Conflict adaptation: adaptive processes that are putatively triggered following the detection of conflict and are recruited for the purpose of resolving this conflict or preventing subsequent occurrences of conflict. This term is sometimes also used to refer specifically to the CSE.
Contingency learning: the general learning process of forming stimulus–stimulus and/or stimulus–response associations based on their co-occurrence, where the strength of the association increases as a function of the frequency of co-occurrence. While contingency learning is often discussed within the context of implicit learning, it is not necessary to make any assumptions about whether this learning occurs explicitly or implicitly, or is strategic or automatic.
Diagnostic items: items that are used to 'measure' the effects of adaptive control on performance. These items are sometimes also referred to as non-manipulated items, unbiased items, transfer items, or test items.
Feature integration: the idea that multiple features of a given stimulus are integrated or bound together in perception and memory. An extension of this idea holds that this integration of the features of an experience (or event) in memory also incorporates one's response to the stimulus into an episodic 'event file'. The subsequent presentation of one of those event features is then thought to facilitate the retrieval of the entire event file from memory. More recently, it has been proposed that event