





Caught in the ACTS: Defining Abstract Cognitive Task Sequences as an Independent Process

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Abstract

■ Cognitive neuroscience currently conflates the study of serial responses (e.g., delay match to sample/nonsample, n -back) with the study of sequential operations. In this essay, our goal is to define and disentangle the latter, termed *abstract cognitive task sequences* (ACTS). Existing literatures address tasks requiring serial events, including procedural learning of implicit motor responses, statistical learning of predictive relationships, and judgments of attributes. These findings do not describe the behavior

and underlying mechanism required to succeed at remembering to evaluate color, then shape; or to multiply, then add. A new literature is needed to characterize these sorts of second-order cognitive demands of studying a sequence of operations. Our second goal is to characterize gaps in knowledge related to ACTS that merit further investigation. In the following sections, we define more precisely what we mean by ACTS and suggest research questions that further investigation would be positioned to address. ■

INTRODUCTION

What Is the Problem? (e.g., What Abstract Cognitive Task Sequences Are NOT)

The goal of this first section is to characterize an issue of conflation in cognitive neuroscience. Researchers commonly examine behavioral responses across multiple trials over time in many tasks. We carefully probe how factors such as practice, stimulus familiarity, reappraisal, and so forth, change behavioral patterns. This section references existing literatures that tile these areas to reveal in the negative space an orphan region that is not well-defined in the field.

What Is Abstract Cognitive Task Sequences?

Abstract cognitive task sequences (ACTS) are ordered series of operations with a beginning and an end. They unfold through time, but, importantly, they are abstract in that they are not required to be bound by exactitude in timing or stimuli (see Figure 1). By way of metaphor, we note that existing literatures are interested in what goes into the mix whereas ACTS is interested in examining how the mixer itself operates. For example, the order of operations is essential to solving arithmetic problems. If you remember “multiplication and division, then addition and subtraction,” then regardless of the numbers themselves, that sequence of operations remains constant. Given a query such as $2 + 5 \times 3$, the proper sequence of

operations is to multiply 5×3 and then add 2 yielding 17. The same sequence unfolds in a new problem (e.g., $4 + 2 \times 8$), but yielding a different outcome. The operations must proceed in the correct order, but whether you spent 2 sec or 2 min between the steps is inconsequential, as is the size of the digits, the font color, or even the modality (e.g., visual or auditory).

To carve out a territory for ACTS, we systematically summarize how different processes and existing task arenas that include serial processes are also distinct from ACTS. We organized these topics, roughly, from least to most complex. The goal of this summary is to define the attributes of ACTS that distinguish it from existing paradigms and observations. In other words, by laying out a foundation from existing literatures, we aim to distinguish a separate cognitive operation in its own right.

Repeating Stimuli

The most basic presentation that can be considered a “sequence” is a repeated stimulus. They are construed as a sequence by examining the response to rare violations, or deviants, from the established order. Tasks used to examine the responses to the deviants are termed “oddball” tasks.

Early studies examining the neural responses to deviants, or “oddballs” were performed in the 1970s and used EEG in humans to extract ERPs (e.g., Näätänen, Astikainen, Ruusuvirta, & Huotilainen, 2010). One useful tool to characterize the novelty response is the MMN. An MMN is calculated by subtracting the ERP response to the repeated

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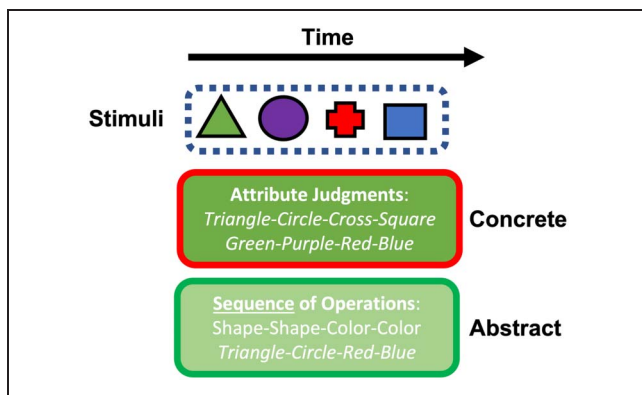


Figure 1. Defining ACTS: Given a sequence of colored shapes presented individually to a participant over time, a concrete task could impose a perceptual judgment task such as reporting the shape or the color of each item. In contrast, an abstract sequence of operations requires participants to recall a series of operations to impose on whatever stimuli arrive. It is this second-order condition that we term: ACTS.

(standard) stimulus from the response to the uncommon (oddball) stimulus. This subtraction reveals a negative potential beginning ~ 100 msec poststimulus onset and localized to lateral and anterior electrode sites (reviewed in the work of Garrido, Kilner, Stephan, & Friston, 2009). The underlying dipoles are localized to auditory and frontal regions (Jemel, Achenbach, Muller, Ropcke, & Oades, 2002). The MMN extends to the visual modality (e.g., Pazo-Alvarez, Cadaveira, & Amenedo, 2003) and continue during sleep (Sallinen, Kaartinen, & Lyytinen, 1994). Responses may be entrained such that they persist even when a stimulus is withheld (Hughes et al., 2001). Similar novelty signals extend beyond humans to other species, with novelty responses identified in retinal ganglion cells in salamanders and mice (Schwartz, Harris, Shrom, & Berry, 2007), and in the superior colliculus of monkeys (Boehnke et al., 2011).

Why Repeating Stimuli Are Not ACTS

Despite some elements of sequence detection and processing, repeating stimuli with or without oddballs are not ACTS because they are low-level tasks requiring no behavioral response. Furthermore, repeating stimuli and oddballs are defined by the preceding stimulus or context. The stimuli themselves evoke the response rather than being grist for an operational response.

Statistical Learning

Statistical learning (SL) is the process of extracting regularities from co-occurring stimuli in the environment. Participants typically view or hear a series of stimuli, but embedded within the sequence are statistical probabilities of one stimulus to another so that some combinations are highly likely. This familiarization phase may be entirely passive, or there may be a cover task ensuring

participants are attending to the stimuli and experiencing the frequent pairings as intended. SL is established when participants respond more quickly to the predicted stimulus having viewed the predictor (Conway, 2020). In this section, we focus first on SL of sensory sequences, followed by implicitly acquired motor sequences.

Arising from the infant language development literature, sensory SL and its neural mechanisms spawned a vast literature. Initial studies focused on behavior, illustrating that infants spend longer time listening to auditory streams of unfamiliar syllable pairs compared with familiarized pairs. This habituation effect was an evidence of expectancy violations built by acquiring the transition probabilities between syllables (Saffran, Aslin, & Newport, 1996). These responses are present in nonhuman primates (Hauser, Newport, & Aslin, 2001). The neural substrates of SL include sensory processing areas for specific domains such as vision or audition, and domain general areas in the medial temporal lobe (Henin et al., 2021; Park, Rogers, Johnson, & Vickery, 2021). Neuropsychological patients with hippocampal (Schapiro, Gregory, Landau, McCloskey, & Turk-Browne, 2014) or memory deficits (Cerreta, Vickery, & Berryhill, 2018) show reduced visual SL, consistent with modeling implicating the hippocampus in SL acquisition (Schapiro, Turk-Browne, Botvinick, & Norman, 2017). In nonhuman primates, neural recordings complement the human data. Visual areas such as inferotemporal cortex respond more strongly to unanticipated stimuli (Meyer & Olson, 2011). This result has also been demonstrated during awake monkey fMRI, in which viewing random images elicits increased inferotemporal cortex and early visual area responses, once adaptation to familiar images has occurred (Vergnienx & Vogels, 2020). Both humans and monkeys detect rule violations during artificial grammar tasks with auditory and visual sequence components (Milne, Wilson, & Christiansen, 2018). Both humans and nonhuman animals identify and respond to regularities as SL pairs occur in sequence.

For SL involving motor sequences, several studies have dissected implicitly acquired action sequences by looking at serial reaction time tasks (SRTTs). In an SRTT, participants view serially presented stimuli and respond with compatible button presses. Participants are never told of the repeating sequence. Participants' RTs improve with practice and slow when the stimuli are randomized, revealing implicit learning of the sequence (Nissen & Bullemer, 1987). Few participants can accurately report the motor sequence when queried (Cohen, Ivry, & Keele, 1990). The implicit nature of sequential learning in SRTTs provides an opportunity to investigate how the brain responds to the kinds of regular sequences we execute every day.

Human and animal studies of the neural correlates of SRTTs identify the hippocampus as well as cortico-basal ganglia-cerebellar circuitry in acquiring the sequence (Clark & Lum, 2017; Will et al., 2013; Christie & Dalrymple-Alford, 2004; Schendan, Searl, Melrose, &

Stern, 2003). Parkinson's patients with basal ganglia lesions are impaired at SRTTs, suggesting a causal role for subcortical structures (Clark, Lum, & Ullman, 2014). A meta-analysis of 20 SRTT human neuroimaging studies supports these conclusions, converging on activity in the globus pallidus, putamen, and caudate nucleus (Janacsek et al., 2020). However, much remains unknown about the roles that each region plays in supporting implicit sequence learning.

A construct frequently associated with SL (across modalities) is the concept of a cognitive map. Cognitive maps are an internal model of the world that connect events and stimuli to predictions of actions and consequences (Behrens et al., 2018). Neurally, such maps are usually discussed as being instantiated in the hippocampus and surrounding structures. They can support sequence learning (Stiso et al., 2022), and they can be abstract in that second-order relationships can be learned (e.g., if $A > B$ and $B > C$ then $A > C$). An interesting open question is whether a structure like a cognitive map could support the execution of ACTS, but this is currently unknown because the tasks used to study cognitive maps are not ACTS themselves.

Why SL Is Not ACTS

SL paradigms share the serial aspect of ACTS. SL tasks also are used to understand higher-order cognitive processing that require serial presentation of information across time and some relationship between stimuli. However, SL cannot be considered ACTS because of SL's reliance on the passive, implicit acquisition of regularities. This contrasts with the higher-order abstraction central to ACTS. SL tasks are not ACTS because they do not impose task sequences, nor require explicit knowledge of the task architecture.

Perceptual Pattern or “Grammar”

Tasks involving perceptual patterns contain elements discussed in the Statistical Learning section but incorporate an element of abstraction. Such paradigms may include serially presented stimuli, with predictable transition probabilities between them. However, unlike SL tasks where the transition probabilities of items are bound to and defined by specific stimuli, tasks containing perceptual patterns rely on abstract rules that are independent of stimulus identity. Algebraic patterns provide an example. Algebraic patterns describe the relationship that can exist between a series of stimuli (Wang, Uhrig, Jarraya, & Dehaene, 2015). For example, the presentation of the symbols “\$\$\$%” and “&&&*” can be represented by the algebraic pattern “AAAB.” Other lines of research have termed these relationships as “hierarchical structures” that can be learned by infants (e.g., Kovacs & Endress, 2014). These perceptual patterns can be summarized by a higher-order structure that is independent of the specific stimuli.

Our knowledge of the neural mechanisms underlying the detection of perceptual patterns were shaped by

paradigms investigating deviations from patterns. One such paradigm is the “local–global” paradigm (Bekinschtein et al., 2009). The local–global paradigm has two kinds of deviations. The “local” deviations resemble the oddball paradigms discussed above, in which one element is different (schematized as AAAB). There are also “global” deviations based on a structure that is established by repetition in which participants are habituated to a higher-order algebraic pattern, for example, AAAB or @@@# that is independent from the component stimuli (e.g., ABAB). In addition, there is specific neural activity that occurs during the local–global paradigm. The local oddball (a change from A to B in AAAB) elicits a mismatch response as described above (“Repeating Stimuli”) and persists after extended experience or lack of conscious awareness (Strauss et al., 2015; Bekinschtein et al., 2009). Unlike the local deviant mismatch responses, global deviant responses only occur when there is awareness of the higher-order algebraic pattern. Unlike local deviants that mainly elicit neural responses in sensory cortices, global deviants elicit neural activity in a variety of higher-order brain areas including PFC and temporal cortex, a finding replicated in humans and nonhuman primates (Dürschmid et al., 2016; Wang et al., 2015; Uhrig, Dehaene, & Jarraya, 2014). Paradigms including deviations to established perceptual patterns report persistent neural responses only if there is awareness of the higher-order global structure in the task. Human and nonhuman primate brains process perceptual patterns in higher-order cortices compared with simpler tasks lacking this level of abstraction.

Why Perceptual Pattern Is Not ACTS

Several features in the perceptual patterns are essential components of ACTS. As in ACTS, there is a representation of a higher-order abstract sequence that can be summarized independently of the stimuli employed. In addition, these paradigms are distinct because explicit awareness of the sequence structure is required, unlike SL. However, perceptual patterns cannot be described as ACTS because they are passive and no behavioral response is required.

Motor Sequences

In the Statistical Learning section, we focused on the relationship between *implicit* motor sequences and ACTS. A separate class of motor sequences falls under explicit awareness and merits a separate discussion. Habitual actions are ordered motor outputs that may be executed without intentional supervision of individual steps, for instance, brushing one's teeth. Conversely, instructed/supervised action sequences require active monitoring of the individual steps being executed. A supervised motor sequence, say making an omelet, requires monitoring of the individual steps of the sequence (heating the oil, chopping an onion, cracking the egg, etc.).

Animal research into habitual action sequences revealed the important role of subcortical structures including the

striatum and basal ganglia (Desrochers, Burk, Badre, & Sheinberg, 2015). The striatum may represent the boundaries individuating action sequences (Desrochers, Amemori, & Graybiel, 2015; Jin & Costa, 2010; Fujii & Graybiel, 2005), without representing intermediate steps (Jin, Tecuapetla, & Costa, 2014). These results suggest habitual motor sequences are not actively monitored at each stage, but are executed as an automated chain of events. In contrast, instructed sequences require more sophisticated control. When monkeys were taught to push, pull, and turn a handle in designated orders, neurons in the SMA and pre-SMA responded to the ordinal position of each step (Shima & Tanji, 2000; see also the work of Clower & Alexander, 1998). Learning new motor sequences recruits the dorsolateral PFC and the frontal eye fields, which exhibit activity related to the rank of individual actions (Berdyeva & Olson, 2010; Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994).

Supervised motor sequences can be end points of ACTS. The completion of a motor step can cue a subsequent step. This chaining shifts emphasis away from an overarching sequence of multiple steps and refocuses it to individual transitions (Bancroft, Weiss, Libby, & Ahearn, 2011). Although research into supervised action sequences has advanced our understanding of how sequences are represented, few studies separate the abstract cognitive from motor requirements. Recent work has begun to answer pertinent questions regarding potential hierarchies of abstractly tracked sequences and motor actions (Trach, McKim, & Desrochers, 2021), but questions remain under active investigation.

Why Motor Sequences Are Not ACTS

Habitual motor sequences are represented as automated chains of events with little attention to individual steps. In contrast, ACTS, by definition, requires active step-wise executive monitoring. One can execute ACTS without a predesignated motor sequence. These questions highlight the issues of conflation noted earlier, and indicate the need for research into ACTS to clarify the boundaries and interplay between motor and abstract sequences.

Serial Attention

The role that attention plays in ACTS is worth consideration. Among the vast literatures associated with attention, phenomena associated with changes over time are relevant because of the relationship to sequences of events intrinsic to ACTS. Of these, selection history is particularly relevant and reflects changes in behavior as a function of recent task demands (Anderson et al., 2021; Awh, Belopolsky, & Theeuwes, 2012). One example is the impact of a search template or a recent target feature in driving subsequent attentional focus. For example, finding a green olive makes you more likely to attend to the green celery rather than orange carrots because working

memory (WM) retains the color feature (Wolfe, Cain, & Aizenman, 2019). Selection history affects attentional deployment in the next trial (reviewed in the work of Anderson et al., 2021). Stimuli that were targets convert to powerful distractors when designations flip (Kristjansson & Driver, 2008). In addition, items that predict reward or punishment attract more attention even after they become task irrelevant (Anderson & Britton, 2020; Bucker & Theeuwes, 2017). Related behavioral effects are associated with invalid cues in the spatial orienting task (Posner, 1980). Ignoring a cue is more likely after an invalid cue (Qian et al., 2020). To reiterate, the sequence of serial attention influences behavior.

Selection history involves diverse neural underpinnings. Reward circuitry and its interaction with sensory and attention-related brain areas are involved (but see the work of Anderson et al., 2021). Similarly, attentional priming has multiple neural mechanisms on many levels of the processing hierarchy that can bias neural processing for variable duration (Kristjansson & Asgeirsson, 2019). Emerging findings indicate that attentional sampling follows a periodic cycle across frontoparietal networks (Fiebelkorn & Kastner, 2019). In understanding the source of any attentional effects, the roots are deep and the trunk is broad.

Why Serial Attention Is Not ACTS

Beyond its inherently serial nature, selection history can be abstract but it is permanently linked to the previously attended stimulus. Thus, selection history is the first-order serial effect that contributes to the second-order effects that ACTS captures. They might benefit or hinder performance. In contrast to ACTS, serial attention effects can proceed automatically. Findings that relate to serial attention effects should inform how research on ACTS is done to avoid biasing attention with these automatic attentional biases that can arise from sequential processing.

Episodic Memory Segmentation

Although the research on episodic memory may seem removed from ACTS, we note that it is inherently sequential. Indeed, research on spatial navigation, temporal processing, autobiographical memory, prospective memory, and episodic future thinking include sequential events. The continuous nature of time imposes a major challenge on episodic memory, that of encapsulating one set of moments as a single chapter. The research that addresses the parsing of memory into episodes, termed *event segmentation*, is currently a burgeoning, well-reviewed literature (e.g., Clewett, DuBrow, & Davachi, 2019; Sugar & Moser, 2019; Brunec, Moscovitch, & Barense, 2018; Richmond & Zacks, 2017). Importantly, the hippocampus and its interactions with the medial PFC and other cortical structures keep track of temporal order both within (Ezzyat & Davachi, 2021) and across events (Davachi &

DuBrow, 2015). This literature focuses on detailing the role the hippocampus and other medial temporal lobe regions play in instantiating memory.

Why Episodic Memory Segmentation Is Not ACTS

There are several key differences between ACTS and episodic memory. Time is constantly flowing making episodic memories naturally sequential. The order of some events cannot be altered (e.g., death cannot come before birth). The tasks within ACTS are not necessarily meaningful, and the order is changeable. Furthermore, it is unclear how time is divided into meaningful events. ACTS have clearly defined and reasonable segmentation points. Last, episodic memories are not abstract. Instead, they are concrete events. These memory sequences are created through encoding specific stimuli and environments. ACTS are abstract sequences that do not rely on stimuli.

WM for Sequences

To this point, we have discussed classes of tasks and their differences and similarities with ACTS. For this last section, we reorient to serial WM tasks. Relevant tasks require keeping track of a sequence of steps unfolding in time (reviewed in the work of Manohar, Pertzov, & Husain, 2017). Often, these tasks mimic activities of daily life. For example, in making breakfast, there is a WM demand imposed by brewing coffee and remembering to put the water in the machine while also remembering to get the toast from the toaster and recalling that you should grab a knife on route to grabbing the butter (see also the literature on “everyday tasks,” e.g., Divers et al., 2021). Experimental tests of serial order WM can involve sequential presentation of items and, after a delay, ask participants to report the ordinal position of a single probe item, or to replicate the sequence (e.g., Guitard, Saint-Aubin, & Cowan, 2021; Berryhill & Olson, 2008). Findings support a cognitive architecture that includes both domain-general WM and modality-specific visuospatial/verbal stores to conduct serial ordering WM tasks (Gorin, Mengal, & Majerus, 2018).

Indeed, an active literature in cognitive psychology debates models of serial order (see also the work of Henson, 1998; recently reviewed in the work of Logan & Cox, 2021). Prominent models include *chaining*, reflecting serial linkages between items; *positioning*, which supposes that there is a representation of the item’s position independent of neighbors; and *competitive queueing*, which argues that the strongest representation is selected in descending order (reviewed in the work of Hurlstone, Hitch, & Baddeley, 2014). Serial order WM is clinically relevant because of behavioral deficits in several clinical populations including dyslexia (Majerus & Cowan, 2016) and Down syndrome (Godfrey & Lee, 2018). The cognitive neuroscience of serial order identifies a broad

frontoparietal and subcortical network showing activity associated with maintaining WM for serially presented items that develops over childhood (Ye et al., 2020). Neural correlates emphasize the roles of the basal ganglia and PFC networks in models of serial order (Parto Dezfouli, Davoudi, Knight, Daliri, & Johnson, 2021; Johnson et al., 2018; Beiser & Houk, 1998). Nonhuman primate data provide converging evidence regarding the underlying neural correlates. In a task of spatial ordering, a proportion of neurons in lateral PFC showed sensitivity to spatial order (Ninokura, Mushiake, & Tanji, 2003; Funahashi, Inoue, & Kubota, 1997). In essence, WM for serial order provides a closely relevant comparator because it includes the WM demand for keeping track of the conjunction of item identity and ordinal position as presentations occur in time.

Other task structures discussed within the domain of WM also bear resemblance to ACTS. Complex tasks that are structured hierarchically (e.g., Duncan, Schramm, Thompson, & Dumontheil, 2012), such that context at upper hierarchical “levels” dictates how it is applied at lower levels, have overlap in their abstract, cognitive, and task nature. Yet, participants are not asked to remember and apply rules sequentially; therefore, the task does not fit the requirements of ACTS. Further research is needed to investigate hierarchical structures and whether they can support sequential processes within individual steps. It may become clear that there are areas of overlap with ACTS.

Why WM for Serial Order Is Not (Always) ACTS

Despite significant overlap, there is at least one important difference between WM for serial order and ACTS. Most commonly, serial order stimuli are objects, locations, or words. All of these are concrete representations. This means that current serial order tasks fail to meet the requirement of an abstract representation for an operation that ACTS requires.

In summary, complex serial order WM tasks have intriguing points of overlap with ACTS, but fail in one or more of the requirements. WM tasks typically require a single judgment for each trial (e.g., old/new, confidence 1–6). In reading span or auditory span tasks, the WM demands are higher, as participants must remember the final word of each sentence. The WM difficulty is heightened by a greater number of distractors. We argue that it is not ACTS because it does not require different kinds of processes. Adjusting the task could satisfy the ACTS requirements. For example, a language span task that required participants to alternately produce a synonym or antonym would qualify. Similarly, in a multispan task such as the Operation Span Task (Unsworth, Heitz, Schrock, & Engle, 2005), two different tasks (spatial span and arithmetic) are interleaved. Again, the WM challenge is high, but it does not satisfy the ACTS criteria of abstraction. Such a task could be modified to become ACTS if the participants were required to recall the correct math operand on, say, even

and odd trials. In other words, ACTS requires the storage and maintenance of the instructions to determine the task per trial. Task paradigms where the instructions remain constant trial per trial cannot be ACTS. Indeed, WM is a fundamental component of ACTS, but not all WM tasks are ACTS.

ACTS

We discussed many sequential processes that could be related to ACTS (see Figure 2). It is currently unknown if perceptual, memory, attentional, and motor sequences can collectively be thought of as components of ACTS, or if they are entirely separate processes, with their own separate neural mechanisms. We summarized the challenge we faced in pinpointing ACTS by looking at what it is not.

Few studies have investigated the neural basis of ACTS. One study (Desrochers, Chatham, & Badre, 2015) asked human participants to make judgements (indicated by a button press) about the properties of simple stimuli while undergoing fMRI scanning (see Figure 3). The judgment was either about the stimulus' color (red or blue) or shape (circle or square). Participants were instructed as to the sequential order of judgments (e.g., color, color, shape, shape) at the beginning of each block. This sequence of judgements was repeated through the block (~5 times), and there were no cues provided as to whether the judgment on a given trial was color or shape. The absence of cues meant participants had to "track" their position within the judgment sequence themselves. Furthermore, because the stimulus was not predictive of the task demands, participants could not prepare a motor response ahead of stimulus presentation. This paradigm explicitly created ACTS that could be separated from perceptual or motor sequences.

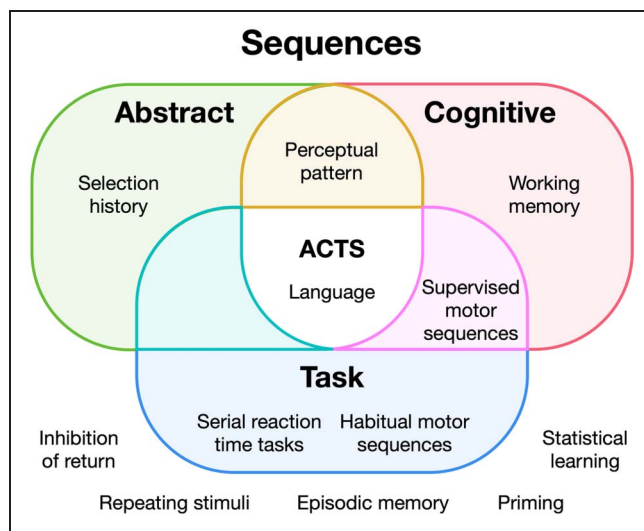


Figure 2. A Venn diagram of several types of sequences discussed above. Several sequence types have features that make them Abstract, Cognitive, or related to a Task, but few lie at the intersection of all to create true ACTS.

This ACTS experiment identified a novel brain dynamic associated with completing the task sequences: a steady increase (“ramp”) in activity from the first to the last position in each four-item sequence. Further, with noninvasive brain stimulation (TMS), the authors showed that a specific region in the anterior prefrontal cortex, the rostralateral prefrontal cortex (RLPFC), was necessary to complete ACTS. In addition, ramping activity was observed in a network of brain areas, such as the medial frontal, superior parietal, and anterior temporal cortices, that are commonly identified as part of the fronto-parietal control network (Yeo et al., 2011). Subsequent experiments have replicated these general results and the specific engagement of ramping activity in RLPFC during ACTS (McKim & Desrochers, 2022; Desrochers, Collins, & Badre, 2019). A small number of other studies have examined task-level sequential control (Farooqui, Mitchell, Thompson, & Duncan, 2012; Koechlin & Jubault, 2006; Koechlin, Corrado, Pietrini, & Grafman, 2000) and shown similar activation in an overlapping set of areas that includes the RLPFC (see the work of Desrochers, Chatham, & Badre, 2015, for further discussion). However, these studies did not explicitly test for ramping dynamics, and differed in the degree of external cues and sequence consistency. Further investigation will be necessary to examine ACTS based on other paradigms.

Although we propose that neural ramping activity may be an important mechanism that supports ACTS, we acknowledge that these signals have been observed in relation to many other cognitive processes such as accumulating evidence, time, anticipation of reward, and motor preparation (for a review, see the work of Desrochers & McKim, 2019). Computational models support the hypothesis that a time-varying signal could be employed to uniquely code position in a sequence (e.g., Anderson & Matessa, 1997) and there is neural evidence that such low dimensional representations are preferred by the brain to track events that unfold through time (Cueva et al., 2020). Therefore, the precise connection between ramping activity and ACTS requires further investigation.

In animals, to our knowledge, only one study has approached ACTS-like behavior. Monkeys were trained to reproduce two- or three-item sequences of touches, either repeating (ABC, ABC) or mirroring (ABC, CBA) their original order (Jiang et al., 2018). These “rules” could be generalized such that they could perform novel sequence locations and orders. Critically, the animals could combine the two rules “repeat” and “mirror” to produce a simple two-item task sequence. The authors discuss that this task, although sophisticated, could be solved with a memory “stack” that could be read out in one order or another without necessarily performing an abstract task operation. Furthermore, children could clearly complete this task with much less training. Therefore, it remains unknown if monkeys could learn more complex ACTS and what neural mechanisms support them.

Given the similarities in the network of areas observed during ACTS to brain areas observed in many other kinds of sequences, it is tempting to argue that these other non-ACTS serve as the building blocks for ACTS. However, limited behavioral evidence indicates that the relationship

is not that simple (Trach et al., 2021). Participants performed a modified version of the ACTS paradigm in which some conditions contained an embedded (implicit) motor sequence. This manipulation enabled the direct examination between “higher-level” ACTS control processes and “lower-level” motor sequences. If motor sequences were the building blocks of ACTS, then behavioral indicators of motor sequence performance might be additive with behavioral indicators of ACTS performance, and not interactive. However, there was an interaction observed such that the current step in the upper-level ACTS influenced the performance of the motor action, and the presence of the motor sequence influenced sequence-specific indicators of ACTS performance (and not overall cognitive control processes). These results underscore the importance of studying ACTS themselves—together and separate from other sequences—and the neural basis of these interactions remains an important avenue of future research.

ACTS Required: Research Questions

Further scientific investigations are needed to better characterize ACTS. What is the advantage of doing so? We posit that without a direct understanding of any superordinate structure that may govern ordered tasks, it would be too easy to misattribute brain function to the wrong processes and/or mistake processes being part of a particular area’s or network’s function. Disambiguating these confounds is critical to push theory and the general field of scientific inquiry forward, particularly as scientists naturally progress toward more complex questions and corresponding behavioral paradigms.

Another advantage to clearly defining ACTS and their underlying neural circuitry is the potential to confer a greater understanding of diseases and disorders that have deficits in ACTS processing. Often, patients with frontal lobe disorders can perform well on classic test of executive function but fail on the kinds of ACTS that are common in daily life, such as cooking for themselves, that make them incapable of independent living (Shallice & Burgess, 1991;

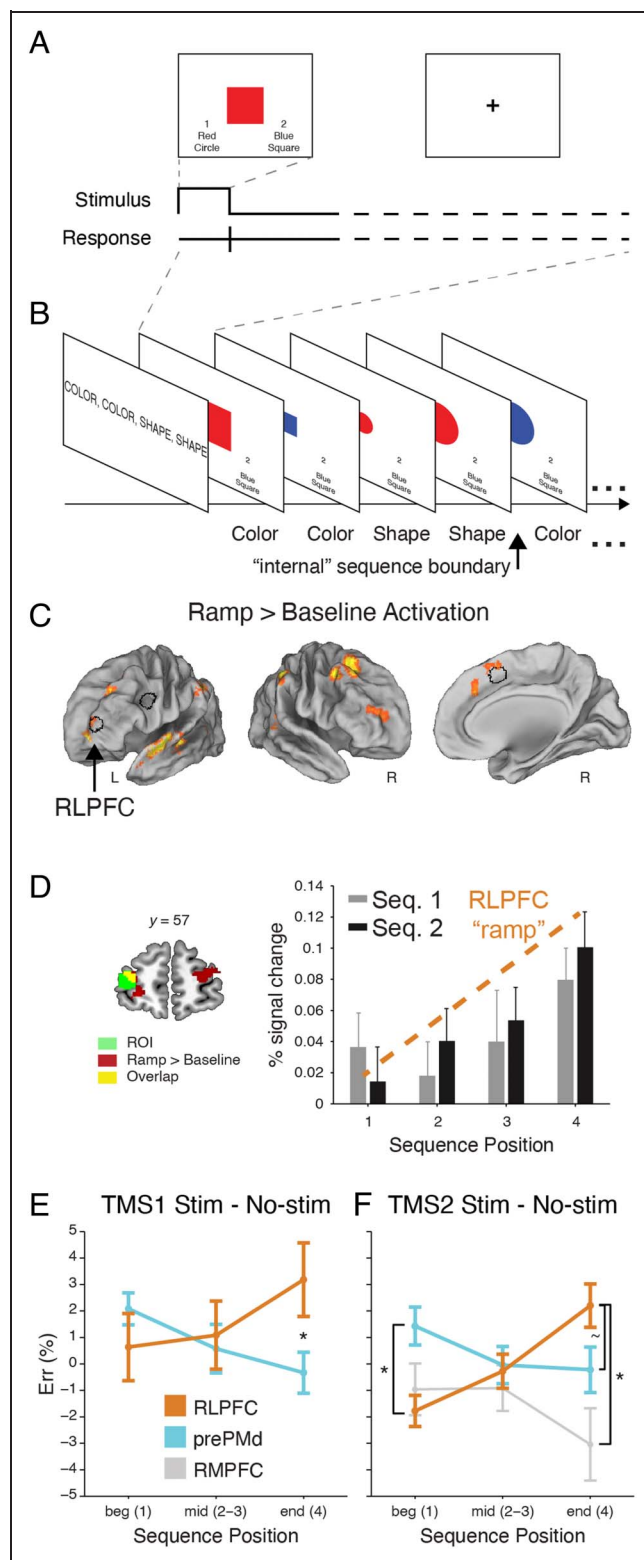


Figure 3. RLPFC is necessary during sequential task control. (A) Example trial of sequential task from Desrochers, Chatham, and Badre (2015). (B) Partial example block showing the instruction screen and the first five trials in the block. The categorization task to be performed on each trial, as remembered from the instruction screen, is indicated below. (C) Whole-brain contrast showing ramping activation (cluster corrected $p < .05$). RLPFC ROI outlined in black. (D) Ramping activation in RLPFC ROI across the four positions in two different types of sequences. (E) Difference in error rate (Err) between stimulated and nonstimulated trials during single-pulse TMS targeting two different sequential control regions: RLPFC and prePMd. The effect of stimulation significantly increased across the sequence positions in the RLPFC, in contrast to the prePMd. (F) In a second replication TMS experiment, stimulation to the RLPFC (orange) again produced an increase in error rates. In contrast, stimulation to a control region, the rostromedial prefrontal cortex (RMPFC; gray), showed no reliable effect of stimulation (reprinted with permission from Desrochers, Chatham, & Badre, 2015).

Eslinger & Damasio, 1985). Understanding ACTS may relate to addiction and substance use disorders. The neural circuitry underlying ACTS and brain areas that are disrupted in those with substance use disorders have a striking overlap (reviewed in the work of Desrochers & McKim, 2019), suggesting that the inability to control ACTS may underlie some part of the disorder. Attentional disorders such as attention-deficit/hyperactivity disorder have been found to impair the processing of sequences. People with attention-deficit/hyperactivity disorder show impaired sequence learning (Shephard, Groom, & Jackson, 2019) as well as reduced sensitivity to sequence violations (Karatekin, White, & Bingham, 2010). A similar overlap in neural circuitry and behavioral deficits in ACTS exists in obsessive-compulsive disorder and related diagnoses (Remijnse et al., 2009). In summary, many diseases and disorders may have deficits in ACTS, and the relatively small scope by which we understand them may be one reason that so many of these disorders are difficult to treat.

In conclusion, myriad open questions remain that are related to ACTS, precisely because we have only begun to define them and their underlying neural circuitry. We also note that there are surely other areas of research that may intersect with ACTS that we have not explicitly discussed here. For example, the abstract, temporal nature of language processing could be a special case of ACTS (reviewed elsewhere, e.g., Dehaene, Meyniel, Wacongne, Wang, & Pallier, 2015), and there may be similarities in neural processing, as the ACTS-related ramping activity in the frontal cortex may be present for sentence comprehension processes as well (Fedorenko et al., 2016). However, research on language processing alone is unlikely to fully address all pertinent topics pertaining to ACTS (for instance, consider the fact that animals do not possess the same kind of language capabilities of humans, and we propose that animals may be capable of ACTS). These nuances thus underscore ACTS's ties to other important processes, and how they are critical to bring out into the open for investigation.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JocN)* during this period were $M(\text{an})/M = .407$, $W(\text{oman})/M = .32$, $M/W = .115$, and $W/W = .159$, the comparable proportions for the articles that these authorship teams cited were $M/M = .549$, $W/M = .257$, $M/W = .109$, and $W/W = .085$ (Postle and Fulvio, *JocN*, 34:1, pp. 1–3). Consequently, *JocN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this article report its proportions of citations by gender category to be as follows: $M/M = .471$; $W/M = .299$; $M/W = .115$; $W/W = .115$.

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