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Sequential effects and sequence learning in a three-choice serial reaction time task

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A B S T R A C T

The recent history of events can influence responding despite there being no contingent relationship between those events. These 'sequential effects' are ubiquitous in cognitive psychology, yet their study has been dominated by two-choice reaction time tasks in which sequences necessarily comprise simple response repetitions and alternations. The current study explored sequential effects in a three-choice reaction time task where the target was constrained to either move clockwise or anticlockwise on each trial, allowing for assessment of sequential effects involving the direction of target transitions rather than target location. Across two experiments, a reliable pattern of sequential effects was found in the absence of contingencies, whereby the most notable feature was that participants were fastest to respond to subsequences where the target moved in a consistent direction on consecutive trials, compared to when the target direction alternated. In Experiment 2, the direction of motion was biased to move in one direction 75% of the time and in a subsequent transfer phase, participants showed evidence of learning this probabilistic sequence but still exhibited the same pattern of sequential effects on trials where the target moved in the more prevalent or less prevalent direction. Simulations with a connectionist model of sequence learning (the Augmented Serial Recurrent Network, Cleeremans & McClelland, 1991) produced an adequate replication of the sequential effects in both experiments in addition to an effect of sequence learning in Experiment 2. We propose that sequential effects may represent learning about transient contingencies and may be described using the same associative learning mechanisms intended for sequence learning.

The recent history of events produces noticeable effects on both controlled decision-making (e.g. the gambler's fallacy, Burns & Corpus, 2004; Jarvik, 1951; categorization judgements, Jones, Love, & Maddox, 2006; Jones & Sieck, 2003), as well as more automatic responses (e.g. conditioned responding, Perruchet, 1985; pain sensation, Link, Kos, Wager, & Mozer, 2011). These transient differences in performance as a function of trial history are known as sequential effects, and have been studied most extensively in choice reaction time (RT) procedures, such as the serial reaction time (SRT) task (Nissen & Bullemer, 1987). In this task, participants usually observe a target appearing in one of several locations on the screen, and have to respond with a corresponding keypress. When the task is entirely unstructured, such that there is no consistent sequence to the target's movement between positions, participants are nevertheless faster to respond on certain trials. These "sequential effects" suggest that in the absence of any predictive information, responding is still influenced by recent prior events.

In SRT tasks, sequential effects are normally differentiated from sequence learning. To examine the latter, contingencies are embedded between target locations, such that reductions in RTs for predictable (sequenced) trials reliably occur over the course of the experiment. The aim of many studies on sequence learning is to demonstrate that participants are able to learn about repeated regularities in the sequence, and to determine whether this learning is accompanied by awareness or attributable to an implicit learning mechanism (e.g. Cleeremans & Jiménez, 1998; Jiménez, Méndez, & Cleeremans, 1996; Reber, 1989; Willingham, Nissen, & Bullemer, 1989). In such experiments, sequential effects are often regarded as variance to be controlled for or minimized on test (Jones, Curran, Mozer, & Wilder, 2013). The methods that researchers have employed to this end include devising an appropriate sequence to minimize sequential effects (e.g. avoiding first-order repetitions, Cleeremans & McClelland, 1991), or using a control group who are trained with a pseudorandom sequence containing no contingencies but with a trial order that would produce equivalent sequential effects (e.g. Anastasopoulou & Harvey, 1999; Jones & McLaren, 2009). The need to partial out sequential effects is a valid concern when attempting to measure sequence learning, since if sequential effects are merely performance effects, they may obscure or inflate evidence of learning (Vaquero, Jiménez, & Lupiáñez, 2006). Despite this, and the general treatment of sequential effects and sequence learning as separate phenomena in the literature, several researchers have suggested that sequential effects and sequence learning effects may result

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from the same learning mechanism (Audley, 1973; Laming, 1969; Soetens, Melis, & Notebaert, 2004).

Early studies on sequential effects were mostly confined to two-choice SRT tasks for the purpose of constraining the possible number of events (e.g. left and right) and transitions (repetitions and alternations of target location). For example, in a two-choice RT task (e.g. left and right responses) where the appearance of the target is randomly determined, participants are usually fastest to respond on trials where either repetitions or alternations of target location have occurred consecutively (e.g. Bertelson, 1961; Cho et al., 2002). This means that if a target had just appeared on the left 3 times, participants are usually faster to respond left than they are to respond right (i.e. LLLL would be faster than LLLR). Conversely, if participants have just experienced a series of alternations (left, right, left), they are faster at responding right than left (i.e. LRLR is faster than LRLL), but this facilitation is usually observed to be weaker than the equivalent effect for repetitions (e.g. Bertelson, 1961; Cho et al., 2002; Remington, 1969). These patterns of sequential effects have been attributed to participants' subjective expectancies (Soetens, Boer, & Hueting, 1985), which in this context refer to the predictions generated by some internal learning process. However, it is worth noting that these expectancies have been shown to be independent of the individual's explicit beliefs about impending events: recent work that has directly compared trends in choice RT and trends in explicit expectancy for the relevant events has found them to be widely divergent (Barrett & Livesey, 2010; Livesey & Costa, 2014; Lee Cheong Lem, Harris, & Livesey, 2015, see also Hale, 1967, and Hyman, 1953, for earlier informal observations of similar trends).

The internal learning process that leads to these subjective expectancies may be similar to the mechanisms that underlie sequence learning. Arguments in favor of a common mechanism include the fact that both sequence learning (e.g. Frensch & Miner, 1994) and sequential effects (e.g. Soetens, Boer, & Hueting, 1985) are highly sensitive to the length of the response-stimulus interval (RSI), practice affects sequence learning and sequential effects alike (Soetens et al., 2004), and the pattern of sequential effects is mirrored in electroencephalogram (EEG) studies investigating the P300 component, which is thought to code for prediction error (Squires, Wickens, Squires, & Donchin, 1976). These observations suggest that participants do form and update expectancies while responding to unstructured material, and thus the question of interest is what kind of mechanism leads to these expectancies. One possible answer is that sequential effects are a natural consequence of a rapid learning mechanism that is sensitive to short-term transient contingencies as well as long-term stable contingencies. In this way, sequential effects may represent a by-product of a highly adaptive ability to learn and change according to the statistics of a dynamic environment (Jones et al., 2013; Yu & Cohen, 2009).

Sequential effects models, however, have been largely developed separately of sequence learning models. Some models of sequential effects use simple associative architectures to represent the two-choice RT procedure, in combination with error-correction mechanisms. Despite variations between current models, there is some agreement that sequential effects in two-choice RT tasks can be explained by assuming that participants learn about the base rate of target locations (repetitions of specific target locations), and the frequencies of first-order transitions (repetitions and alternations of target location) (Jones et al., 2013; Wilder, Jones, & Mozer, 2009). Other successful attempts to model sequential effects have used detectors that track first-order contingencies to bias the system towards repetitions or alternations depending on trial history (Cho et al., 2002), or have omitted all hidden units and set up direct associations between representations of stimuli and responses (Gureckis & Love, 2010). These models of sequential effects provide good fits to empirical data and provide some indication of the statistics to which participants are sensitive. In contrast, models that have most successfully been applied to sequence learning incorporate similar learning principles with relatively complex model architecture, such as the augmented Serial Recurrent Network (SRN; Cleeremans & McClelland, 1991; Elman, 1990). If sequential effects are served by the same mechanisms as sequence learning, models like the augmented SRN, which is held to be the benchmark model of sequence learning (Beesley, Jones, & Shanks, 2012; Yeates, Jones, Wills, McLaren, & McLaren, 2013), should account for sequential effects to the same degree of success as they do for sequence learning involving complex deterministic and probabilistic transitions. The augmented SRN was purposefully modified from the original SRN (Elman, 1990) to account for short-term sequential effects (Cleeremans & McClelland, 1991), yet there has been relatively little reported work using the SRN to model sequential effects. Thus one of the aims of the current study was to test whether the augmented SRN could model sequential effects in addition to sequence learning effects in a novel three-choice RT task.

While there has been some research on sequential effects in choice-RT paradigms with more than two responses (Falmagne, 1965; Hyman, 1953; Schvaneveldt & Chase, 1969), these studies have mostly discussed the effects of repeating a single response location and have not fully examined other possible combinations of subsequences. One study that has investigated sequential effects in a three-choice SRT task used three different targets (geometric shapes), which could appear in the center of the screen, and participants responded by pressing the appropriate button using one finger on their dominant hand (Experiment 3, Gökaydin, Ma-Wyatt, Navarro, & Perfors, 2011). By comparing the sequential effects to an analogous procedure with only two possible targets (Experiment 2, Gökaydin et al., 2011), they concluded that adding an additional target caused participants to display sequential effects consistent with switching from tracking first-order statistics (repetitions and alternations of target location) to tracking base rate statistics (the relative frequency of each target). Their explanation was that introducing three possible responses increased task complexity, which in turn increased the number of possible first-order sequences that could be learned. Under these conditions they argued that participants reverted to learning about the base rates of each target, which was the simplest statistic to learn. This explanation implies a strategic and possibly intentional shift in the participant's learning strategy. It remains to be seen whether a sequence learning model like the SRN could account for changes in the number of target locations simply as a consequence of the changes in contingencies rather than a shift in attention to other event statistics.

In any case, Gökaydin et al.'s (2011) finding accords with the results of two-choice SRT tasks, where it is clear that first-order repetitions of target location (e.g. left-left-left) produce the most marked decreases in RT (e.g. Cho et al., 2002), and participants exclusively report noticing runs of target location when asked to explicitly look for a sequence before training (Experiment 3, Jones & McLaren, 2009). While there are important procedural differences in Gökaydin et al.'s (2011) task that reduce the generalizability to the majority of the two-choice RT literature (such as responding to the identity of the target rather than the location and only using one finger to respond), their findings highlight the importance of investigating sequential effects in different paradigms with more than two target locations in order to provide a more general account of sequential effects.

In the current study, we arranged three target locations on the edges of a computer screen (e.g. left-top-right) and prohibited repetitions of target location (e.g. top-top), to allow us to assess sequential effects concerning the repetition and alternation of the *direction* of target transitions, rather than target location (see Fig. 1). By prohibiting repetitions of target location, this task is similar to two-choice RT tasks in that on any given trial, there are only two possible events that can follow (a clockwise or anticlockwise transition). These spatial transitions add a novel and abstract quality to the SRT task, since direction of target movement (e.g. clockwise rotation) can summarize 3 different sets of contingencies (left-top, top-right, right-left). Using this paradigm, we assessed sequential effects by allowing an equal probability of clockwise or anticlockwise transitions (i.e. where the direction of motion on each trial is randomly determined, Experiment 1), and also assessed