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Serial attention to serial memory: The psychological refractory period in forward and backward cued recall

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ABSTRACT

Guided by the conjecture that memory retrieval is attention turned inward, we examined serial attention in serial memory, combining the psychological refractory period (PRP) procedure from attention research with cued recall of two items from brief six-item lists. We report six experiments showing robust PRP effects in cued recall from memory (1–4) and cued report from perceptual displays (5–6), which suggest that memory retrieval requires the same attentional bottleneck as “retrieval” from perception. There were strong direction effects in each memory experiment. Response time (RT) was shorter and accuracy was higher when the cues occurred in the forward direction (left-to-right, top-to-bottom, first-to-last), replicating differences between forward and backward serial recall. Cue positions had strong effects on RT and accuracy in the memory experiments (1–4). The pattern suggested that subjects find cued items in memory by stepping through the list from the beginning or the end, with a preference for starting at the beginning. The perceptual experiments (5–6) showed weak effects of position that were more consistent with direct access. In all experiments, the distance between the cues in the list (lag) had weak effects, suggesting that subjects searched for each cue from the beginning or end of the list more often than they moved through the list from the first cue to the second. Direction, distance, and lag effects on RT and inter-response interval changed with SOA in a manner that suggested they affect bottleneck or pre-bottleneck processes that create and execute a plan for successive retrievals. We conclude that sequential retrieval from memory and sequential attention to perception engage the same computations and we show how computational models of memory can be interpreted as models of attention focused on memory.

1. Introduction

Since William James (1890), cognitive psychologists have proposed close links between memory and attention. The idea was central in the cognitive revolution (Broadbent, 1957; Norman, 1968) and is an important direction in modern research (Chun et al., 2011; Craik, 2020; Gazzaley & Nobre, 2012; Kiyonaga & Egner, 2013; Logan, 2002). Here we address the specific claim that memory retrieval is selective attention turned inward. Selecting an item in a memory list presents the same computational problem as selecting an item in a perceptual display – choosing a target from a set of distractors – so it can be done with the same computational mechanism. We address the claim empirically by adapting attention paradigms to memory tasks to draw parallels between memory retrieval and specific attentional processes. We address it theoretically by integrating computational models of memory and attention, interpreting

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the retrieval cues from the memory models as spotlights of attention on memory (Logan et al., 2021). Recently, we adapted the Eriksen and Hoffman (1973) and Eriksen and Eriksen (1974) perceptual flanker task to create an episodic flanker task that measures the sharpness of the focus of attention on memory and the ability to resist distraction from flanking items on the list (Logan et al., 2021). We found effects that paralleled the perceptual effects, suggesting a common mechanism. Subsequently, we adapted models of focusing attention on visual displays (Eriksen & Hoffman, 1972, 1973; Logan, 2005; Sperling & Weichselgartner, 1995) to measure the time-course of focusing attention on memory (Logan et al., 2023) and again found parallel effects. Here we extend this approach by adapting another attention paradigm to study the serial nature of serial memory, applying the *psychological refractory period* procedure (PRP; Broadbent, 1957; Davis, 1956, 1957; Pashler & Johnston, 1989; Welford, 1952) to cued recall from serial lists (Norman, 1966; Oberauer, 2003).

Our extension to the PRP procedure is important because many memory tasks involve successive retrievals (e.g., serial recall, free recall, cued recall). If memory retrieval is attention turned inward, this requires successive shifts of attention. The PRP procedure was designed to measure successive shifts of attention and identify attentional bottlenecks in performance by controlling the temporal overlap between two tasks precisely and varying it systematically (Broadbent, 1957; Davis, 1956, 1957; Welford, 1952; also see Byrne & Anderson, 2001; Logan & Gordon, 2001; Meyer & Kieras, 1997; Navon & Miller, 2002; Pashler & Johnston, 1989; Tombu & Jolicœur, 2003; Wu & Liu, 2008). If memory retrieval is attention turned inward, cued recall from serial lists should show a bottleneck when it is implemented in a PRP procedure.

Our implementation of the PRP procedure in serial memory provides a new approach to classic questions about serial order: How is order represented and how is the representation accessed to produce sequences of behavior? Theories of serial order in perception (Grainger, 2018), memory (Hurlstone et al., 2014), and action (Logan, 2018) generally assume the elements of sequences are encoded in *memory structures* that represent their order and support ordered retrieval. The structures may be syntactic frames (Dell et al., 1997), position codes (Farrell, 2012; Henson, 1998), chains of forward and backward associations (Solway et al., 2012), banks of oscillators (Brown et al., 2000; Hartley et al., 2016), or temporal contexts made of fading traces of prior items (Logan, 2021). The theories assume that recall results from applying a *retrieval plan* to these memory structures. The retrieval plan allows subjects to navigate the structures in a way that produces the required sequence (Bower, 1970; Ericsson & Kintsch, 1995; Miller et al., 1960). A retrieval plan is a *control process* that operates on a structured *representation* to produce behavior (Atkinson & Shiffrin, 1968). Attention research focuses more on control processes and memory research focuses more on representations. Our PRP cued recall task combines these foci and measures representations and control processes in the same act of retrieval, exerting stronger constraints on theorizing.

Retrieval plans are like task sets, in that they can be created on demand in response to novel requests for information (Schneider & Logan, 2006). Retrieval plans are like skills, in that plans that are used frequently may become habitual or automatic (Ericsson & Kintsch, 1995; Logan, 2018). Given the ubiquity of lists in daily life, retrieval plans for serial recall in forward order may be habitual (Bhatara et al., 2008; Cortis et al., 2015; Kahana, 1996; Spurgeon et al., 2015; Ward et al., 2010). Our PRP cued recall task breaks the habit by requiring a new plan on each trial, allowing us a different perspective on the memory structure (Kahana & Caplan, 2002; Murdock, 1968) and new insight into the nature of attentional bottlenecks in memory retrieval.

2. The psychological refractory period: Theory and data

The PRP procedure presents two stimuli, S1 and S2, successively (S1 before S2), and asks subjects to respond to each of them in order as quickly and accurately as possible. Subjects perform task1 on S1 to produce R1 with response time RT1, measured from the

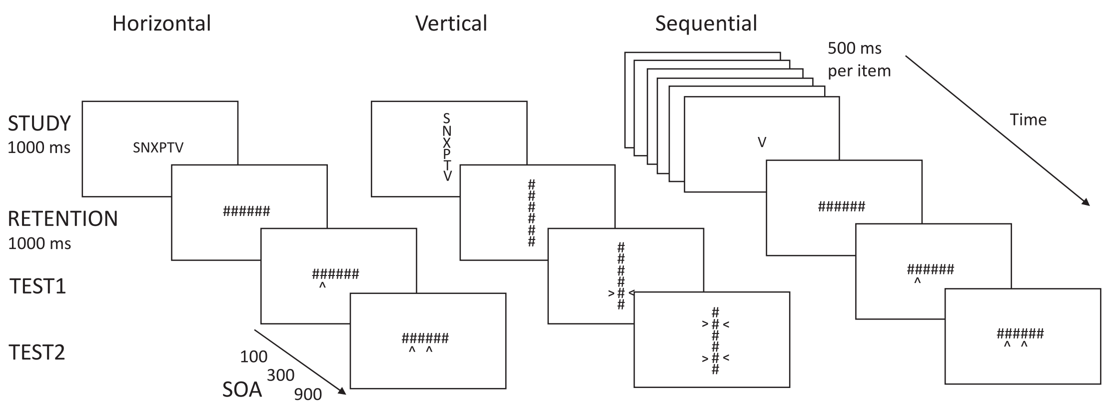

Fig. 1. Time Course of Trial Events Experiments 1–4. Note: Each trial began with a fixation point exposed for 500 ms followed by the study list (not shown). In Experiments 1–3 (Horizontal S, Horizontal P, Vertical), list items were exposed simultaneously for 1000 ms. In Experiment 4 (Sequential), list items were exposed sequentially in the same position for 500 ms each. Lists were followed by a mask of place holders that remained on the screen until the second response was registered, which ended the trial. The first cue appeared 1000 ms after the end of the list. The second cue appeared 100, 300, or 900 ms after the first. Both cues remained on the screen until the second response was registered. The Horizontal and Sequential trials in the figure illustrate cuing in the *forward* direction, reporting N and then P (left before right, start before end, respectively). The Vertical trial in the figure illustrates cuing in the *backward* direction, reporting T and then N (bottom before top).

onset of S1, and perform task2 on S2 to produce R2 with response time RT2, measured from the onset of S2. The interval between their onsets (stimulus onset asynchrony or SOA) is manipulated from short (0–100 ms) to long (700–1500 ms). Accuracy is generally high, so response times RT1 and RT2 are the primary results. RT1 is usually unaffected by SOA but RT2 is strongly affected, becoming longer as SOA becomes shorter (for a review, see Pashler, 1994). The prolongation in RT2 at short SOAs is known as the psychological refractory period effect (Davis, 1956; Telford, 1931; Welford, 1952), and is generally accepted as time spent waiting to access a central bottleneck that only processes one thing at a time. Interactions between SOA and second-task manipulations locate the bottleneck in the chain of processes extending from stimulus to response (Pashler, 1984; Pashler & Johnston, 1989). The interval between R1 and R2 and the correlation between RT1 and RT2 are diagnostic as well (Kahneman, 1973; Miller et al., 2009; Ulrich & Miller, 2008).

Our implementation of the PRP procedure presented lists of six letters to be remembered, followed by two cues separated by SOAs of 100, 300 or 900 ms (see Fig. 1). Subjects were told to recall the letters in the cued positions in the temporal order in which the cues were presented by typing them on the computer keyboard. If the list was SNXPTV and the second and then the fourth position were cued, subjects were supposed to type N and then P. If memory retrieval in cued recall is sequential attention turned inward, our experiments should replicate classical PRP results predicted by models of attention applied to the PRP. The time to recall P should be longer the shorter the SOA between the first cue and the second. To ensure that RTs did not reflect time-consuming hunting and pecking at the keyboard that could compromise their interpretation, we tested skilled typists (Logan et al., 2016).

The Nature of the Bottleneck. The key idea in all theories of the PRP effect is that there is a central bottleneck that only processes one task at a time, either by necessity or by choice. Most theories also assume that prior (perceptual) and subsequent (motor) processes may go on in parallel. They provide ways to identify and measure bottlenecks, but they do not provide a computational explanation of why there are bottlenecks. Theories of the PRP have generally identified processes by the variables that affect them (Pashler & Johnston, 1989) and assumed that performance depends on a structural bottleneck (Pashler & Johnston, 1989; Welford, 1952, 1967), limited resources (Kahneman, 1973; Navon & Miller, 2002; Tombu & Jolicœur, 2003), or a strategic choice (Logan & Gordon, 2001; Meyer & Kieras, 1997; Miller et al., 2009) without specifying how the variables affect the computations, why the bottleneck only processes one thing at a time, what resources are, or why computations depend on them (Navon, 1984). There is some consensus that the bottleneck process in the PRP is *response selection* (Pashler, 1994), but the computations underlying response selection are generally not explained or distinguished from other interpretations, like a decision bottleneck (Broadbent, 1971; Duncan, 1980) or a bottleneck due to processing R1 feedback (Welford, 1967).

Memory theory provides a computational explanation of why there is a bottleneck. All computational models of memory implement decision processes that choose one response at a time (Luce choice rule, signal detection theory, SoftMax, winner-take-all networks, competitive queuing). Many implement stochastic accumulator models to account for both RT and accuracy (Logan et al., 2021; Osth & Farrell, 2019; Polyn et al., 2009; Ratcliff, 1978; Usher & McClelland, 2001). The bottleneck emerges from the mathematical structure of the decision process, which is designed to choose only one alternative out of many. The alternatives may race against each other (Brown & Heathcote, 2008; Tillman et al., 2020). Evidence for one alternative may be evidence against the other alternatives (Ratcliff, 1978). The alternatives may inhibit each other (Usher & McClelland, 2001). In each case, a response is chosen when the first alternative reaches its threshold, and then the decision process ends. Only one item is selected in each decision, like a bottleneck. The next item must be selected by running the decision process again with a new set of inputs (Logan & Gordon, 2001).

We assume that this computational decision process is the bottleneck in serial retrieval in both memory and perception (Broadbent, 1971; Duncan, 1980; Logan & Gordon, 2001; Sigman & Dehaene, 2005). Memory retrieval is attention turned inward because the same decision process extracts information from perception and memory (Logan et al., 2021, 2023).

The Bottleneck Model. All theories of the PRP effect can be represented abstractly with two simple equations that describe RT1 and RT2 (measured from the onsets of S1 and S2, respectively) as the sum of the durations of *pre-bottleneck* processes (A), *bottleneck* processes (B), and *post-bottleneck* processes (C; Pashler & Johnston, 1989):

$$\text{RT1} = \text{A1} + \text{B1} + \text{C1} \tag{1}$$

$$\text{RT2} = \max(\text{A1} + \text{B1}, \text{SOA} + \text{A2}) + \text{B2} + \text{C2} - \text{SOA} \tag{2}$$

At short SOAs, when A1 + B1 is greater than SOA + A2,

$$\text{RT2} = \text{A1} + \text{B1} + \text{B2} + \text{C2} - \text{SOA} \tag{3}$$

At long SOAs, when SOA + A2 is greater than A1 + B1

$$\text{RT2} = \text{A2} + \text{B2} + \text{C2} \tag{4}$$

Together, Equations (1)–(4) explain the major results in the PRP procedure: Equation (1) predicts that RT1 should not vary with SOA. Equation (2) predicts that RT2 should decrease as SOA increases with a slope of −1 (Equation (3) until a critical SOA (i.e., SOA = A1 + B1 – A2), and then remain unaffected by SOA (Equation (4). Pashler and Johnston (1989) originally derived Equations (1)–(4) to illustrate a structural bottleneck theory. Since then, capacity (Navon & Miller, 2002; Tombu & Jolicœur, 2003) and strategy theories (Logan & Gordon, 2001; Meyer & Kieras, 1997; Miller et al., 2009) have assumed the same stage structure and made the same predictions.

When applied to mean RT, Equations (1)–(4) assume no variability in the durations of pre-, post-, and bottleneck processes. Variability in processing time produces RT2 slopes that are shallower than −1 and smooths out the predicted “elbow” at the critical SOA where the −1 slope in Equation (3) transitions to the 0 slope in Equation (4) (Ulrich & Miller, 2008). Nevertheless, Equations (1)–

(4) allow some powerful inferences about the locus and the nature of the bottleneck.

Locus of the Bottleneck. The *locus of slack* procedure was developed by Pashler (1984) and extended by Pashler and Johnston (1989) to determine whether experimental manipulations affect processes before or after the bottleneck by examining the interactions of those manipulations with SOA in RT2. Factors that affect pre-bottleneck processes will produce *underadditive* interactions with SOA: At short SOAs, A2 does not contribute to RT2 (Equation (3) because its effects can be absorbed in the slack time while task2 waits for the bottleneck. At long SOAs, A2 contributes to RT2 (Equation (4) because there is no need to wait for the bottleneck, so there is no slack time to absorb A2 effects. Together, these results predict underadditive interactions between factors that affect A2 and SOA that are diagnostic of pre-bottleneck processing. By contrast, bottleneck and post-bottleneck processes predict null interactions between A2 manipulations and SOA: B2 and C2 both appear in Equations (3) and (4), so manipulations of their durations will have the same effect regardless of SOA.

Inter-Response Interval. The locus of slack procedure focuses on RT1 and RT2 separately. The interval between RT1 and RT2 (*inter-response interval* or IRI) provides converging evidence about the nature of the bottleneck (Kahneman, 1973; Miller et al., 2009; Ulrich & Miller, 2008). It is defined as

$$IRI = RT2 + SOA - RT1, \tag{5}$$

Equations (1)–(4) make predictions about IRI. At short SOAs, before the critical SOA, IRI does not depend on SOA. Task2 can begin as soon as task1 is finished with the bottleneck. IRI equals Equation (3) plus SOA minus Equation (1):

$$IRI = B2 + C2 - C1 \tag{6}$$

At short SOAs, IRI depends mostly on the duration of task2 bottleneck processes (i.e., B2).

At long SOAs, after the critical SOA, task2 no longer has to wait for task1 to finish with the bottleneck but it has to wait for S2 to arrive, so IRI depends on SOA. IRI equals Equation (4) plus SOA minus Equation (1):

$$IRI = A2 + B2 + C2 - A1 - B1 - C1 + SOA \tag{7}$$

Together, Equations (6) and (7) predict that IRI should be constant for SOAs less than the critical SOA and increase linearly with SOA after that. When applied to mean IRI, these predictions assume no variability in process durations. Variability makes the slopes less extreme (>0 and <1) and softens the elbow (Kahneman, 1973; Ulrich & Miller, 2008).

The constant portion of IRI depends mostly on the duration B2 of the bottleneck process in the second task (Equation (6), so it should be larger in experiments that require more bottleneck processing. In our experiments, the two tasks involve the same stimuli (letters) and responses (keypresses), so on average, A1 = A2 and C1 = C2. Consequently, IRI $\approx$ B2 before the critical SOA (Equation (6) and IRI $\approx$ SOA after it (Equation (7).

Correlations between RT1 and RT2. All bottleneck models predict correlations between RT1 and RT2 at short SOAs. This is clear in Equation (3), in which RT2 depends on task1 process durations (A1 and B1) as well as task2 process durations (B2 and C2). The common processes in the two responses share variance and induce a correlation between RT1 and RT2 that is mitigated by the unique variance from B2, C1, and C2. The correlation will decrease as SOA increases because RT1 will contribute less and less to RT2.

Correlations between RT1 and RT2 can also result from a *response grouping* strategy, in which subjects process S1 and S2 before making any response and then execute R1 and R2 together (Borger, 1963). In Equations (1)–(4), A1, B1, A2, and B2 would finish before C1 and C2 begin. Following Pashler and Johnston (1989; also see Ulrich & Miller, 2008),

$$RT1 = \max(A1 + B1, SOA + A2) + B2 + C1 \tag{8}$$

$$RT2 = \max(A1 + B1, SOA + A2) + B2 + C2 - SOA \tag{9}$$

Equations (8)–(9) imply that R1 and R2 are emitted at about the same time, so IRI will be short and RT1 and RT2 will be strongly correlated for all SOAs. Logan and Etherton (1994) found strong grouping effects like these in a semantic memory verification task in which subjects searched simultaneously presented two-item lists for instances of two different categories, making separate decisions about each category. Across two experiments, the mean RT was 1171 ms, the mean IRI was 5 ms, and the mean correlation between RT1 and RT2 was 0.9349.

Equations (8)–(9) also imply that RT1 will increase linearly with SOA with a slope of + 1 after the critical SOA (=A1 + B1 – A2) when responses are grouped. That rarely happens in real data unless subjects are explicitly instructed to group their responses (Pashler & Johnston, 1989). Ulrich and Miller (2008) considered models in which grouping depended on SOA, task1 finishing time (A1 + B1), task2 finishing time (A2 + B2), and both finishing times (A1 + B1 and A2 + B2). They found these models made predictions that were closer to the data and attenuated the correlations between RT1 and RT2. In each model RT1 was longer if grouping occurs, but it did not increase with SOA if grouping only occurred with short SOAs.

3. Dual tasks and memory retrieval

Dual task studies of memory began at the dawn of research on attention and memory (e.g., Daniels, 1895) and remain popular today. Many studies use dual tasks to interfere with specific processes. Peterson and Peterson (1959) used counting backwards to prevent rehearsal. Murray (1968) used articulatory suppression to prevent phonological encoding. Baddeley et al. (1990) and colleagues used spatial and verbal tasks to distinguish subordinate systems in working memory. Many studies use dual tasks to understand the attention demands (Baddeley et al., 1984; Craik et al., 1996) or the automaticity of memory processes (Jacoby, 1991). These studies have advanced memory research in important ways, but they have not taken full advantage of theories and practices in attention research. Often, the dual tasks are continuous and not synchronized with the memory task (e.g., card sorting; listening for two consecutive odd digits), which allows subjects to schedule their attention to minimize interference (Broadbent, 1982; Carrier & Pashler, 1995). Most of the studies focus on accuracy and miss out on the additional constraints available in RT measures (Ratcliff, 1978). The PRP procedure overcomes these problems. It tests a specific aspect of attention (the propensity to make two decisions sequentially), it controls timing precisely, and it addresses RT as well as accuracy (Broadbent, 1957; Byrne & Anderson, 2001; Davis, 1956, 1957; Logan & Gordon, 2001; Meyer & Kieras, 1997; Navon & Miller, 2002; Pashler & Johnston, 1989; Tombu & Jolicœur, 2003; Welford, 1952; Wu & Liu, 2008).

Two studies found PRP effects in memory retrieval. Carrier and Pashler (1995) paired tone discrimination with cued recall of paired associates (Experiment 1) and item recognition (Experiment 2) and found that cued recall and recognition were both much slower at short SOAs than at long ones. They manipulated memory strength by repeating items and interpreted null interactions between memory strength and SOA as indicating that memory retrieval engaged the same bottleneck as perceptual-motor PRP tasks (Pashler & Johnston, 1989). Logan and Delheimer (2001) paired item recognition with item recognition, asking whether two recognition decisions were subject to a bottleneck. They found they were. RT2 was much longer at shorter SOAs. They also found "backward crosstalk" between the tasks (Hommel, 1998; Logan & Gordon, 2001; Miller & Alderton, 2006): RT1 was shorter if R2 was in the same category as R1. "Yes" responses to R1 were faster if R2 also required a "yes" response; "no" responses to R1 were faster if R2 also required a "no" response. Logan and Delheimer (2001) interpreted backwards crosstalk as evidence for parallel retrieval. We interpret it as imperfect selection of S1 such that information about S2 is activated in parallel and leaks into the decision, like a Stroop or flanker effect (Logan et al., 2021; Logan & Gordon, 2001).

Our experiments pair cued recall with cued recall in serial lists. They extend Carrier and Pashler's (1995) results with cued recall of paired associates and item recognition, and Logan and Delheimer's (2001) results with item recognition. They examine an essential attentional phenomenon in memory retrieval, forging links between the literatures by testing the hypothesis that memory retrieval is attention turned inward.

4. Direction, position, and lag in cued recall

In our implementation of the PRP procedure, the list provides a structure that allows us to measure the effects of position, lag, and direction in cued recall. In theory, the list is represented by a memory structure and the cues indicate the components of that structure that require attention. The memory structure represents the order in which items were encoded, from first to last. In theory, the critical variables are defined with respect to the memory structure (in practice, they are defined with respect to the memory list). *Position* is defined by the location of the cued item in the memory structure. *Lag* is defined by the distance between the first and second cued items in the memory structure. *Direction* is defined by the relation between the order of the cues and the order in the memory structure. Direction is *forward* when the first cued location is earlier in the memory structure than the second (given list SNXPTV and cuing positions 2 and 4; Fig. 1, Horizontal). Direction is *backward* when the first cued location is later in the memory structure than the second (given list SNXPTV, and cuing positions 5 and 2; Fig. 1, Vertical). We treat direction as an abstract property of the memory structure that reflects the order of encoding regardless of the method or modality in which the list was presented. For generality, we tested horizontal, vertical, and sequential presentations of the list (Fig. 1). The forward directions are left to right (LR), top to bottom (TB), and start to end (SE) in the three kinds of list presentation, respectively. The backward directions are RL, BT, and ES.

The effects of direction bear on longstanding issues in studies of forward and backward serial recall. The effects of position and lag measure the dynamics of cued recall, indicating how subjects access the cued items in the list and move from the first cued item to the second. These results bear on computational accounts of serial retrieval in forward and backward recall.

Direction of Recall. Research on backward and forward serial recall began at the turn of the 20th century (Bobertag, 1911; Terman, 1916) and continues today, inspired by seminal work by Conrad (1965) and others. Most studies focus on accuracy and find that recalling a list backward is generally (but not always) less accurate than forward recall. RT studies generally find that backward recall is substantially slower than forward recall (Anders & Lillyquist, 1971; Anderson et al., 1998; Bireta et al., 2010; Guitard et al., 2020; Haberlandt et al., 2005; Norris et al., 2019; Surprenant et al., 2011; Thomas et al., 2003). There is evidence that forward and backward recall rely on different processes or strategies at encoding and retrieval (Bireta et al., 2010; Li & Lewandowsky, 1993, 1995; Norris et al., 2019). To assess encoding differences, researchers compare performance when the direction of recall is cued before (pre-cue) or after (post-cue) the list is presented. To rule out encoding differences, researchers post-cue the direction of recall. Our PRP procedure allows both accuracy and RT measures in forward and backward recall and requires post-cuing to implement the SOA manipulation.

There is some evidence for a preference for forward retrieval plans. Subjects often recall items in forward order in free recall tasks (Kahana, 1996). Ward and colleagues have done several direct comparisons of serial and free recall over a broad range of list lengths. They found strong similarities in recall strategies that indicate a preference to start at the beginning of the list or the beginning of a group of items and proceed in the forward direction (Grenfell-Essam & Ward, 2012; Spurgeon et al., 2015; Tan & Ward, 2007; Ward et al., 2010). We may see a similar preference in our cued recall PRP task. Recall may be faster and more accurate when the retrieval plan is in the forward direction.

Moving Through the List to Find the Cued Item. Theories of serial recall generally do not provide computational models of backward recall (but see Anderson et al., 1998; Page & Norris, 1998). They model the representation of order as position codes, chains of associations, etc., and they model the process of retrieving an item, but they are less explicit about how the system moves through the list, even in the forward direction. Models that assume order is represented by associating items with evolving contexts would seem to require forward retrieval through the list: to retrieve item N, the evolution of the context from item 1 to N-1 must be replayed (Burgess & Hitch, 1999; Hartley et al., 2016; Lewandowsky and Farrell, 2008; Logan, 2021). This replay must occur in evolving context models whether the contexts are independent of the items or made of fading traces of previous items (Howard & Kahana, 2002; Logan, 2021). Some models assume position codes that are independent of the items, defined only by coordinates or similarities (Farrell, 2012; Henson, 1998). Such position codes could allow direct access to positions without having to evolve the entire prior context. Thus, evolving context models predict serial access, so retrieval time in cued recall will increase with position in the list, whereas position coding models can predict direct access, and so, no effect. Norris et al. (2019) examined forward and backward recall with lists of digits and spatial positions and found serial access with digit lists and direct access with spatial position lists. The position effects in our PRP experiments provide converging evidence on verbal lists.

In practice, many researchers assume backward recall is explained by an informal "peel off" strategy, which assumes people do backward recall as a series of forward recalls, starting with the first item and proceeding through the list until the desired item is retrieved (Anders & Lillyquist, 1971; Conrad, 1965). Page and Norris (1998) implemented the peel-off strategy in their primacy model and found that it captured differences in accuracy between forward and backward recall. The peel-off strategy makes clear predictions for retrieval time in forward and backward recall: In both forward and backward recall, retrieval time should increase with *input position*, as more retrievals are required to access later positions in the list. In forward recall, retrieval time should increase over *output position* because more retrievals are required for later outputs. However, in backward recall, retrieval time should decrease over output position because fewer retrievals are required for later outputs (which occur earlier in the list). Recently, Norris et al. (2019) reviewed evidence for the peel-off strategy and found it was mixed. Our PRP experiments will provide a new perspective on these strategies.

The formal models of ordered access to ordered representations and the informal peel-off strategy both assume that retrieval moves through the list in the forward direction, so both predict that RT in cued recall will increase monotonically with input position. There may be an exception for the last item, which is often assumed to be available after encoding, but RT should increase with position for all positions but the last. The neglected possibility that subjects can scan backward through the list would predict the opposite result: RT should increase from the last input position (which is retrieved first) to the first (which is retrieved last). Subjects may employ forward and backward scanning strategically, depending on whether the probed position is nearer to the beginning or the end of the list (Fischer-Baum et al., 2011). Our PRP experiments will distinguish these alternatives: Forward access predicts increasing RT with input position, backward access predicts decreasing RT with input position, and strategic access predicts an inverted V or U, with faster access near the ends of the list than in the middle. A third possibility is direct access, in which each item is equally available. Direct access predicts no difference in RT across positions, except for the first and last, which may be privileged.

These predictions apply to RT1 in all our experiments. They apply to RT2 if the second item is also found by scanning through the list from the beginning or the end. They do not apply to RT2 if the second item is found by scanning through the list from the first to the second item.

Moving From One Item to the Next. Theories of serial recall generally explain the forward progression through the list, addressing how the representation of item N (or its position or both) participates in the retrieval of item $N + 1$. They would predict an advantage in our PRP task if the cues required recalling immediately adjacent items in the forward direction because it engages the usual serial order machinery. Retrieving the immediately preceding item or a remote item is usually an error. Retrieving them deliberately requires a special plan, like the peel-off strategy, that engages the serial order machinery in new ways. Subjects may have habitual retrieval plans for successively recalling lists in forward order. This is implicit in the idea of position codes that can be applied to any list (Farrell, 2012; Henson, 1998). Our PRP task disables habitual retrieval plans by presenting cues that specify an arbitrary plan for retrieving only two of the letters, going forward and backward different distances through the list (the *lag* between the cued positions).

The effects of lag are important because they show how subjects move from retrieving one item to retrieving the next. One possibility is that subjects step through the list from the first-retrieved item to the second. This would predict a strong increase in RT2 with lag because longer lags would mean more intervening retrievals, and no effect of position because position and lag are independent. Another possibility, following the peel-off strategy and the forward-ordered representations in formal models of serial recall, is that subjects begin the second recall from the start or end of the list regardless of position of the first item recalled. This would predict a null effect of lag and a strong effect of position on RT2.

5. The experiments

We report six experiments testing SOA, direction, position, and lag effects. Experiments 1–4 were memory experiments involving *cued recall* (see Fig. 1). Memory lists were followed by two cues that indicated which positions to report. The lists were presented in horizontal, vertical, and sequential formats to vary the engagement of reading habits (horizontal $>$ vertical $\gg$ sequential) and to forge connections between memory literatures. Studies of visual short-term memory usually present items simultaneously, while studies of verbal short-term memory and serial recall usually present items sequentially. Simultaneous presentation may invite visual coding and sequential presentation may invite verbal coding (Magro et al., 2022). If cued recall is affected by reading habits and presentation format, SOA, position, and lag effects may vary with format. If cued recall is affected primarily by list order, the effects should not vary with format. To remind readers of the format manipulation, we refer to Experiments 1–4 as Horizontal S, Horizontal P, Vertical, and Sequential, respectively. Horizontal S and P were exact replications with different subject populations (see Method section). Vertical and Sequential were conceptual replications.

Experiments 5 and 6 were perceptual experiments involving *cued report* of visible lists presented horizontally and vertically. The procedure was the same as in Experiments 1–4 except that the "memory" displays remained visible throughout the trial, and the two cues were presented next to the displays (see Fig. 6 below), so perceptual attention was sufficient to retrieve the items. Contrasts between cued recall and cued report reveal differences between attention turned outward and inward. We refer to Experiments 5 and 6 as Perceptual H (for horizontal) and Perceptual V (for vertical), respectively.

The design of the experiments constrained the independence of position, lag, and direction. In all experiments, the first cue sampled each of the six positions and the second cue sampled each of the remaining five positions. Consequently, subjects could not predict the specific position either cue would sample. However, the possible lags and directions were constrained by the first position cued. If position 1 or 6 is cued first, all five lags are possible but if position 3 or 4 is cued first, only lags of 1–3 are possible. If position 1 is cued first, only the forward direction is possible. If position 6 is cued first, only the backward direction is possible. As cue position increases from 1 to 6, the forward direction becomes less likely and the backward direction becomes more likely. Subjects may use these more subtle contingencies to predict the second cued location given the first. Regardless of subjects' predictions, the constraints on independence are important to consider in data analysis to ensure that position does not compromise the interpretation of lag and direction effects.

6. Experiments 1–4: The PRP effect in cued recall

We examined the PRP effect in cued recall in four experiments that were identical in procedure except for the presentation format of the list (see Fig. 1). Experiments 1 and 2 were exact replications. They presented lists horizontally, as in normal text. Experiments 3 and 4 were conceptual replications. Experiment 3 presented lists vertically, in a column, and Experiment 4 presented the lists sequentially with each item appearing in the same position, which is typical in serial recall experiments. Horizontal lists are consistent with reading habits and so are more likely to engage habitual encoding and retrieval plans than vertical lists. Sequential lists remove the spatial component and add a temporal component but represent the same abstract order as simultaneous horizontal and vertical lists. Variation in format allows us to distinguish between memory representations that preserve presentation format and memory representations that only preserve order.

Apart from presentation format, the procedures were the same so the predictions are the same: A significant effect of SOA on RT2 will indicate a retrieval bottleneck. Direction effects on RT1 and RT2 distinguish forward and backward recall. Position effects on RT1 and RT2 indicate whether list positions are accessed in forward or backward order or a mixture of the two (or directly). Lag effects on RT2 will distinguish stepping through the list from the first cued position to the second from accessing the item from the beginning or the end of the list. If the memory representations only preserve order, the pattern of SOA, position, and lag effects should be the same in all four experiments. If the memory representations preserve format, position, and lag effects may differ between experiments, reflecting the constraints of the different perceptual arrangements.

7. Method

Experiments 1–4 were the same except for way the lists were presented (horizontally, vertically, sequentially), so they will be described in a common Method section.

Subjects. We planned to test 32 subjects in each experiment, which is consistent with our previous studies of cued recognition (Logan et al., 2021; 2023). Subjects were recruited online. Experiment 1 recruited subjects from Vanderbilt's SONA system and the remaining experiments recruited subjects through Prolific (https://www.prolific.co/). No subjects were excluded for failing to meet the accuracy criterion (described below). The number of subjects who were replaced for failing to pass the typing speed test (described below) was 1, 11, 6, and 5 for Experiments 1–4 respectively. After running Experiments 1 and 2, we realized we did not tell subjects they needed to type 40 WPM or more in the advertisement or the instructions for the experiment. That was not a big problem for the SONA sample of undergraduates in Experiment 1, as college students typically have strong typing skills (Logan & Crump, 2011). It was a problem in the broader Prolific sample in Experiment 2, where typing skills may be more variable. Consequently, we informed subjects of the speed criterion in the advertisement and instructions in all subsequent experiments.

Subjects who participated in one experiment were excluded from the others (and from Experiments 5 and 6). Due to an oversight, we did not collect demographic information for subjects in Experiment 1. They were sampled from the student population at Vanderbilt University and likely had similar demographics. In Experiments 2–4, subjects matched on reported age (Experiment 2: $M =$ 30.81 years, $SD =$ 6.47 years, 1 withheld; Experiment 3: $M =$ 32.59 years, $SD =$ 4.96 years; Experiment 4: $M =$ 30.94 years, $SD =$ 6.07 years) and had a similar gender distribution (Experiment 2: 17 males, 15 females; Experiment 3: 23 males, 9 females; Experiment 4: 18 males, 14 females). Their mean typing speeds (SD) on the typing test were 67.26 (20.82), 66.82 (14.51), 70.68 (21.08), and 65.81 (19.74) words per minute (WPM) for Experiments 1–4, respectively. Their mean accuracies were 0.9000 (0.0487), 0.9231 (0.0382), 0.9363 (0.0361), and 0.9323 (0.0297) for Experiments 1–4, respectively. These typing speeds indicate a high level of skill. In the days of professional typists, the criterion for expertise was 50 WPM (Logan & Crump, 2011).

The eligibility criteria were similar in the SONA and Prolific experiments. All experiments were set to only include native English speakers between 18 and 40 years of age. In the SONA experiment, subjects were required to have 20–20 vision or close to it. In the Prolific experiments, subjects were required to be located within the United States of America with an approval rating of over 95%.

Subjects completed the consent process in REDCap (https://www.project-redcap.org/). The experimental sessions ranged from 1 to 1.5 h and subjects were paid USD $6 per hour half hour. SONA subjects were compensated with course credit. The study was approved by the Vanderbilt University Institutional Review Board.

Apparatus and stimuli. The experiments were conducted online and run on subjects' personal computers. The design of each session was generated and sent to each subject's computer using a custom Python backend. The experiment was controlled by Javascript running within the web browser by using a custom function written to operate within jsPsych (de Leeuw, 2015). Subjects were instructed to use either Google Chrome or Mozilla Firefox to complete the experiment and instructed not to use phones or tablets. The program would not allow a keyboard to pop up on the screen during the experiment, so no responses could be registered (unless they attached a keyboard). At the start of the experiment, the subject's web browser automatically entered fullscreen mode to reduce distractions from other applications. As in all online experiments, we could not prevent subjects from using phones or tablets or opening other windows. We assume they complied with our instructions.

The memory lists consisted of six uppercase letters selected at random from the set of consonants (excluding vowels and Y). The probes consisted of six hash marks (#) displayed horizontally (Experiments 1, 2, and 4) or vertically (Experiment 3). The cue was an upward pointing caret (^) presented under the probed position (Experiments 1, 2, and 4) or a > sign to left and a < sign to the right of the cued position (Experiment 3; see Fig. 1). Each position was cued equally often for each task, and every combination of first cue and second cue positions was tested. Characters were presented in a monospaced typeface (Courier New or Courier if those fonts were installed on subjects' computers), displayed in white at 45 pixels in height on a gray background ([127, 127, 127] in 24-bit RGB values).

Data and programs for presenting the experiments and analyzing the data are available on the Open Science Framework at https://osf.io/t85gm/.

Procedure. The events on a trial are presented in Fig. 1. Each trial began with a fixation point exposed for 1000 ms. It was replaced by the memory list, which was exposed for 1000 ms and replaced by a row of hash symbols (#), which remained on for the duration of the trial. The first cue was presented after a 1000 ms retention interval. The second cue was presented 100, 300, or 900 ms after the first.

The basic design required 30 trials to include all positions for the two cues. The first cue could occur in any of the six positions; the second cue could occur in any of the remaining five positions. Direction and lag were defined by the positions of the first and second cues. There were 18 replications of the basic design for a total of 540 trials. The order of trials was randomized separately for each subject within each replication. The 540 trials were split into 12 blocks of 45 trials with a brief break allowed between blocks.

Instructions were written and presented in a subject-paced series of manually controlled slides. Subjects were allowed to review the instructions if they wished. Subjects were instructed to report the letter that occupied each cued position in the list by typing it as quickly as possible onto the computer keyboard. Prior to the instructions, subjects were given a typing test in which they typed one of four ~ 100-word paragraphs about the many merits of border collies (Logan & Zbrodoff, 1998). Subjects who typed less than 40 WPM were tested but excluded from analysis.

Subjects had to respond within 4000 ms of the presentation of the first cue. If they took longer, the trial was terminated with the message "TOO SLOW" presented centrally in a red font for 3000 ms. These trials were excluded from the analysis and treated as errors in calculating feedback during the task. At the end of each block, a screen was presented indicating the overall accuracy for the preceding block, and subjects were allowed to take a self-timed break. Every five minutes, the experiment checked whether accuracy was greater than 60%. If subjects fell below this accuracy criterion, they were warned to improve performance and given an opportunity to review the instructions. On the third warning, subjects were excluded from the experiment and from all subsequent analysis.

8. Results and discussion

SOA and Direction. The effect of SOA on RT2 defines the PRP effect and indicates whether memory retrieval shares the same bottleneck as perceptual tasks (Pashler, 1994). The weaker SOA effect on RT1 is a classic result typical of the PRP procedure. Mean RT (for correct responses) and accuracy were calculated for each response (R1, R2)[1] for each combination of direction (forward, backward) and SOA (100, 300, 900 ms) for each subject. Summary tables for 2 (Response) × 2 (Direction) × 3 (SOA) ANOVAs on the RTs and accuracy scores are presented in Table A1 in Appendix A. The means across subjects are plotted for each experiment in Fig. 2. The pattern of results was very similar across experiments for both RT and accuracy despite the differences in format. RTs in the Sequential experiment were 205 ms longer than RTs in the other experiments, but the pattern was the same.

The RT data in the top panels of Fig. 2 showed robust PRP effects: RT2 was longer the shorter the SOA in each experiment, for every subject with complete data (2 subjects had missing data in the Sequential experiment). RT1 was also longer with shorter SOAs, but the increase for RT2 was much stronger. The difference in SOA effects appeared in each experiment in every subject with complete data, suggesting that retrieval was engaged serially in response to the two cues. Contrasts supporting these conclusions are presented in Table A2 in Appendix A. The increase in RT1 at short SOAs could reflect capacity sharing (Kahneman, 1973; Navon & Miller, 2002; Tombu & Jolicœur, 2003), response grouping (Borger, 1963; Pashler & Johnston, 1989; Ulrich & Miller, 2008), or strategic slowing. We address strategic slowing below and in Appendix B, and we address capacity sharing in the General Discussion.

There were strong effects of direction in each experiment. The forward order (L before R for Horizontal S and P, T before B for

[1] An analysis of mean RT for trials on which both responses were correct yielded nearly identical results.

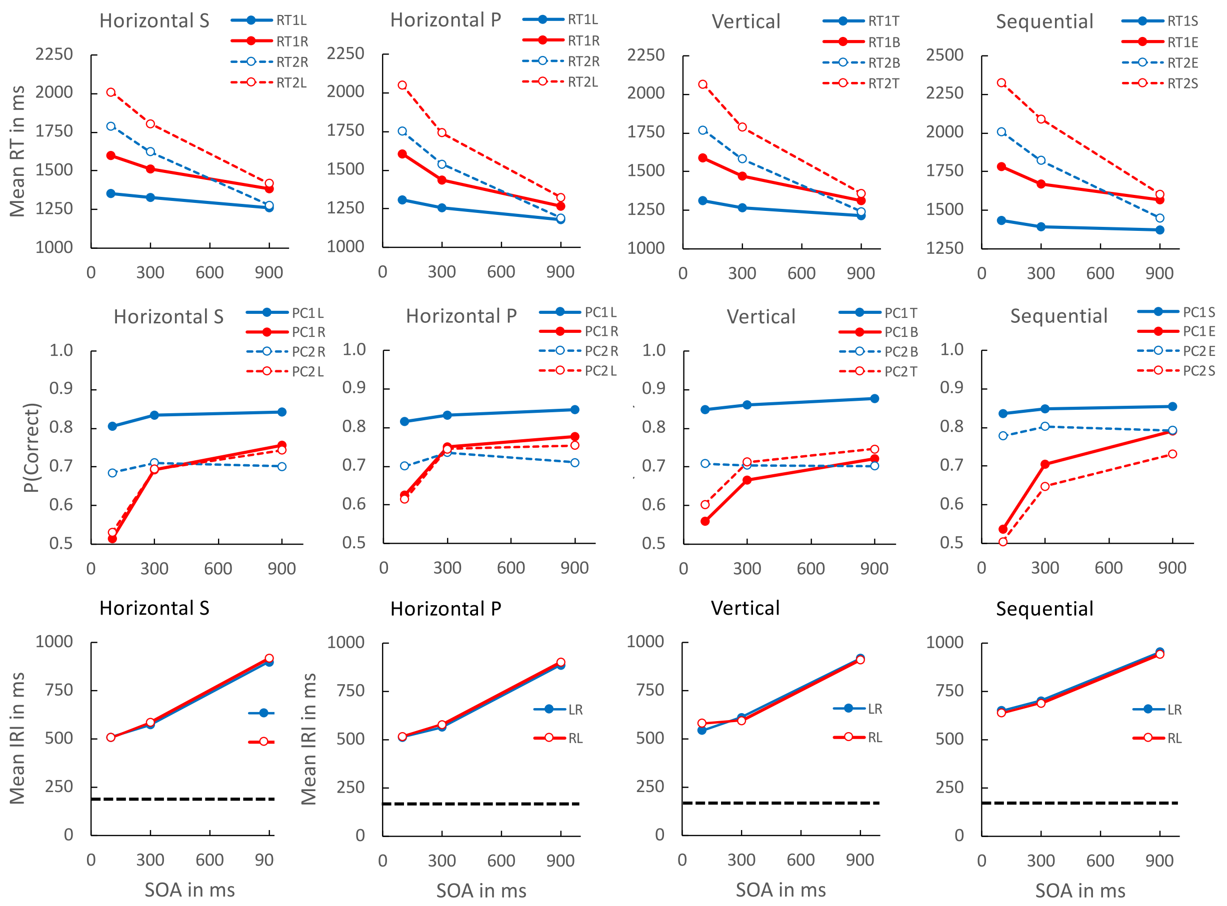

Fig. 2. SOA Effects Experiments 1–4. Note: Mean response time (RT; top row) and accuracy (P(Correct); middle row) for the first (solid lines) and second (dashed lines) responses as a function of the stimulus onset asynchrony (SOA) between the first cue and the second cue and the direction of recall (*forward* = blue; *backward* = red) in Experiments 1–4. Note that the scale is shifted by 250 ms in the Sequential condition (Experiment 4). Horizontal S = horizontal lists with Sona subjects; Horizontal P = horizontal lists with Prolific subjects (exact replication). In the Horizontal experiments, L = letter nearest to the left end of the list, R = letter nearest to the right end; in the Vertical experiment, T = letter nearest to the top of the list, B = letter nearest to the bottom; in the Sequential experiment, S = letter nearest to the start of the list, E = letter nearest to the end. Cues in the *forward* direction (L before R, T before B, and S before E) are colored blue. Cues in the *backward* direction (R before L, B before T, and E before S) are colored red. The bottom row contains mean inter-response intervals (IRIs) for pairs of responses in the forward (blue) and backward (red) directions as a function of SOA. The dashed black horizontal line in each graph is the mean interkeystroke interval (IKSI) from the typing test, which reflects the expected IRI if the bottleneck was only due to selecting and executing keystrokes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Vertical, S before E for Sequential) was consistently faster than the backward order (R before L for Horizontal S and P, B before T for Vertical, E before S for Sequential) for both RT1 and RT2, conceptually replicating the differences between forward and backward serial recall (Anders & Lillyquist, 1971; Anderson et al., 1998; Bireta et al., 2010; Guitard et al., 2020; Haberlandt et al., 2005; Norris et al., 2019; Surprenant et al., 2011).[2] It is interesting that the advantage of forward recall replicates when cued recall disables habitual forward retrieval plans for serial recall and requires a novel retrieval plan on each trial. Perhaps the advantage stems from the structure of the representation of the list rather than the automaticity of the retrieval plan.

It is surprising that the direction effect occurs in RT1 because the order of recall is not determined until the second cue is presented. However, in each experiment, mean RT1 (~1400 ms) was substantially longer than the longest SOA (900 ms), so the second cue would be available before the first response was selected on many trials. Another possibility is that subjects may have waited for the second cue before initiating retrieval. We tested this possibility in an experiment reported in Appendix B that replicated the Horizontal P

[2] Note that the plots of the direction x position interaction at each SOA in Fig. C1 show that RT1 is shorter in the forward direction than in the backward direction for each shared position (i.e., positions 2–5) for SOA = 100. RT1 is shorter in the forward direction in all cases except for position 5 in the Sequential experiment for SOA = 300. RT1 in forward and backward directions overlap at SOA = 900. For RT2, forward is shorter than backward at all positions except 5 at all three SOAs. This indicates that the direction effects are not the result of nonindependence between position and direction.

experiment with longer SOAs (300, 900, and 1800 ms) to discourage waiting. In the long-SOA experiment, RT1 at the 300 and 900 ms SOAs was 91 ms shorter than RT1 at the same SOAs in the short-SOA horizontal (Prolific) experiment (see Fig. B1), suggesting strategic waiting in the short-SOA experiment. The difference was not significant, $t(62) = 1.2327$, $p = .2224$, $SEM = 73.5931$, $BF_{10} = 0.4850$. but the Bayes Factor does not provide convincing support for the null hypothesis. In the long-SOA experiment, the longest SOA (1800 ms) was longer than mean RT1 (1196 ms), but the forward order was 67 ms faster than the backward order at that SOA, $t(31) = 15.1625$, $p < .0001$, $SEM = 4.4194$, $BF_{10} = 8.5451 \times 10^{12}$, suggesting that another factor besides waiting may be responsible for the order effect in RT1. Subjects may have used the location of the first cue to predict recall order, allowing them to create a forward or backward retrieval plan before the second cue appeared. First cues in the first and last positions predict forward and backward order perfectly; first cues in the second and second-to-last positions predict forward and backward order on 80% of the trials; and so on.[3] If the retrieval plan must be created before retrieval begins and if forward retrieval plans take less time to create (because they are consistent with habit), this possibility might explain the direction effects on RT1. It could be tested by manipulating direction probability explicitly. We chose to leave that for future research.

We used the locus of slack logic to determine whether direction affected processes before or after the bottleneck, examining its interaction with SOA in RT2 in each experiment in the ANOVAs presented in Table A1. The interactions between SOA and direction were significant in each experiment, but they were overadditive, ruling out the hypothesis that direction affects pre-bottleneck processes (which predicts underadditivity) and supporting the hypothesis that direction affects bottleneck processes.

The locus of slack conclusions are based on the failure to find underadditive interactions between direction and SOA. The observed overadditive interactions did not directly confirm the hypothesis that direction affected bottleneck processes. Usually, the direct evidence for bottleneck processing is a null interaction with SOA (Pashler & Johnston, 1989).

The *inter-response intervals* (IRIs) provide direct evidence about the duration of bottleneck processes. According to Equation (6), at short SOAs, IRI equals the duration of task2 bottleneck processing plus the difference in the durations of postbottleneck processes for task1 and task2. Since the tasks were the same (typing letters), this postbottleneck component should drop out of the equation, so IRI simply equals the duration of task2 bottleneck processing. We used Equation (5) to calculate mean IRI for pairs of correct responses for forward and backward directions for each SOA for each subject in each experiment. The means across subjects are plotted in the bottom panels of Fig. 2. The pattern was the same in each experiment: IRI increased with SOA and the slope of the increase was shallower for the shorter SOAs (100–300) than for the longer SOAs (300–900), suggesting a transition from a flat function (Equation (6) to a function that depends only on SOA (Equation (7). The function was never flat, so the observed IRIs at the shortest SOA were probably mixtures of flat and increasing functions. This urges some caution in interpreting IRIs as direct measures of bottleneck processing time. That said, there was no difference between the forward and backward directions at any SOA. Contrasts supporting these conclusions are presented in Table A3 in Appendix A. The null effect of direction on IRI suggests that direction affects pre-bottleneck processing, but that is inconsistent with the lack of underadditive interactions in the locus of slack analysis. An alternative possibility is that direction affects bottleneck processing in task1 but not in task2. The retrieval plan subjects create on each trial may include both responses, and it may be created before task1 retrieval begins (as in the waiting strategy). We assume creating a plan involves decision making and so would require bottleneck processing.

We assume that the PRP effects and IRIs reflect the effects of memory retrieval on bottleneck processing. An alternative possibility is that memory retrieval depends on prebottleneck processing and the PRP and IRI effects reflect bottleneck processing for selecting and executing keystrokes (i.e., response selection; Yamaguchi et al., 2013). We tested this possibility by calculating the mean *interkeystroke interval* (IKSI) from the typing test for each subject. The typing test requires typing continuous text that is continuously visible, so performance is limited by the rate at which the bottleneck can select and execute keystrokes. IKSI = IRI. The horizontal dashed line in each graph represents the mean IKSI on the typing test across subjects. It was clearly shorter than the shortest IRIs in the 100 ms SOA (178 ms vs. 555 ms), suggesting that IRI measures bottleneck processing time for memory retrieval.

The accuracy data in the middle panels of Fig. 2 showed strong interactions between SOA, response (R1, R2), and direction. In the forward order, accuracy was not affected much by SOA and R1 was consistently more accurate than R2. In the backward order, accuracy was strongly affected by SOA and was especially low at the 100 ms SOA. The effect of order was weaker and less consistent across experiments. Later we report an exploratory analysis of error types, which provides some insight into the interaction between direction and SOA (see Transposition, Intrusion, and Reversal Errors).

Position and Direction. The position effect indicates how subjects access the cued items in the list, starting from the beginning, starting from the end, mixing the two, or accessing the items directly. Mean RT (for correct responses) and accuracy were calculated for each response (R1 and R2) in each combination of position (1–6) and direction (forward, backward), collapsed over SOA, for each subject. The combinations form an incomplete factorial design. Forward R1 and backward R2 are defined only for positions 1–5, while forward R2 and backward R1 are defined only for positions 2–6. Consequently, we analyzed the data with planned contrasts instead of a factorial ANOVA. A linear contrast with weights {-2—1 0 1 2} for positions 1–5 (or 2–6) tested for accessing the list from the beginning (positive slope) or the end (negative slope). A quadratic contrast with weights {-2 1 2 1—2} for positions 1–5 (or 2–6) tested for accessing the list from the nearest end. The mean RTs and proportions of correct responses across subjects are plotted in Fig. 3. The linear and quadratic contrasts for each experiment are presented in Table C1 in Appendix C.

Each experiment showed strong interactions between position, direction, and response (R1, R2) in both RT and accuracy. The patterns were very similar across experiments. In the forward order, the linear and quadratic contrasts were significant for RT1 and

[3] An analysis excluding positions 1 and 6 yielded nearly identical direction effects.

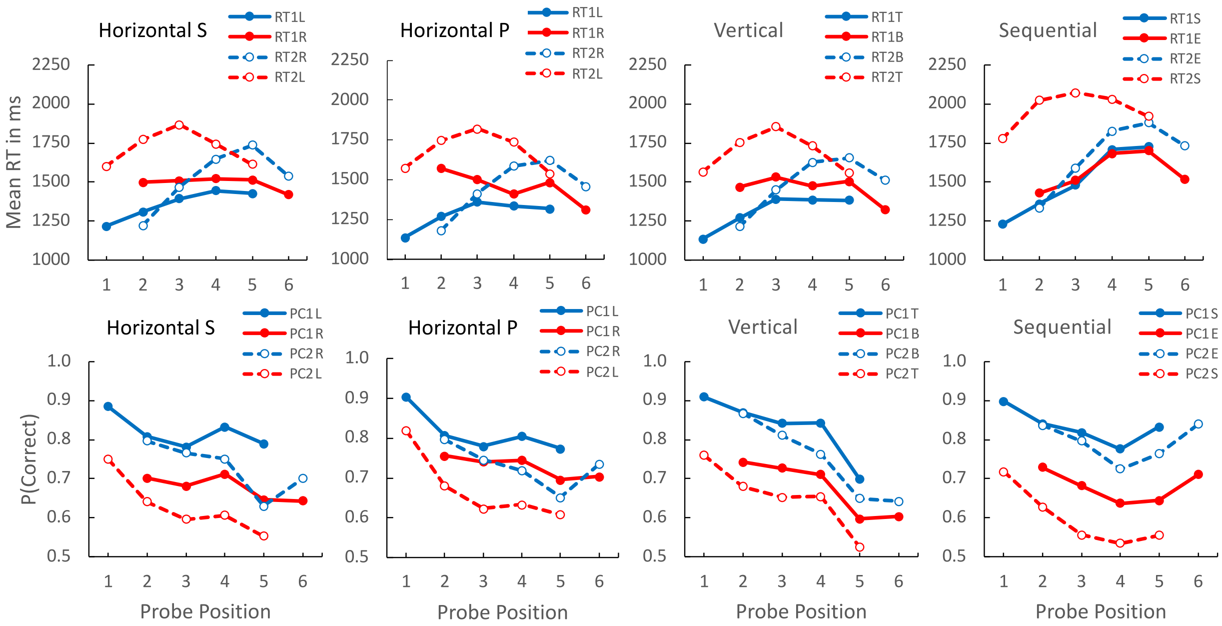

Fig. 3. Probe Position Effects Experiments 1–4. Note: Mean response time (RT; top row) and accuracy (P(Correct); bottom row) for first (solid lines) and second (dashed lines) responses in forward (L before R, T before B, S before E = blue) and backward (R before L, B before T, E before S = red) cue orders in Experiments 1–4 as a function of probe position. L, R (horizontal), T, B (vertical), and S, E (sequential) refer to the relative positions of the cues in the list. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

RT2 in all experiments but Sequential, where the quadratic component of RT1 was not significant. This suggests forward access for the first few items and backward access for the last one or two items. In the backward order, RT1 was less consistent. The linear trend was not significant in Horizontal S, significantly negative in Horizontal P and Vertical, and significantly positive in Sequential, suggesting a mixture of forward and backward access. Direct access is less plausible because RT1 was so long (cf. Experiments 5–6). In the backward order, the quadratic trend in RT2 was significant in each experiment and the linear trend was only significant in the Sequential experiment, suggesting forward access for cues near the front of the list and backward access for cues near the end. Together, these results suggest that subjects find both the first and second cued items by moving forward from the beginning of list or backwards from the end.

The locus of slack analysis of position effects was complicated by its strong interactions with direction (Fig. 2). It would be misleading to collapse over direction (it flattens the functions relating RT to position). Instead, we asked how the position x direction interaction changed with SOA by plotting it for each SOA in Fig. C1 in Appendix C. In each experiment, the pattern was essentially the same across SOAs but reduced in magnitude as SOA increased. There was no evidence of underadditive interactions that would indicate pre-bottleneck processing, so we conclude that finding the cued item in the list requires bottleneck or post-bottleneck processing.

IRI cannot be defined for position because different positions were cued for the two responses on each trial.

The accuracy data showed typical serial position effects. There were strong primacy effects. Each experiment showed an advantage for the first position and a decline in accuracy afterwards, suggesting that all the lists were encoded in the same first-to-last order. The recency effects were typical of the literature. Simultaneous presentation in the Horizontal and Vertical experiments produced no recency but sequential presentation in the Sequential experiment produced robust recency. The effects were not markedly different for the forward and backward directions, though accuracy was consistently higher in the forward direction. R1 was more accurate than R2 in each experiment, and the difference was generally larger in the backward direction.

Lag and Direction. The lag effect indicates how subjects move through the list from the first cued item to the second. Lag is the difference between the position of the first and second cued items in the list, ranging from 1 to 5. Lags in the forward direction are positive; lags in the backward direction are negative. To make the comparison easier, we calculated absolute lags. Lags of 1 and 5 are special. Lags of 1 require recall of adjacent items in the list, which is consistent with habitual retrieval plans in forward recall but not in backward recall. Lags of 5 always involve the end items, which may be accessed differently from the other items. If subjects step through the list from the first cued item to the second, RT2 should increase and R2 accuracy should decrease with lag, as each step adds time and provides another opportunity for error. If subjects start searching for the second item from the beginning or end of the list, the lag effect should be null.

We calculated mean RT (for correct responses) and accuracy for R1 and R2 for each combination of lag and direction. The results are plotted in the top and middle rows of Fig. 4. Again, the patterns were very similar across experiments. Excluding lags 1 and 5, RT2 tended to increase with lag for transitions in the forward direction (LR, TB, SE), suggesting that subjects stepped forward through the

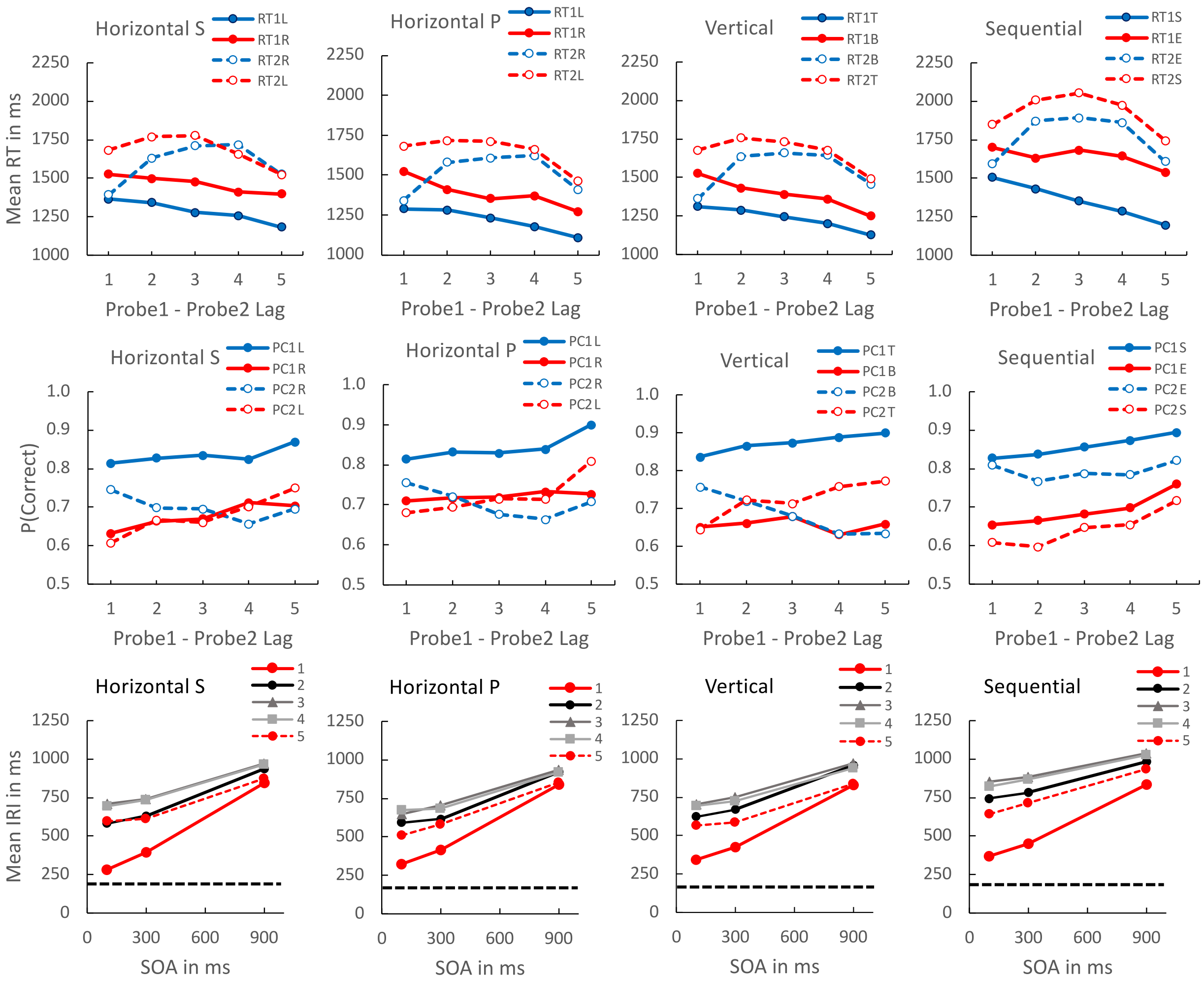

Fig. 4. Lag Effects Experiments 1–4. Note: Mean response time (RT; top row) and accuracy (P(Correct); middle row) for first (solid lines) and second (dashed lines) in forward (blue) and backward (red) cue orders (forward = L before R, T before B, and S before E; backward = R before L, B before T, and E before S) in Experiments 1–4 as a function of absolute lag (distance in the list) between the first cue and the second cue. L, R (horizontal), T, B (vertical), and S, E (sequential) refer to the relative positions of the cues in the list. Forward cue orders represent positive lags. Backward cue orders represent negative lags. The bottom row contains inter-response intervals (IRIs) for each lag as a function of SOA. The dashed black horizontal line is the mean interkeystroke interval (IKSI) from the typing tests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

list from the first cued position to the second. However, RT2 tended to decrease with lag for transitions in the backward direction (RL, BT, ES), which is inconsistent with stepping backward through the list from the first cued position to the second. Neither of these tendencies was robust. Contrasts evaluating the increasing linear trend in the forward direction were significant only in Horizontal S. Contrasts evaluating the decreasing linear trend in the backward direction were significant only in Horizontal S and Vertical (see Table D1 in Appendix D). These results do not provide strong support for the hypothesis that subjects find the second cued item by moving through the list from the first. The null effects are more consistent with the alternative hypothesis that they start at the beginning or end of the list.

At lag 1 where transitions are between adjacent list items, RT2 was only slightly longer than RT1 in the forward direction, as if subjects deployed their habitual forward retrieval plan. There was some lag 1 sparing in the backward direction, but it was smaller in magnitude. Contrasts evaluating lag 1 sparing are presented in Table D2 in Appendix D.

In the forward direction (LR, TB. SE), RT1 decreased significantly with lag in each experiment. In the backward direction (RL, BT, ES) RT1 decreased with lag as well but the decrease was only significant in the Horizontal S and Vertical experiments. Contrasts evaluating these linear reductions are presented in Table D1 in Appendix D.

We did a locus of slack analysis to determine whether lag affected pre- or post-bottleneck processes, performing 5 (Lag: 1–5) × 3 (SOA: 100, 300, 900) ANOVAs on the RT2 data and we did ANOVAs with the same structure on RT1, PC1, and PC2 data. Mean RTs and accuracy scores are plotted in Fig. D1 in Appendix D. Summary tables for these ANOVAs are presented in Table D3 in Appendix D. The interactions between lag and SOA were significant, but they were overadditive (lag had stronger effects with short SOAs), indicating

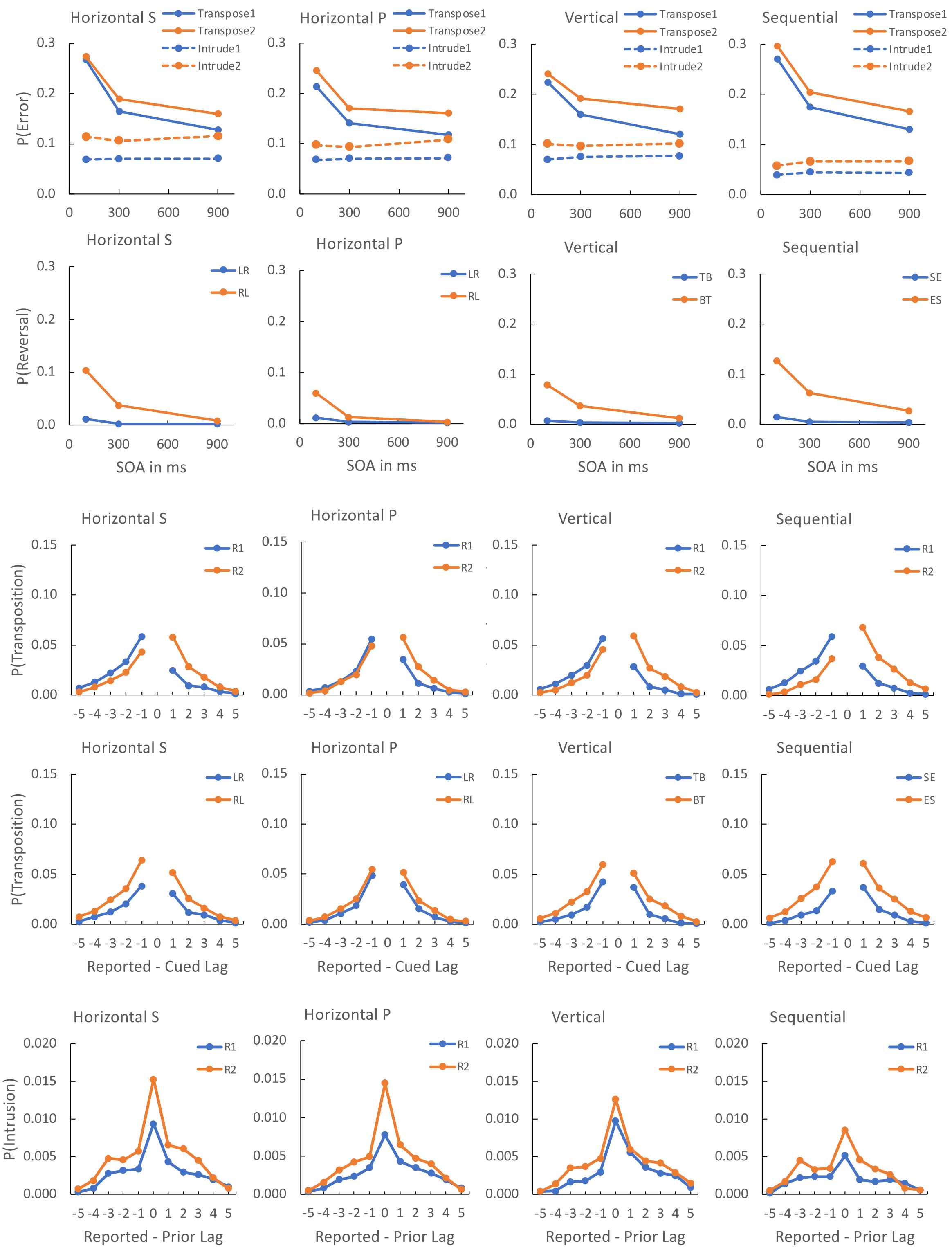

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Fig. 5. Transpositions, Intrusions, Reversals Experiments 1–4. Note: Error analysis in Experiments 1–4. Top row: Transposition and Intrusion errors as a function of stimulus onset asynchrony (SOA) between the first cue and the second cue and response (blue = first; red = second). Second row: Response reversal errors as a function of SOA when cues were presented in the forward (LR, TB, SE = blue) and backward (RL, BT, ES = red) directions. Third row: Probability of a transposition error (transposition gradients) for first (blue) and second (red) responses as a function of the lag between cued (correct) position and the position of the transposed item. Fourth row: Transposition gradients for forward (LR, TB, DR = blue) and backward (RL, BT, ES = red) cue orders. Bottom row: Probability of a prior list intrusion as a function of the lag between the cued position and the position the intrusion occupied in the immediately previous list. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that lag affected bottleneck or post-bottleneck processes.

We did an IRI analysis to complement the locus of slack analysis. The mean IRIs for lags 1–5 are plotted as a function of SOA in the bottom row of Fig. 4. The pattern was the same in each experiment. Lag 1 had the shortest IRIs, reflecting lag 1 sparing. Lag 5 was second shortest, reflecting the advantage of end items. IRI tended to increase with lag for lags 2–4, suggesting that bottleneck processing is required to move through the list. Contrasts supporting this conclusion are reported in Table A4 in Appendix A. The dashed black horizontal lines in the figure represent the mean IKSIs from the typing test, as in Fig. 2. IRIs in the memory task were substantially longer than the IKSIs, suggesting that memory retrieval requires bottleneck processing.

The accuracy data generally show an increase in accuracy as lag increases, which is contrary to stepping through the list from the first cued item to the second. Accuracy decreased with lag for R2 in the forward condition, suggesting forward movement through the list (consistent with the RT2 data). Lag 1 sparing was observed in the forward direction. Accuracy was about the same across lags for R1 and R2 in the backward direction, suggesting no lag 1 sparing. Contrasts evaluating lag 1 sparing are presented in Table D2 in Appendix D.

Transposition, Intrusion, and Reversal Errors. The nature of recall errors is a major focus of theory and research in serial memory because of the insights they provide into the representations and decision processes (e.g., Henson et al., 1996). We performed exploratory analyses of errors to connect with that literature and to examine possible sources of the SOA effect on accuracy. First, we classified errors for R1 and R2 as *intrusions* (recalling an item that was not on the list) or *transpositions* (recalling an item from an uncued position), collapsing across order. The results, plotted in the top row of Fig. 5, show that intrusion errors were not affected by SOA for either response, but transposition errors were affected strongly by SOA for both responses, especially at the shortest (100 ms) SOA. Contrasts supporting these conclusions are presented in Table E1 in Appendix E.

Second, we examined *response reversals* as a function of SOA and direction, collapsing across R1 and R2, counting cases in which the two responses were correct but in reverse order (if C was cued before A, recalling A and then C). The results, plotted in the second row of Fig. 5, show a peak in reversals at the shortest SOA for the backward order but not for the forward order, suggesting a tendency to recall items in forward order even when the backward order is cued. Contrasts evaluating these differences are presented in Table E1 in Appendix E.

Third, we examined transposition errors as a function of the lag between the correct item and the reported item (*transposition gradients*). Lag is negative for items from earlier positions in the list and positive for items from later positions. The third row of Fig. 5 shows transposition gradients for first and second responses, collapsed across SOA and direction. There was a clear (significant) asymmetry between the responses in each experiment: R1 errors tended to come from earlier positions in the list while R2 errors tended to come from later positions. This could reflect a left–right bias in encoding the position of the cue, such that first cues are perceived earlier in the list and second cues are perceived later. Contrasts supporting these conclusions are presented in Table E2 in Appendix E. The fourth row of Fig. 5 shows transposition gradients for forward and backward directions. There were more transposition errors in the backward direction than in the forward direction in each experiment, suggesting a preference to respond in the forward order, but there was no bias toward earlier or later positions. Contrasts supporting these conclusions are presented in Table E2 in Appendix E.

In serial recall tasks, subjects sometimes recall items from the previous list. These *prior-list intrusions* are often *position specific*. They are more likely to come from the intended position in the prior list than from more distant positions. Given ABCDEF then JKLMNO, an intrusion when recalling the third item (after recalling JK) is more likely to be from the third position in the prior list (C) than from the second (B) or fourth (D). Position-specific prior list intrusions are important because they are uniquely predicted by *position coding* theories of serial memory (Henson, 1998; Osth & Hurlstone, 2022; but see Caplan et al., 2022).

We did an exploratory analysis of prior list intrusions to determine whether they are position specific in cued recall. The bottom row of Fig. 5 plots the mean proportion of prior list intrusions observed for first and second responses as a function of the lag between the cued position and the position of the intruded item in the prior list. We assessed position specificity for each response with a contrast that compared lag 0 with lags −1 and + 1 using contrast weights 2, −1, and −1, respectively. The contrast values for each experiment are presented in Table E3. There were significant position-specific prior list intrusions for both responses in each experiment.

The observation of position-specific prior list intrusions in our data is consistent with position coding theories of serial memory (Henson, 1998; Osth & Hurlstone, 2022; but see Caplan 2022). In terms of the three theories of retrieval as attention turned inward in the General Discussion, the prior list intrusion results support the start–end model (SEM) and challenge the overlap (OVL) and context retrieval and updating (CRU) model. However, position-specific prior list intrusions were rare, occurring on less than 2% of the trials, so position coding may not have been used very often (Logan & Cox, 2023).

9. Conclusions

The data from Experiments 1–4 provide converging support for four conclusions: First, we replicated classic PRP results: RT2 increased dramatically as SOA decreased, indicating a PRP effect, while RT1 increased more modestly. The SOA effects suggest that sequential memory retrieval involves the same sequential attention as perceptual tasks, supporting the conclusion that memory retrieval is attention turned inward (Logan et al., 2021, 2023).

Second, there was a direction effect. Cuing in the forward direction produced shorter RT and higher accuracy than cuing in the backward direction, suggesting that the advantage of forward over backward serial recall does not depend entirely on habitual retrieval plans. It can be observed with arbitrary, trial-specific plans, so it may also depend on the (forward) structure of the memory representation. The IRI analyses suggested that direction affected prebottleneck processes or bottleneck processes that were only required in the first task. The analyses of errors suggest that the reduction in accuracy at the shortest SOA (100 ms) may result from a tendency to report nearly simultaneous cues in the forward order.

Third, there were position effects that interacted strongly with direction and response (R1, R2). Linear and quadratic trend analyses suggest that subjects accessed the cued items by scanning from the beginning or the end of the list, with a preference for forward scanning.

Fourth, the lag effects were weak. As lag increased from 2 to 3, RT2 in the forward direction tended to increase and RT2 in the backward directed tended to decrease, but the effects were not robust statistically. The IRI analyses showed some evidence that lag affected the duration of bottleneck processing. Together, the RT and IRI results do not provide strong support for the hypothesis that subjects move through the list from the first item to the second. The weak results may reflect a mixture of strategies, in which subjects sometimes find the second item by moving through the list from the first item and sometimes find the second item by moving inward from the start or end of the list. The immediate transitions at lag 1 were different. In the forward direction, there was little cost in RT2 or R2 accuracy for immediate transitions, as if subjects followed habit and retrieved the next item on the list. In the backward direction, RT and accuracy costs were reduced for immediate transitions (lag −1) but not by as much as in the forward direction.

These four effects varied little across experiments despite variations in format. This suggests that performance was determined primarily by memory representations of order and not influenced much by reading habits or reliance on specific presentation formats.

10. Experiments 5–6: The PRP effect in cued report

Experiments 1–4 suggest that retrieving two items from memory sequentially requires the same serial attention mechanism that is engaged in perceptual PRP tasks. So far, we have interpreted the effects of position, lag, and direction as constraints imposed on serial attention by the memory representation: Lists are ordered structures and must be accessed in order. However, position, lag, and direction effects may reflect constraints on the process of serial attention rather than the structure of the memory representation. Experiments 5–6 test this possibility by replicating the horizontal and vertical memory experiments (2 and 3) with perceptual displays. The procedure is illustrated in Fig. 6. Subjects were shown a horizontal (Experiment 5) or vertical (Experiment 6) list of six letters, as in the memory experiments, but the list remained visible on the screen throughout the trial until the second response was registered. The first cue appeared 500 ms after the onset of the list and the second cue appeared 100, 300, or 900 ms after the first. Like Experiments 1–4, the task was to type the letter indicated by the first cue and then type the letter indicated by the second cue, but "retrieval" was from perception rather than memory.

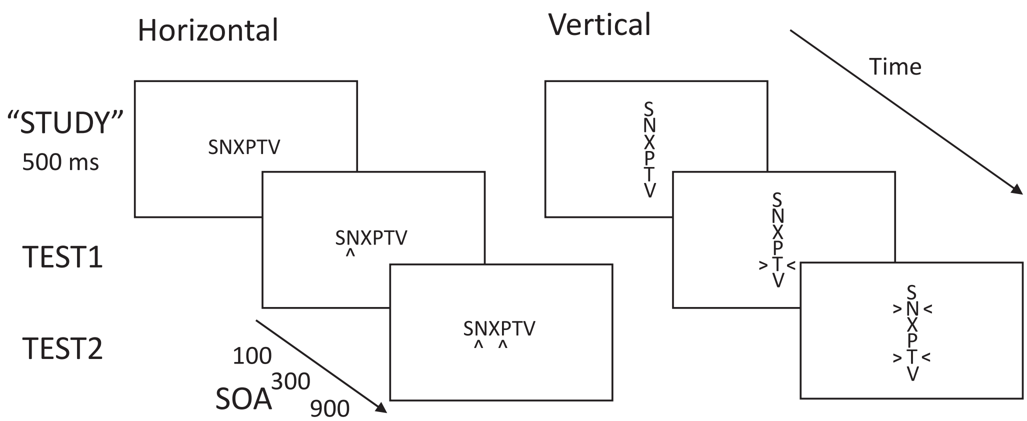

Fig. 6. Time Course of Trial Events Experiments 5–6. Note: Each trial began with a fixation point exposed for 500 ms followed by the study list (not shown). List items were presented simultaneously throughout the trial until the second response was registered, which ended the trial. The first cue appeared 500 ms after the list was presented. The second cue appeared 100, 300, or 900 ms after the first. Both cues remained on the screen until the second response was registered. The Horizontal trial illustrates cuing in the *forward* direction, reporting N before P (left before right). The Vertical trial illustrates cuing in the *backward* direction, reporting T before N (bottom before top).

If the position, lag, and direction effects in Experiments 1–4 are due to constraints on serial attention, then they should replicate in Experiments 5–6 because the constraints on attention are the same. However, if the effects in Experiments 1–4 are due to constraints imposed by the memory representation, they should be quite different in Experiments 5–6 because perceptual representations impose different constraints than memory representations. Experiments 1–4 suggest that memory representations contain ordinal information but not metric information about the details of presentation. Perceptual representations contain both ordinal and metric information, and the metric information may enable direct access to the cued positions without having to step through the list.

11. Method

Subjects. We recruited 32 subjects in each experiment from Prolific. In Experiment 5, mean age was 27.94 years, *SD* = 6.35 years; 22 subjects identified as male and 10 identified as female. In Experiment 6, mean age was 32.22 years, *SD* = 5.87 years; 14 subjects identified as male and18 identified as female. In Experiment 5, their mean typing speed was 67.28 WPM (SD = 20.37) and their mean accuracy on the typing test was 0.9147 (SD = 0.0472). In Experiment 6, mean typing speed was 63.64 WPM (SD = 16.71) and mean accuracy on the typing test was 0.9328 (SD = 0.0320). Again, the typing speeds suggest a high level of typing skill.

Apparatus and Stimuli. These were the same as in Experiments 1–4 except that the lists remained on the screen throughout the trial.

Procedure. The events on each trial are displayed in Fig. 6. They were the same as in Experiments 1–3 except that the list was presented throughout the trial, and the first cue appeared 500 ms after the list was presented to give subjects an opportunity to encode the list before they were cued to recall from it. The basic design required 30 trials and there were 540 trials in total. Instructions and exclusion criteria were the same as in Experiments 1–4, except that subjects were told to report the cued items in the display instead of reporting the cued items in memory.

12. Results and Discussion

SOA and Direction. Mean RT (for correct responses) and accuracy were calculated for each response (R1, R2) for each combination of SOA (100, 300, 900 ms) and direction (forward, backward) for each subject. Results of 2 (direction) × 3 (SOA) ANOVAs on the RTs and accuracy data are presented in Table A1 in Appendix A. The means across subjects are plotted for each experiment in Fig. 7. The pattern of results in the two experiments was very similar for both RT and accuracy despite the difference in format. Overall, RTs were 512 ms shorter than RTs in the corresponding memory experiments with horizontal and vertical lists (2 and 3). There was a robust PRP effect (RT2 slowing) in every subject in each experiment (see Table A2 in Appendix A), replicating the classic effect in perception once again (Pashler, 1994). The elevation of RT2 at short SOAs was smaller than in the memory experiments because RT1 was shorter, so the second response did not have to wait as long to access the bottleneck.

The direction effects were small (23 and 27 ms for Experiments 5 and 6, respectively) compared to the memory experiments (200 and 202 ms for Experiments 2 and 3, respectively) but they were highly significant in both experiments. They could reflect attentional habits driven by reading left-to-right and top-to-bottom or they could reflect left-to-right or top-to-bottom encoding of the lists. A locus of slack analysis suggested that direction affected bottleneck processes: The interaction between SOA and direction was significant but overadditive in each experiment (Table A1). The IRI analysis revealed a small but significant advantage for the forward direction in the horizontal experiment and no advantage for the forward direction in the vertical experiment (see Fig. 9, bottom row; the contrasts evaluating these effects are presented in Table A3 in Appendix A). The mean IRI for the 100 ms SOA was closer to the mean IKSI in these experiments (281 vs. 180 ms, respectively) than it was in the memory experiments (555 vs. 178 ms, respectively), but it was still longer, suggesting that the perceptual tasks require bottleneck processing beyond selecting and executing keystrokes.

Accuracy was near ceiling, but results were similar to the memory experiments (2 and 3) except for a compression in scale. In particular, accuracy was lower in the backward direction than in the forward direction at the shortest SOA.

Position and Direction. The interactions between position, direction, and response (R1, R2) are plotted in Fig. 8. Planned contrasts evaluating linear and quadratic trends for each response are presented in Table C1 in Appendix C. Compared to the memory experiments (2 and 3), the effects were much smaller, and the quadratic contrast was negative in each combination of direction and response, reflecting better performance at the middle of the lists (closer to fixation) than at the beginnings or ends (farther from fixation). This is opposite to the pattern in the memory experiments, in which performance was worse in the middle of the lists. The perceptual results suggest direct access.

The incomplete factorial design prevented us from testing locus of slack predictions with ANOVA. Instead, we plotted the interaction between position, direction, and response separately for each SOA in Fig. C2 in Appendix C. The magnitude of the interactions decreased over SOA, which suggests they did not reflect pre-bottleneck processes.

Accuracy was very high. The differences between conditions were small.

Lag and Direction. The interactions between lag, direction, and response (R1, R2) are plotted in Fig. 9. The lag effects were small compared to the memory experiments (1–4). In the forward direction, RT2 increased with lag for lags 2–4 in both experiments. In the backward direction, RT2 increased linearly with lag in Experiment 6 but not in Experiment 5. RT1 increased linearly with lags 2–4 in all but the forward condition in Experiment 6. Contrasts evaluating linear effects of lag are presented in Table D1 in Appendix D. A small amount of lag 1 sparing was observed in each experiment, but unlike the memory experiments, it was not stronger in the forward direction. Contrasts evaluating lag 1 sparing are presented in Table D2 in Appendix D.

We did a locus of slack analysis of the lag effects, performing 5 (Lag: 1–5) × 3 (SOA: 100, 300, 900) ANOVAs on the RT2 data in Fig. D2 and we did ANOVAs with the same structure on the RT1, PC1, and PC2 data. The interaction between lag and SOA in RT2 was

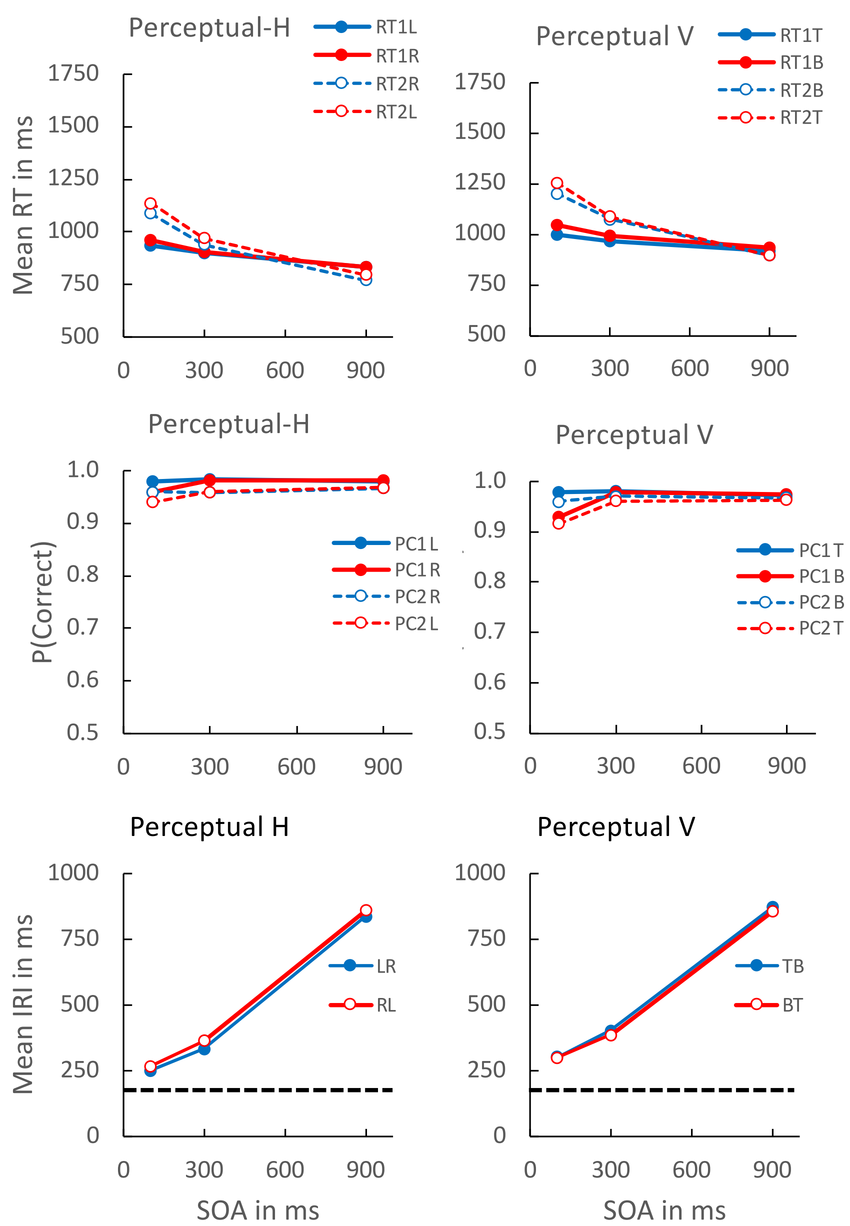

Fig. 7. SOA Effects Experiments 5–6. Note: Mean response time (RT; top row) and accuracy (P(Correct); middle row) for the first (solid lines) and second (dashed lines) responses as a function of the stimulus onset asynchrony (SOA) between the first cue and the second cue and the direction of recall (forward = L then R, T then B = blue; backward = R then L, B then T = red) in Experiments 5–6. Note that the scale is shifted downward by 500 ms relative to the memory experiments plotted Fig. 2. L, R (horizontal), T, B (vertical), and S, E (sequential) refer to the relative positions of the cues in the list. Bottom row: Mean inter-response interval (IRI) for pairs of responses in the forward (LR, TB = blue) and backward (RL, BT = red) directions as a function of SOA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

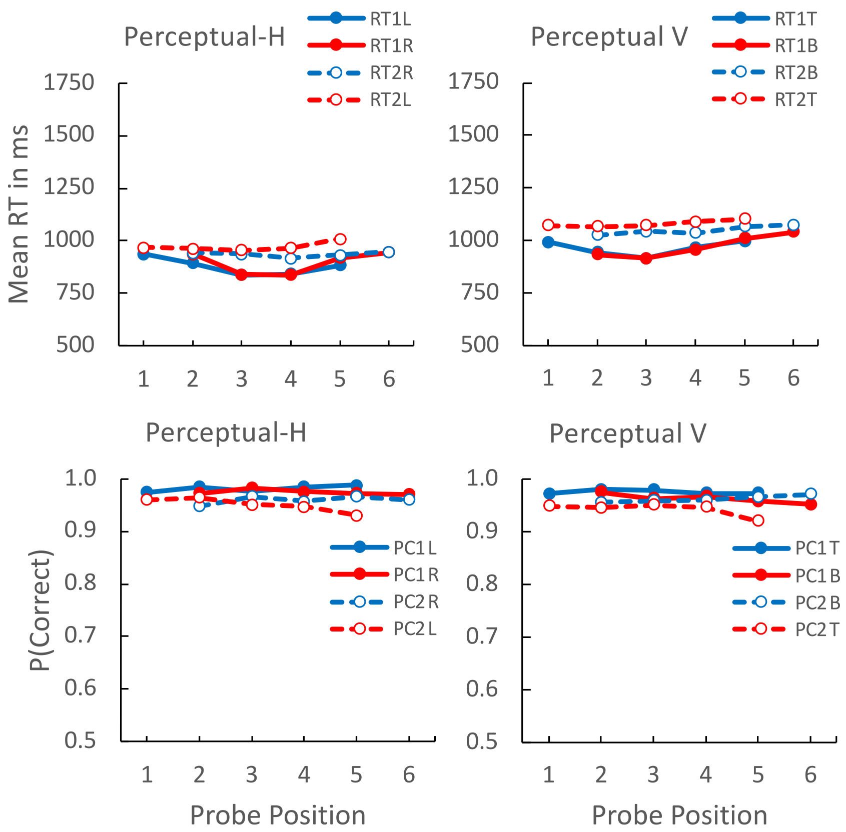

Fig. 8. Probe Position Effects Experiments 5–6. Note: Mean response time (RT; top row) and accuracy (P(Correct); bottom row) for first (solid lines) and second (dashed lines) in *forward* (L then R, T then B = blue) and *backward* (R then L, B then T = red) cue orders in Experiments 5 (left) and 6 (right) as a function of probe position. L, R (horizontal), and T, B (vertical) refer to the relative positions of the cues in the list. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

not significant in Experiment 5 (horizontal) but was significant in Experiment 6, suggesting a tendency toward underadditivity. The IRI analysis (Fig. 9, bottom row) showed a small advantage for lag 1 and lag 5. The contrast evaluating the linear trend from lags 2–4 was null in the horizontal experiment and significant in the vertical experiment for the 100 ms SOA. It was significantly negative in the horizontal experiment at the 300 ms SOA. No other effects were significant (see Table A4 in Appendix A).

Transposition, Intrusion, and Reversal Errors. We did an exploratory analysis of errors, as in Experiments 1–4. The error patterns, plotted in Fig. 10, were similar but reduced in scale. Transpositions were more likely at the shortest SOA than at longer SOAs, but intrusions did not vary with SOA. Response reversals occurred at the 100 ms SOA when cues were presented in backward (right-left) order but not in forward (left–right) order. The transposition gradients for first and second responses were asymmetrical. Backward transpositions were more likely for the first response. Forward transpositions were more likely for the second response. Transpositions were more likely when cues appeared in the backward direction than in the forward direction. Prior list intrusions were different. They were very rare and not position specific. Contrasts supporting these conclusions are presented in Tables E1 and E2 in Appendix E.

The similarities between these perceptual report results and the cued recall results in Experiments 1–4 suggests the representations and decisions processes were similar. That is consistent with the hypothesis that memory retrieval is perceptual attention turned inward.

13. Conclusions

Experiments 5 and 6 were designed to determine whether the PRP, direction, position, and lag effects observed in Experiments 1–4 were due to constraints imposed by memory representations or to constraints imposed by serial attention. If the constraints were imposed by serial attention, then the effects should be the same with perceptual representations as they were with memory

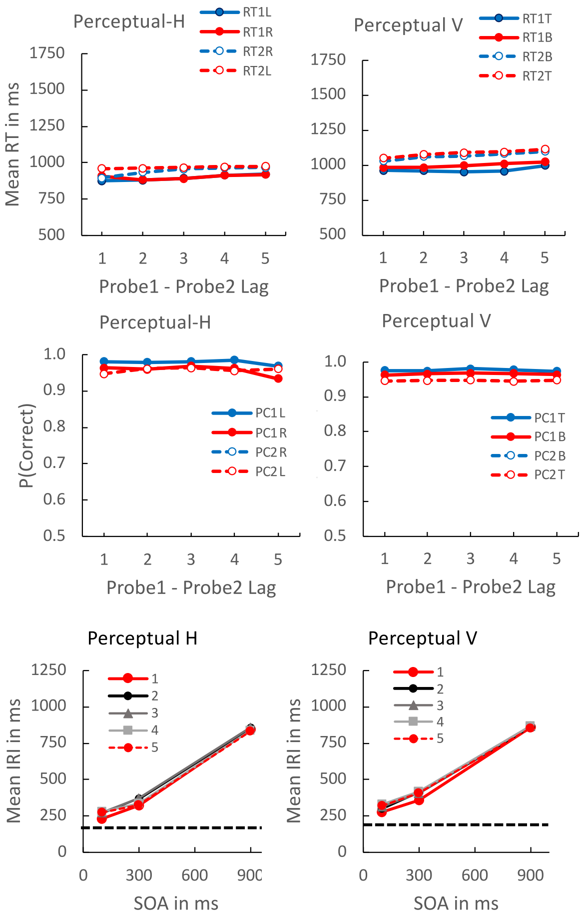

Fig. 9. Lag Effects Experiments 5–6. Note: Mean response time (RT; top row) and accuracy (P(Correct); middle row) for first (solid lines) and second (dashed lines) responses in *forward* (L then R, T then B = blue) and *backward* (R then L, B then T = red) cue orders in Experiments 1–4 as a function of absolute lag (distance in the list) between the first cue and the second cue. Forward cue orders represent positive lags. Backward cue orders represent negative lags. L, R (horizontal), and T, B (vertical) refer to the relative positions of the cues in the list. Bottom row: Mean inter-response interval (IRI) for lags 1–5 as a function of SOA. The dashed black horizontal line is mean interkeystroke interval (IKSI) on the typing test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

representations. This was the case for the PRP effect, supporting our conjecture that memory retrieval is attention turned inward and extending it to serial attention. It was also the case for the direction effect, which was small but robust. This suggests an attentional bias to move left-to-right and top-to-bottom through list structures in both perception and memory, though it is attenuated in perception. Direction did not affect IRI. Position and lag effects were different in Experiments 5 and 6. Position effects were small and opposite to the effects in memory, showing an advantage in the middle of the list instead of a disadvantage. Lag effects were small and different from the effects in memory, showing a weak advantage of immediate (lag 1) transitions that was the same in forward or backward directions and very small differences in IRI. This suggests that the position and lag effects in Experiments 1–4 were due to constraints imposed by the memory representations.

14. General Discussion

The present experiments are part of our research program that evaluates the conjecture that memory retrieval is selective attention turned inward (Chun et al 2011; Craik, 2020; Gazzaley & Nobre 2012; Kiyonaga & Egner 2013; Logan 2002), asking whether sequentially retrieving items from memory engages the same computational mechanisms as sequentially “retrieving” items from perception (Logan et al., 2021, 2023). The present experiments addressed that question by combining cued recall (Experiments 1–4) and cued report (Experiments 5–6) with the PRP procedure and requiring subjects to retrieve two cued items in rapid succession. The cued recall experiments showed strong PRP effects: RT2 was delayed substantially at shorter SOAs in each experiment (Fig. 2), conceptually replicating previous experiments showing PRP effects in episodic (Carrier & Pashler, 1995; Logan & Delheimer, 2001) and semantic (Fischer et al., 2007; Logan & Gordon, 2001; Logan & Schulkind, 2000) memory. The cued report experiments (5 and 6) showed strong PRP effects when the lists were visible throughout the trial and engaged perceptual attention (Fig. 7), replicating many

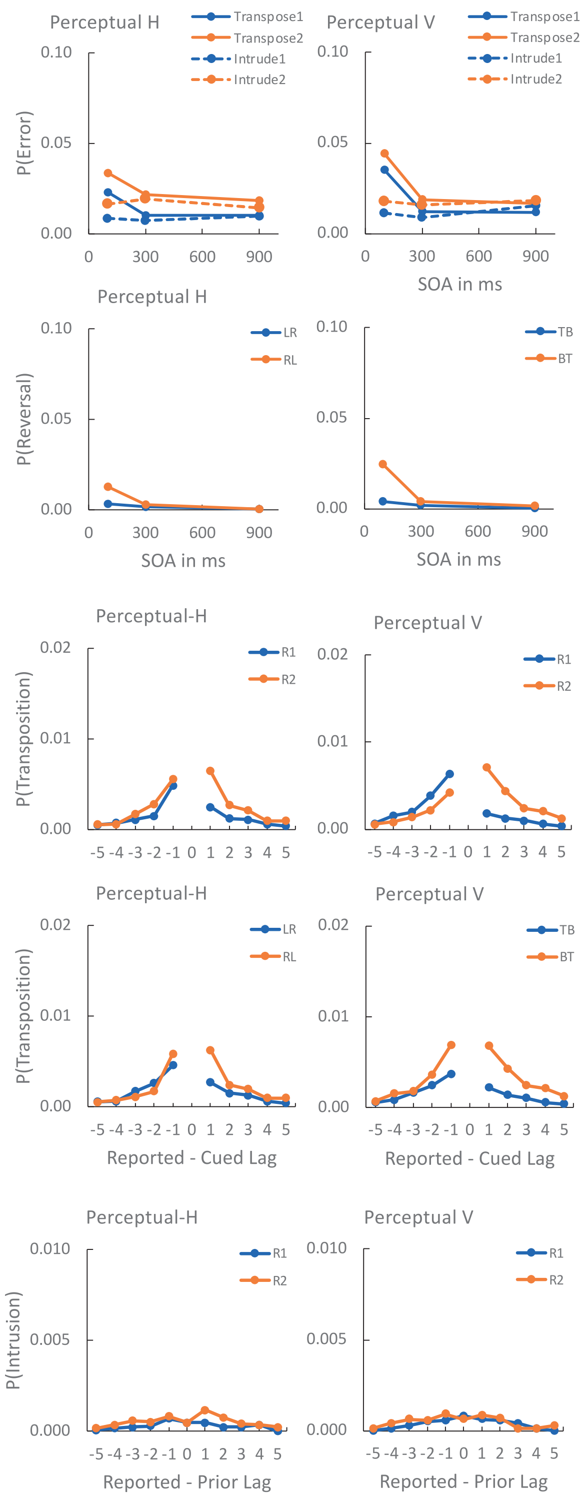

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Fig. 10. Transpositions, Intrusions, Reversals Experiments 5–6. Note: Error analysis in Experiments 5–6. Top row: Transposition and Intrusion errors as a function of stimulus onset asynchrony (SOA) between the first cue and the second cue and response (blue = first; red = second). Second row: Response reversal errors as a function of SOA when cues were presented in the forward (blue) and backward (red) directions. Third row: Probability of a transposition error (transposition gradients) for first (blue) and second (red) responses as a function of the lag between cued (correct) position and the position of the transposed item. Fourth row: Transposition gradients for *forward* (LR, TB = blue) and *backward* (RL, BT = red) cue orders. Bottom row: Prior list intrusions for first (blue) and second (red) responses as a function of lag between the cued position and the position the intrusion occupied in the prior list. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

previous PRP experiments (Pashler, 1994). Analyses of transposition, intrusion, and reversal errors suggested similar representations and decision processes in cued recall and cued report. These results establish empirical parallels between sequential attention in memory and perception that suggest they engage common computational mechanisms. They show that serial retrieval requires serial attention.

15. Are memory and Perceptual bottlenecks the Same?

The Empirical Claim. The claim that memory retrieval is attention turned inward implies that the bottleneck is the same in memory retrieval and perceptual report. Our experiments reveal commonalities and differences between them. Both memory and perceptual experiments showed PRP effects, suggesting a common bottleneck, and the patterns of transposition and reversal errors were quite similar, suggesting a common decision process, but direction, position, and lag effects differed. They were much larger in the memory experiments (1–4) than in the perceptual experiments (5–6). The locus of slack analyses in the memory experiments suggest that direction, position, and lag affect bottleneck processes. The IRI analyses provide converging evidence, suggesting that direction affects bottleneck processes that are only required for the first task, and lag affects bottleneck processing for the second task.

The IRI analyses quantify bottleneck processing time and reveal that the memory experiments (1–4) required more than the perception experiments (5–6). Mean IRIs for each experiment (collapsing across direction, position, and lag) are plotted in left panel of Fig. 11 along with the mean IKSI from the typing tests (averaged over experiments). As in previous plots, the IRIs increased from the 100 to the 300 ms SOA, indicating that the IRIs are not pure measures of bottleneck processing (Equation (6). They are informative nevertheless. At the 100 ms SOA, IRIs for the horizontal (2) and vertical (3) memory experiments were 256 and 250 ms longer than IRIs for the horizontal (5) and vertical (6) perception experiments, respectively, $t(62) = 9.4057$, $p < .0001$, $SEM = 27.2110$, $BF_{10} = 32{,}830{,}421{,}297$ for horizontal; $t(62) = 9.0051$, $p < .0001$, $SEM = 27.7141$, $BF_{10} = 7{,}312{,}160{,}771$ for vertical. These results corroborate the conclusion that the longer RTs in the memory experiments were due to longer bottleneck processing. At the 100 ms SOA, IRI was 100 ms longer for the sequential memory experiment (4) than for the vertical memory experiment (3), $t(62) = 2.5662$, $p = .0127$, $SEM = 39.0067$, $BF_{10} = 3.856$, suggesting that retrieval from a sequentially presented list requires more bottleneck processing than retrieval from a simultaneous list.

The IRI analyses indicate that bottleneck processing in memory and perception involved more than selecting and executing keystrokes. At the 100 ms SOA, the difference between mean IRIs and the mean IKSIs in the typing tests was 379 ms in the memory experiments (1–4) and 103 ms in the perception experiments (5–6). Contrasts reported in Table F1 in Appendix F show that the differences were significant in each experiment.

The correlations between RT1 and RT2 provide further evidence that bottleneck processing took longer in the memory experiments (1–4) than in the perceptual experiments (5–6). We calculated the correlation between RT1 and RT2 at each SOA for each subject in

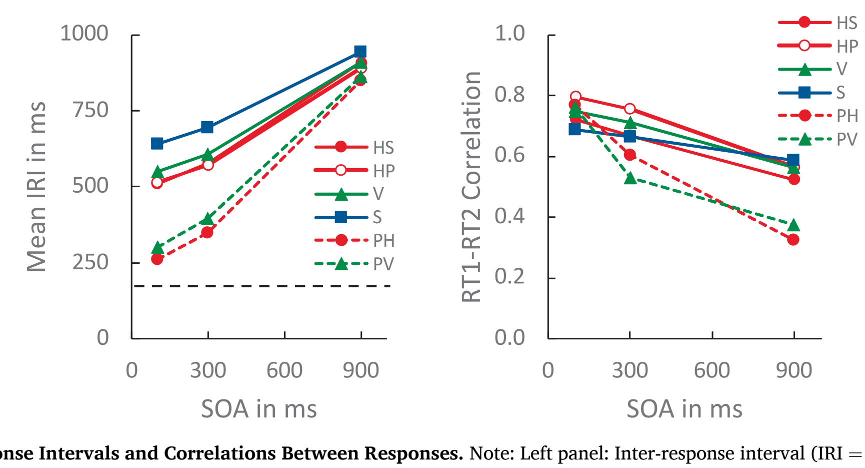

Fig. 11. Inter-Response Intervals and Correlations Between Responses. Note: Left panel: Inter-response interval (IRI = RT2 + SOA – RT1) as a function of stimulus onset asynchrony (SOA) between the first and second cues. Right panel: Correlation between RT1 and RT2 as a function of SOA. HS = Horizontal Sona (Experiment 1); HP = Horizontal Prolific (Experiment 2); V = Vertical (Experiment 3); S = Sequential (Experiment 4); PH = Perceptual Horizontal (Experiment 5); PV = Perceptual Vertical (Experiment 6).

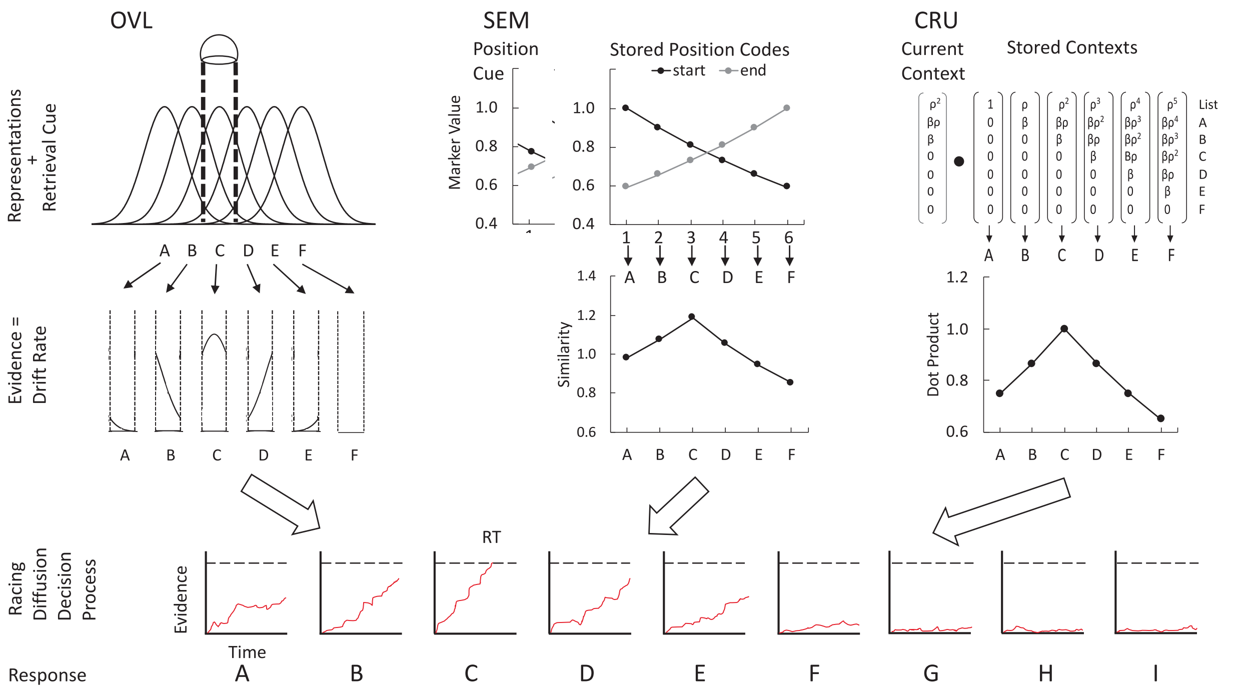

Fig. 12. Models of Attention to Memory. Note: Models of serial recall interpreted as models of attention. List ABCDEF is presented, and the third item is cued. Top row: Representations of items and order and the retrieval cue applied to them in each model. Second row: Evidence sampled by the retrieval cue applied to the representations in the top row. Bottom row: Evidence becomes drift rate in a racing diffusion decision process. Letters on the list (ABCDEF) compete more strongly than letters that were not on the list (GHI). The first alternative to finish determines the response and the response time (RT). OVL = overlap model. Items are represented as distributions in space and order is represented by position. At retrieval, evidence is sampled from a region surrounding the cued item, like the focus of a spotlight, which includes evidence from adjacent distributions that overlap with the cued region. SEM = start–end model. Order is represented by position markers that measure distance from the start and end of the list. At retrieval, the position code (pair of marker values) for the cued item is used to probe memory, and evidence from nearby positions is sampled in proportion to its similarity to the probe. CRU = context retrieval and updating model. Order is represented by stored contexts built by adding each presented item (with weight β) to the context made from traces of previous items (with weight ρ). At retrieval, memory is probed by a context vector built from previously retrieved items by the same updating process and evidence is the similarity (dot product) between the probe and each stored context. The evidence values in each model are drift rates in a racing diffusion decision process that chooses a response when the first alternative crosses its threshold (dotted line).

each experiment, collapsing across direction, position, and lag. The means across subjects in each experiment are plotted in the right panel of Fig. 11. As the bottleneck model predicts (Equations (1), 3, and 4), correlations were moderately large (mean = 0.7444) at the 100 ms SOA and decreased as SOA increased, reflecting the transition from RT2s that contain RT1 (Equation (3) and RT2s that do not (Equation (4). The transition was steeper for the perception experiments than the memory experiments, suggesting that task1 required less bottleneck processing. The difference between memory and perception correlations was not significant at SOA = 100 ms, $t(62) = 1.2168$, $p = .2283$, $SEM = 0.0218$, $BF_{10} = 0.4771$, for horizontal; $t(62) = 0.8848$, $p = .3797$, $SEM = 0.0238$, $BF_{10} = 0.3558$ for vertical. The difference between memory and perception correlations was significant at SOA = 300 ms, $t(62) = 4.3901$, $p < .0001$, $SEM = 0.0352$, $BF_{10} = 447.5$ for horizontal; $t(62) = 4.5901$, $p < .0001$, $SEM = 0.0396$, $BF_{10} = 835.8$ for vertical, suggesting shorter bottleneck processing in perception.

The Theoretical Claim. We interpret the differences between memory and perception as the effects of the same attention mechanism (the retrieval process) operating on representations with different structures. In memory, items are associated with structures that represent their order but not (necessarily) their metric positions in time and space (Anderson et al., 1998; Farrell, 2012; Henson et al., 1996; Howard & Kahana, 2002; Lewandowsky & Farrell, 2008; Logan, 2021; but see Brown et al., 2007; Burgess & Hitch, 1999; Hartley et al., 2016; Howard et al., 2015). The structures represent snapshots of past experiences that can no longer be renewed or revised by perceptual information. In perception, metric information about position and orientation in space is available directly and continuously, so samples can be revised and updated as needed. Consequently, memory provides fewer options for retrieval plans than perception, and most involve stepping through the list serially instead of accessing items directly. We assume that stepping through the list requires decisions (about where to go next), and decisions are made in the bottleneck. Once the target is found, the retrieval decision is the same in memory and perception. Thus, cued memory retrieval requires the same bottleneck processing as cued perceptual report plus some more to move through the list and find the target.

This analysis assumes the computations are the same in memory and perception, but the empirical results do not show that they are the same. Theories of attention provide little guidance in testing this assumption. The operational definition of the PRP effect relates SOA to RT2 without making any claims about the computations that underlie it. Central bottleneck theories (Broadbent, 1957; Pashler & Johnston, 1989; Welford, 1952, 1967) and central capacity theories (Kahneman, 1973; Navon & Miller, 2002; Tombu & Jolicœur, 2003) explicitly claim that all tasks are subject to the same "central" bottleneck or capacity limitation. The claim is supported by many observations of PRP effects with different combinations of stimuli and responses (Pashler, 1994). Indeed, presenting stimuli in different modalities (tone vs. light) and requiring responses in different modalities (speech vs. keypress) is viewed as a positive design feature in PRP experiments because it rules out "peripheral" interference. From this perspective, both memory and perceptual bottlenecks are "central" and therefore the same. However, neither bottleneck nor capacity theories model the computations, so they do not address our question of whether the computations are the same.

Theories that claim the bottleneck results from decision processes (Broadbent, 1971; Duncan, 1980; Logan & Gordon, 2001; Sigman & Dehaene, 2005) have the potential to provide a computational answer if they are implemented as formal decision models, like those in the literature on RT and memory retrieval, that choose only one response at a time. The formal decision models specify the computations and provide accurate, detailed accounts of correct and error RT distributions and response probabilities in many tasks in many domains, including attention and memory (Brown & Heathcote, 2008; Logan et al., 2021; Osth & Farrell, 2019; Polyn et al., 2009; Ratcliff, 1978; Ratcliff et al., 2016; Tillman et al., 2020; Usher & McClelland, 2001). These models assume that all decisions are made by different parameterizations of the same computational process, which usually involves sampling evidence for the choice alternatives and accumulating it until one alternative reaches a threshold. The nature and number of inputs and choice alternatives may vary, but the essential computation is the same. From this perspective, the bottlenecks are the same in memory and perception because they both result from the same decision process. Focusing on memory and perceptual representations requires decisions about where to focus (depending on the cues), how to get there (stepping through the list in memory; direct access in perception), and which choice alternative should be reported (in both tasks). In principle, each of these decisions can be explained by the same computational model, perhaps with different parameterizations for different decisions. More broadly, the decision bottleneck hypothesis provides a parsimonious account of sequential attention. It implies that any model of memory or attention that includes a theory of the decision process already includes theory of the bottleneck.

Conclusion. On balance, our results are consistent with the hypothesis that the bottleneck is the same in memory and perception but they do not establish the hypothesis definitively. They do not rule out alternative hypotheses, though there are few alternatives to a common central bottleneck in the literature. Accounting for our results requires new hypotheses about sequences of decisions leading up to the final retrieval decision that are currently underspecified. Nevertheless, our results encourage further research integrating theory and empirical results in attention and memory.

16. Sequential attention in serial memory

Our implementation of the PRP procedure in cued recall provides a new perspective on classic questions about how serial order is represented and how the representation of serial order is accessed to produce sequences of behavior. We replicated classic differences between forward and backward serial recall (Anders & Lillyquist, 1971; Anderson et al., 1998; Bireta et al., 2010; Guitard et al., 2020; Haberlandt et al., 2005; Norris et al., 2019; Surprenant et al., 2011) in each of the memory experiments (1–4): Forward cued recall was faster than backward cued recall for both responses (Fig. 2). Forward cued recall was more accurate than backward cued recall for the first response (Fig. 2) and produced fewer transposition, intrusion, and reversal errors (Fig. 3). To our knowledge, these are the first comparisons of backward and forward recall in a cued recall procedure. It is reassuring to find that classic effects replicate across retrieval tasks.

The similarity of direction effects with different retrieval tasks suggest that serial and cued recall tasks tap the same representations of order. Differences between forward and backward recall may reflect differences in that representation (Bireta et al., 2010; Guitard et al., 2020; Li & Lewandowsky, 1993, 1995; Norris et al., 2019), differences in the retrieval plan for accessing it (Anderson et al., 1998; Page & Norris, 1998), or both. In our experiments, differences in representation are unlikely because order of recall was post-cued, and the strong primacy effects in the serial position data (see Fig. 4) suggest a forward encoding strategy in all experiments regardless of presentation format. Position and lag effects on RT are more consistent with differences in retrieval plans.

Our cued recall procedure was intended to disrupt habitual serial retrieval plans by requiring a novel retrieval plan on each trial. Subjects were able to engage the required retrieval plans and produce appropriate behavior, but the position and lag effects on RT suggest that they may have adapted habitual forward retrieval plans to do so, like the peel-off strategy adapts forward habits to backward recall. When cues appeared in the forward direction, subjects seemed to step through the list from the beginning to find each cued item (there were strong positive linear trends in the RT1 and RT2 data; see Table C1), except for the last one or two positions, which were accessed more rapidly (there were strong quadratic trends in the RT1 and RT2 data; see Table C1). When cues appeared in the backward direction, access was less consistent. Linear trends were weaker and negative for RT1 and absent for RT2, and quadratic trends were apparent in RT1 and strong in RT2, suggesting a mixture of forward access and backward access. Backward access is not consistent with habitual forward serial recall retrieval plans.

The lag 1 sparing results provide converging evidence on the use of habitual serial retrieval plans in cued recall (Fig. 5). In the forward direction, there was a strong advantage in RT and accuracy for lag 1 transitions, which would be the next item produced in forward serial recall. In the backward direction, there was an advantage in RT for lag 1 transitions, which is not consistent with habitual forward serial retrieval plans. However, theories of serial and free recall often assume that the last item is available for recall at the end of the list, so in principle, the last item that was retrieved could also be available. This would give an advantage to backward lag 1 transitions, as the item would have just been retrieved in stepping through the list to find the first cued item (Nairne et al., 2007).

Together, the position and lag data suggest that our cued recall PRP task engaged a strategic mixture of forward and backward retrieval plans that balance habit and opportunity (Fischer-Baum & McCloskey, 2015). Unraveling the components and discovering the principles that govern how they are combined is a challenge for future research. Backward access is not consistent with computational models that represent order by associating items with contexts that evolve over time (Burgess & Hitch, 1999; Hartley et al., 2016; Lewandowsky and Farrell, 2008; Logan, 2021; but see Anderson & Matessa, 1997; Page & Norris, 1998). Those models would have to replay the context from the beginning to find the cued position, which would predict strong positive linear trends in the RT data with no quadratic components, unlike the data (also see Norris et al., 2019). Extending those models to include retrieval plans for backward access and representations that support it is an important goal for future research. Backward recall is still a problem for theory.

17. Steps toward models of Sequential attention to memory

Logan et al. (2021) addressed the conjecture that memory retrieval is attention turned inward by adapting models of serial recall and interpreting their retrieval cues as spotlights of attention focused on memory. They considered three memory models, illustrated in Fig. 12. The *overlap* model (OVL) is a combination of Estes et al. (1972), Estes (1997) perturbation model of serial recall, Ratcliff's (1981) overlap model of same-different judgments, and Logan's (1996) CODE theory of visual attention. OVL assumes noisy coding. Items are represented as distributions in space (top row). Distributions from nearby positions overlap, and the overlap is greater for nearby positions than for remote ones. The retrieval cue samples memory from a region surrounding the center of the cued item, like a spotlight focused on memory, gaining evidence about the target and its neighbors in proportion to the areas of their distributions that fall within the sampled region (middle row), so items from adjacent positions are more likely to be reported. The evidence for item i when item j is cued is

$$\eta_{ij} = \int_{j-.5}^{j+.5} f_i(x)dx \tag{10}$$

where $f_i(x)$ is the distribution for item i, items are 1 unit apart, and the boundaries for sampling are halfway between the centers of the item distributions. The sampled evidence, η_{ij}, becomes the drift rate for item i in a racing diffusion decision process (Tillman et al. 2020), in which the first alternative to finish determines the response and the RT. Logan et al. (2021) assumed the distributions were normal, characterized by two parameters, μ and σ. The means are given by the (serial) positions of the items; the standard deviations are free parameters that determine the overlap of the distributions, and hence, RT, accuracy, and the distributions of errors.

The *start–end* model (SEM) is an adaptation of Henson's (1998) model of serial recall. It assumes items are associated with *position codes* that consist of a start marker and an end marker that reflect the distance from the beginning and end of the list, respectively. The start (s(i)) and end marker values ($e(i)$) for position i are.

$$s(i) = S_0 \times S^{i-1} \tag{11}$$

and

$$e(i) = E_0 \times E^{N-i} \tag{12}$$

respectively, where S_0 and E_0 are marker values for the beginning and end positions, and S and E represent the decay of marker values with (forward and backward) position in the list (see Fig. 12). At encoding, items are associated with position codes. At retrieval, the position code for the probed item is the spotlight of attention that retrieves the item associated with it. It is compared to the set of position codes by calculating a similarity measure for each position (see Henson, 1998), which becomes a drift rate in the racing diffusion decision process. Codes for adjacent positions are more similar than codes for remote positions, so items from adjacent positions are more likely to be reported.

The *context retrieval and updating* model (CRU) assumes items are associated with the contexts in which they occur. It was developed to explain serial order phenomena in typing text (Logan, 2018) and perceiving, typing, and recalling letter strings (Logan, 2021). It is an adaptation of Howard and Kahana's (2002) temporal context model (TCM) and its descendants (Lohnas et al., 2015; Polyn et al., 2009; Sederberg et al., 2008). CRU assumes that items are associated with contexts made of fading traces of previously experienced (or retrieved) items, following the TCM updating equation,

$$\boldsymbol{c}_{N+1} = \beta \boldsymbol{r}_N + \rho \boldsymbol{c}_N \tag{13}$$

where $\boldsymbol{c}_{N+1}$ is a vector representing the updated *current context* for the next step ($N+1$), $\boldsymbol{r}_N$ is a vector representing the item that was presented or retrieved on the current (N^{th}) step, and $\boldsymbol{c}_N$ is a vector representing the current context on the N^{th} step. At encoding, each new item is associated with the context in which it appears, then the item and context are associated to produce a *stored context* in memory, and then the item is added to the current context with the updating equation. Retrieval uses the same updating equation to generate current contexts, which are the spotlights of attention in CRU. The current context is compared with the set of stored contexts generated during encoding by calculating the similarities (dot products) between the vectors. The similarities become drift rates in the racing diffusion decision process, which selects a response (Fig. 12). Stored contexts for nearby items are more similar than stored contexts for remote items, so items from adjacent positions are more likely to be reported.

Logan et al. (2021) applied these models to a *cued recognition* task that is much like our cued recall tasks. Subjects were given lists of six consonants to remember, followed by a probe in which one position was cued. The cued position contained a letter, and the task was to say whether or not that letter occurred in the cued position in the memory list. The steps in the models were the same as in cued recall, except that the recognition decision was based on the match between the probed item and the corresponding item in the memory list. Logan et al. used cued recognition to implement an episodic memory version of the Eriksen and Hoffman (1973) and Eriksen and Eriksen (1974) flanker tasks, replicating classic distance and compatibility effects associated with a spotlight of attention turned outward on perception. OVL, SEM, and CRU provided very similar accounts of the data, explaining distance and compatibility effects quite well. Distinguishing between the models will require further research.

Fig. 12 shows the application of OVL, SEM, and CRU to cued recall. Encoding and retrieval (gathering evidence) are the same as in cued recognition, and the decision process is simpler. There is one diffusion for each alternative. Evidence sampled from memory drives the decision process directly by determining the drift rate for each alternative. These versions of OVL, SEM, and CRU can account for some of our results with the PRP procedure, but not all of them. All three models account for the clustering of transposition errors around the cued position (Figs. 3 and 8) because items in or near the spotlight are more likely to be reported than remote items. All three models would account for the basic PRP effects by running themselves twice, starting with the first cued position and going on to the second (Logan & Gordon, 2001). All three models assume a decision process that is designed to select one response at a time, so the second run would have to wait for the first run to finish, producing a bottleneck and the associated effects on RT and accuracy (Logan et al., 2021).

In their present forms, OVL, SEM, and CRU cannot account for direction, position, and lag effects. (Logan et al., 2021, accounted for position effects with variation in non-decision time, which is an "account" but not an explanation.) These effects require assumptions about how subjects move forward and backward through the list. OVL and SEM assume that subjects move through the list in the required direction but do not provide a mechanism that accounts for the movement. CRU's updating process (Equation (12) provides a mechanism for moving forward through the list, which could explain the direction effects, but it does not (yet) explain moving backward.

We are considering an extension of CRU to backward recall, in which the associations between contexts and items are bi-directional (imagine bi-directional arrows in Fig. 12). Forward recall uses context-to-item associations to retrieve items (List + A + B => C). Backward recall uses item-to-context associations to retrieve the context that was current at the time the item was presented (C => List + A + B). That context contains the previously experienced items (A and B) but not the current item (C). The immediately preceding item (B) has the strongest representation in that context. It can be retrieved by calculating the dot product between that context and a set of vectors representing the items and selecting the item with the largest dot product (Equation (13) implies $\text{dot}(A,\text{context}) = \beta \cdot \rho$, $\text{dot}(B,\text{context}) = \beta$, and $\text{dot}(C,\text{context}) = 0$). Once retrieved, the item can be reported or used as a cue to retrieve the context that preceded it, or both. Applied iteratively, this retrieval plan will step through the list backwards, from the last item to the first. In cued recall, it would predict a strongly negative linear trend in the function relating RT to input position. Evaluating this extension of CRU is an important goal for future research.

We think the three models provide a strong basis for developing a more complete model, despite their difficulties in moving backwards through the list. They describe the basic machinery of encoding and retrieval—attending to perception and attending to memory. They provide a specific computational mechanism for the bottleneck (the racing diffusion model), which is currently lacking in the attention literature. The models do not (yet) provide a theory of the control processes that adapt the computational mechanism to the demands of cued recall in the PRP procedure. That is a major goal for our future research.

18. Merging attention and memory

We believe that the strategy of applying memory models to attention tasks and attention models to memory tasks will lead to significant progress in understanding the computations underlying cognition. It offers a desirable economy of mechanism, using the same computations to account for selection and limitations on performance in perception and memory. Theories of memory and attention may be proposing the same mechanisms without realizing it. Memory theory invokes attention to tie up loose ends, like how stimuli enter the system or how executive processing is controlled. Attention theory invokes memory to tie up its own loose ends, like how experience, habit, and knowledge affect performance. We see value in tying the loose ends together to create a single theory that accounts for attention and memory with the same computations. We see value in applying the methods and procedures from each literature to the other. Our application of the flanker task to cued recognition clarified the relation between retrieval and focused attention (Logan et al., 2021). Our application of attentional cuing procedures to cued recognition clarified the role of focusing attention on memory and highlighted the need to explain the control processes that enabled it (Logan et al., 2023). Our current application of the PRP procedure to cued recall clarified the role of serial attention in memory retrieval and highlighted the importance of understanding control processes in executing retrieval plans on memory structures, echoing Atkinson and Shiffrin's (1968) clarion call more than 50 years ago. Since James (1890), researchers have thought that attention and memory are deeply intertwined (Broadbent, 1957; Chun et al 2011; Gazzaley & Nobre 2012; Kiyonaga & Egner 2013; Norman, 1968; Logan 2002). Our results suggest they may be even more strongly related. They may be one and the same.

Author notes

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and programs are available on OSF

Appendix A. SOA, Direction, and lag effects and error analyses

Table A1 contains summary tables for 2 (direction) × 3 (SOA) analyses of variance (ANOVAs) for RT and accuracy for each response in Experiments 1–6.

Table A1
Direction × SOA *Summary tables for direction (RL,LR) × SOA (100, 300, 900 ms) ANOVAs on RT1, RT2, Accuracy for the first task (PC1) and the second task (PC1) for all experiments.*

Effect	*F*	df	MSe	*p*	η_p^2
RT1 – Horizontal S					
SOA	31.6710	2,62	12132.6463	0.0000	0.5054
Direction	50.1733	1,31	32052.5981	0.0000	0.6181
SOA × Direction	12.4427	2,62	5074.4649	0.0000	0.2864
RT1 – Horizontal P					
SOA	53.8431	2,62	16245.2134	0.0000	0.6346
Direction	53.5402	1,31	32102.7315	0.0000	0.6333
SOA × Direction	35.5256	2,62	5009.8095	0.0000	0.5340
RT1 – Vertical					
SOA	37.3694	2,60	15675.9697	0.0000	0.5547
Direction	60.7754	1,30	26703.5329	0.0000	0.6695
SOA × Direction	23.8541	2,60	4883.8140	0.0000	0.4429
RT1 – Sequential					
SOA	20.0935	2,60	20245.2110	0.0000	0.4011
Direction	64.5674	1,30	55040.8322	0.0000	0.6828
SOA × Direction	16.1442	2,60	6431.9857	0.0000	0.3499
RT1 – Perceptual H					
SOA	14.4053	2,62	15318.4279	0.0000	0.3173
Direction	3.8154	1,31	1493.8577	0.0599	0.1096
SOA × Direction	6.2552	2,62	667.9709	0.0034	0.1679
RT1 – Perceptual V					
SOA	17.1186	2,62	8622.8226	0.0000	0.3558
Direction	23.0300	1,31	2117.3456	0.0000	0.4262
SOA × Direction	8.3451	2,62	598.6910	0.0000	0.2121
RT1 – Long SOA					
SOA	2.8152	2,62	43152.1406	0.0676	0.0833
Direction	30.2824	1,31	14931.9297	0.0000	0.4941
SOA × Direction	11.5383	2,62	3151.0177	0.0000	0.2712
RT2 – Horizontal S					
SOA	538.1279	2,62	9362.1037	0.0000	0.9455
Direction	145.2535	1,31	10856.5162	0.0000	0.8241
SOA × Direction	5.7945	2,62	4416.2259	0.0049	0.1575
RT2 – Horizontal P					
SOA	807.9795	2,62	8284.9383	0.0000	0.9631
Direction	100.0966	1,31	21335.3374	0.0000	0.7635
SOA × Direction	18.5954	2,62	5946.9246	0.0000	0.3749
RT2 – Vertical					
SOA	916.8048	2,62	6752.8373	0.0000	0.9673
Direction	105.3831	1,31	19254.3930	0.0000	0.7727
SOA × Direction	15.1572	2,62	8419.4434	0.0000	0.3284
RT2 – Sequential					
SOA	319.6480	2,58	19540.9024	0.0000	0.9168
Direction	67.7127	1,29	35143.9954	0.0000	0.7001
SOA × Direction	8.6730	2,58	9196.1084	0.0000	0.2302
RT2 – Perceptual H					
SOA	251.3295	2,62	6935.4522	0.0000	0.8902
Direction	62.9024	1,31	928.3939	0.0000	0.6699
SOA × Direction	4.2610	2,62	576.4332	0.0185	0.1208
RT2- Perceptual V					

(*continued on next page*)

Table A1 (*continued*)

Effect	*F*	df	MSe	*p*	η_p^2
SOA	276.6670	2,62	6439.5264	0.0000	0.8992
Direction	16.9745	1,31	1373.5728	0.0000	0.3538
SOA × Direction	22.0319	2,62	547.1352	0.0000	0.4154
RT2 – Long SOA					
SOA	519.3167	2,62	10171.2420	0.0000	0.9437
Direction	105.7389	1,31	7741.3501	0.0000	0.7733
SOA × Direction	2.9449	2,62	3051.3788	0.0600	0.0868
PC1 – Horizontal S					
SOA	51.9596	2,62	0.0064	0.0000	0.6263
Direction	33.8918	1,31	0.0420	0.0000	0.5223
SOA × Direction	24.8689	2,62	0.0071	0.0000	0.4451
PC1 – Horizontal P					
SOA	29.2959	2,62	0.0051	0.0000	0.4859
Direction	17.6101	1,31	0.0350	0.0000	0.3623
SOA × Direction	11.1718	2,62	0.0062	0.0000	0.2649
PC1 – Vertical					
SOA	40.8969	2,62	0.0036	0.0000	0.5688
Direction	35.3990	1,31	0.0616	0.0000	0.5331
SOA × Direction	16.0309	2,62	0.0046	0.0000	0.3409
PC1 – Sequential					
SOA	46.0393	2,62	0.0067	0.0000	0.5976
Direction	19.2769	1,31	0.0714	0.0000	0.3834
SOA × Direction	37.1925	2,62	0.0061	0.0000	0.5454
PC1 – Perceptual H					
SOA	13.4489	2,62	0.0003	0.0000	0.3026
Direction	5.1970	1,31	0.0004	0.0297	0.1436
SOA × Direction	8.8662	2,62	0.0002	0.0000	0.2224
PC1 – Perceptual V					
SOA	5.0438	2,62	0.0023	0.0093	0.1399
Direction	5.4382	1,31	0.0025	0.0264	0.1492
SOA × Direction	7.6979	2,62	0.0016	0.0010	0.1989
PC1 – Long SOA					
SOA	19.9153	2,62	0.0021	0.0000	0.3911
Direction	25.9802	1,31	0.0369	0.0000	0.4560
SOA × Direction	4.5118	2,62	0.0017	0.0148	0.1270
PC2 – Horizontal S					
SOA	33.8171	2,62	0.0071	0.0000	0.5217
Direction	1.5507	1,31	0.0586	0.2224	0.0476
SOA × Direction	23.3549	2,62	0.0070	0.0000	0.4297
PC2 – Horizontal P					
SOA	28.8669	2,62	0.0045	0.0000	0.4822
Direction	0.2078	1,31	0.0263	0.6517	0.0067
SOA × Direction	13.4852	2,62	0.0053	0.0000	0.3031
PC2 – Vertical					
SOA	23.7814	2,62	0.0035	0.0000	0.4341
Direction	0.2497	1,31	0.0613	0.6208	0.0080
SOA × Direction	19.9569	2,62	0.0049	0.0000	0.3916
PC2 – Sequential					
SOA	37.3408	2,62	0.0065	0.0000	0.5464
Direction	21.3987	1,31	0.0596	0.0000	0.4084
SOA × Direction	26.8726	2,62	0.0067	0.0000	0.4643
PC2 – Perceptual H					
SOA	10.9092	2,62	0.0004	0.0000	0.2603
Direction	3.2986	1,31	0.0005	0.0790	0.0962
SOA × Direction	3.9915	2,62	0.0005	0.0234	0.1141
PC2 – Perceptual V					
SOA	7.6252	2,62	0.0021	0.0011	0.1974
Direction	6.1145	1,31	0.0029	0.0191	0.1647
SOA × Direction	3.8311	2,62	0.0019	0.0270	0.1100
PC2 – Long SOA					
SOA	3.0008	2,62	0.0033	0.0570	0.0883
Direction	6.5989	1,31	0.0365	0.0152	0.1755
SOA × Direction	3.7183	2,62	0.0025	0.0298	0.1071

Table A2
Contrasts assessing linear trend for SOA in RT1 and RT2 and the difference in linear trend between RT1 and RT2 in each experiment.

	t	df	MSe	*p*	*BF*$_{10}$	N > 0
RT1						
Horizontal S	7.0115	31	273.2173	0.0000	204,318	29
Horizontal P	8.0004	31	353.3602	0.0000	2,523,028	31
Vertical	6.1009	31	368.9665	0.0000	18,914	26
Sequential	4.4844	30	425.7109	0.0001	259.1	26
Perceptual H	3.9789	31	364.1414	0.0004	75.7	30
Perceptual V	4.2508	31	276.1710	0.0113	149.8	27
Long SOA	0.6096	31	623.1826	0.5466	0.2243	28
RT2						
Horizontal S	34.2280	31	203.8089	0.0000	7.336×10^{22}	32
Horizontal P	33.7345	31	235.9116	0.0000	4.797×10^{22}	32
Vertical	36.4513	31	211.1051	0.0000	4.636×10^{23}	32
Sequential	21.2977	29	377.0006	0.0000	1.424×10^{16}	30
Perceptual H	17.3180	31	230.1854	0.0000	2.98×10^{14}	32
Perceptual V	19.0668	31	213.5315	0.0000	4.134×10^{15}	32
Long SOA	22.9124	31	272.8097	0.0000	7.005×10^{17}	32
RT2 – RT1						
Horizontal S	20.3823	31	248.2702	0.0000	2.625×10^{16}	32
Horizontal P	18.3684	31	279.3557	0.0000	1.483×10^{15}	32
Vertical	15.5806	31	349.4097	0.0000	1.753×10^{13}	32
Sequential	12.6088	29	450.3227	0.0000	2.778×10^{10}	30
Perceptual H	8.2356	31	308.1093	0.0000	4,523,544	32
Perceptual V	10.5851	31	273.7259	0.0000	1.098×10^{9}	32
Long SOA	10.7992	31	543.6394	0.0000	1.754×10^{9}	32

Table A3
Direction and Inter-Response Interval *Contrasts comparing inter-response intervals (IRIs) in the forward direction (LR, TB, SE) with the backward direction (RL, BT, ES) in Experiments 1–6.*

SOA	*t*	df	*MSe*	*p*	*BF*$_{01}$	*N* > 0
Horizontal S						
100	−0.1509	31	26.22	0.8811	5.240	16
300	0.6558	31	19.25	0.5168	4.340	15
900	0.9381	31	18.81	0.3554	3.535	17
Horizontal P						
100	0.1594	31	16.89	0.8744	5.234	19
300	0.7627	31	17.88	0.4514	4.049	20
900	0.6912	31	18.53	0.4946	4.246	19
Vertical						
100	1.6009	31	23.23	0.1195	1.680	18
300	−0.8069	31	18.53	0.4258	3.922	15
900	−0.3548	31	21.65	0.7251	4.995	16
Sequential						
100	−0.7399	29	29.55	0.4653	3.999	14
300	−1.1398	29	24.23	0.2637	2.851	12
900	−1.1386	29	23.48	0.2642	2.854	13
Perceptual H						
100	2.1475	31	7.47	0.0397	0.712	21
300	4.6557	31	6.56	0.0001	0.002	24
900	3.8364	31	6.77	0.0006	0.019	27
Perceptual V						
100	−0.1123	31	5.68	0.9113	5.265	14
300	−2.1860	31	7.64	0.0365	0.665	10
900	−1.6554	31	9.37	0.1079	1.556	7

Table A4
Lag and Inter-Response Interval *Contrasts evaluating the linear trend for lags 2, 3 and 4 in the mean inter-response intervals (IRIs) in Experiments 1–6.*

SOA	*t*	df	*MSe*	*p*	BF_{10}	*N* > 0
Horizontal S						
100	4.4790	29	12.4316	0.0001	242.918	25
300	4.3683	29	12.1706	0.0001	184.451	24
900	0.9099	29	14.8751	0.3699	0.284	15
Horizontal P						
100	3.5212	31	11.2569	0.0014	24.916	21
300	2.6568	31	12.7704	0.0124	3.685	25
900	−0.0518	31	12.4331	0.9590	0.189	18
Vertical						
100	3.1817	31	10.5866	0.0033	11.367	23
300	2.7131	31	10.1262	0.0108	4.134	21
900	−0.4998	31	13.8780	0.6208	0.212	15
Sequential						
100	3.0746	31	12.3711	0.0044	8.949	23
300	3.4827	31	12.0185	0.0015	22.751	23
900	1.9949	31	10.6088	0.0549	1.083	18
Perceptual H						
100	1.4740	31	3.2586	0.1506	0.503	19
300	−3.8319	31	4.3699	0.0006	52.675	9
900	−1.8601	31	4.7804	0.0724	0.872	11
Perceptual V						
100	3.2115	31	4.5968	0.0031	12.158	25
300	0.7836	31	5.4635	0.4392	0.251	16
900	0.0293	31	6.6716	0.9768	0.189	15

Table A2 contains contrasts evaluating linear trends in SOA effects (using contrast weights [10, 4, −14]) on RT1, RT2, and the difference between RT1 and RT1 SOA effects (using contrast weights [10, 4, −14, −10, −4, 14]) in Experiments 1–6.

Table A3 contains contrasts comparing IRIs in the forward and backward direction.

Table A4 contains contrasts evaluating linear trends in IRIs for lags 2–4.

Table A5 contains contrasts assessing linear trends in SOA effects on the probability of transposition, intrusion, and reversal errors.

Table A6 contains contrasts comparing positive and negative lag 1 transpositions as a function of response and direction. Table A7 contains contrasts evaluating position-specific prior list intrusions.

Appendix B. Long SOA experiment

To assess the possibility that the direction effects in Experiments 1–4 may be due to strategic slowing (i.e., waiting for the second cue to determine the direction of report), we ran a control experiment, replicating Experiment 2 (horizontal displays) with longer SOAs (300, 900, and 1800 ms). The method was the same as in Experiment 2 except for the longer SOAs and we accepted responses within 3000 ms of the second cue. We tested 32 subjects, recruited from Prolific. Their mean age was 29.68 years, $SD = 5.45$ years; 23 identified as male and 9 identified as female. Their mean typing speed was 61.28 WPM (SD = 16.09) and their mean accuracy on the typing test was 0.9280 (SD = 0.0401).

Mean RTs and accuracy scores were computed as in Experiments 1–6. The means across subjects are plotted as a function of SOA, response, and direction in the top row of Fig. B1. The SOA effects in Experiments 1–4 were replicated (see Tables A1-A4). The middle panel presents RT and accuracy data for the first cue plotted along with the corresponding data from Experiment 2. RT1 at the 300 and 900 ms SOAs in the long SOA experiment were 91 ms shorter than RT1 same SOAs in the short-SOA horizontal (Prolific) experiment. This suggests strategic waiting in the short-SOA experiment, but the difference was not significant, $t(62) = 1.2327$, $p = .2224$, $SEM = 73.5931$. In the long-SOA experiment, the longest SOA (1800 ms) was longer than mean RT1, but the forward order was 67 ms faster than the backward order at that SOA, $t(31) = 15.1625$, $p < .0001$, $SEM = 4.4194$, suggesting that another factor besides waiting may be responsible for the order effect in RT1. The data for the second response, plotted in the bottom panel of Fig. B1, show similar effects at the 300 and 900 ms SOAs in the long and short SOA experiments.

Position (left) and lag (effects) for RT (top) and accuracy (bottom) are presented in Fig. B2. Data analyses are presented in Tables C1, D1, and D2. Position and lag effects were similar to those in Experiments 1–4.

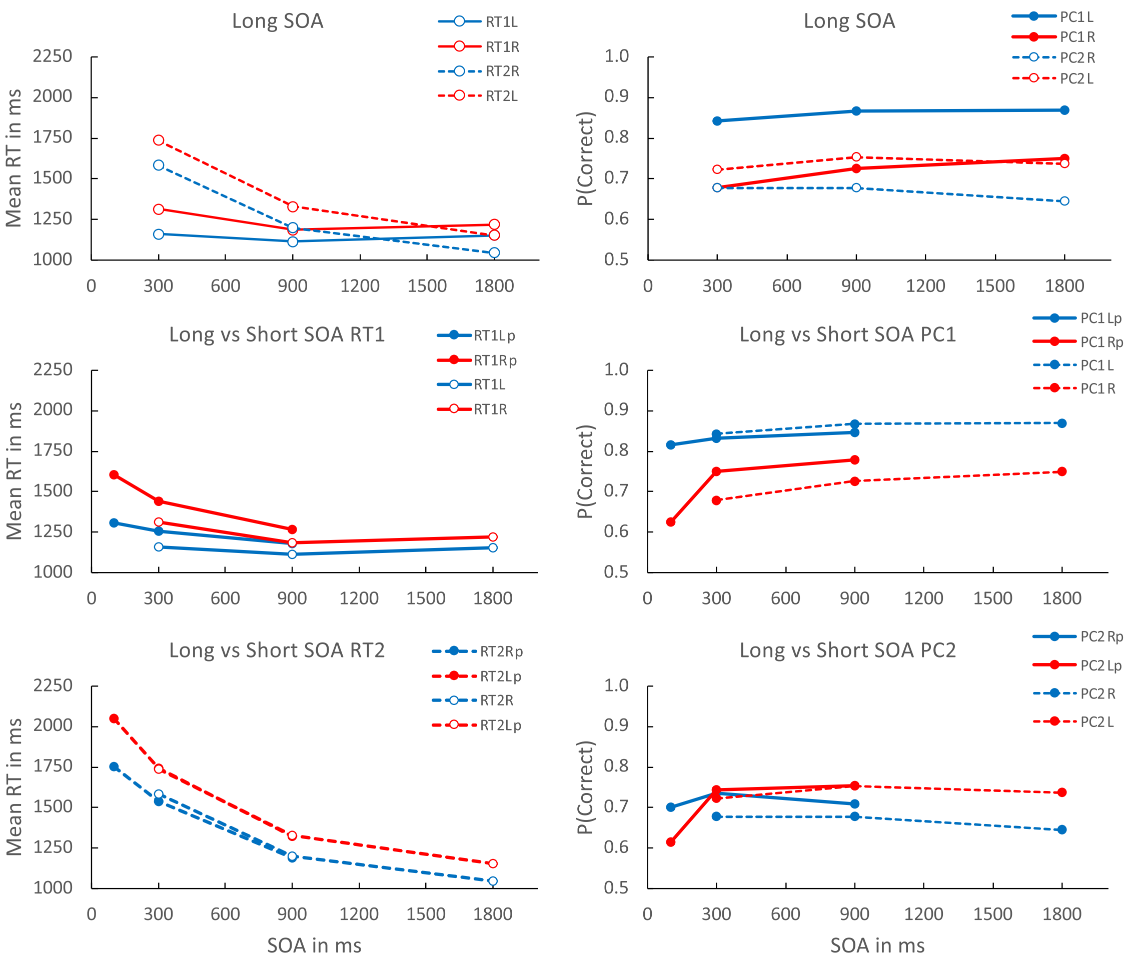

Fig. B1. SOA Effects with Long SOAs. Note: Response time (RT; left panels) and accuracy (P(Correct); right panels) as a function of stimulus onset asynchrony (SOA) and direction (*forward* = L then R = blue; *backward* = R then L = red) in the long SOA experiment. L and R refer to the relative positions of the cues in the list. The top row shows RT1 and RT2 (left) and PC1 and PC2 (right panel) as a function of SOA. The middle row compares RT1 and PC1 from the long SOA experiment with data from a short SOA experiment (Experiment 2: Horizontal P). Slowing is apparent in the RT1 data. The bottom row compares RT2 and PC2 from the long SOA experiment with data from the short SOA experiment (Experiment 2).

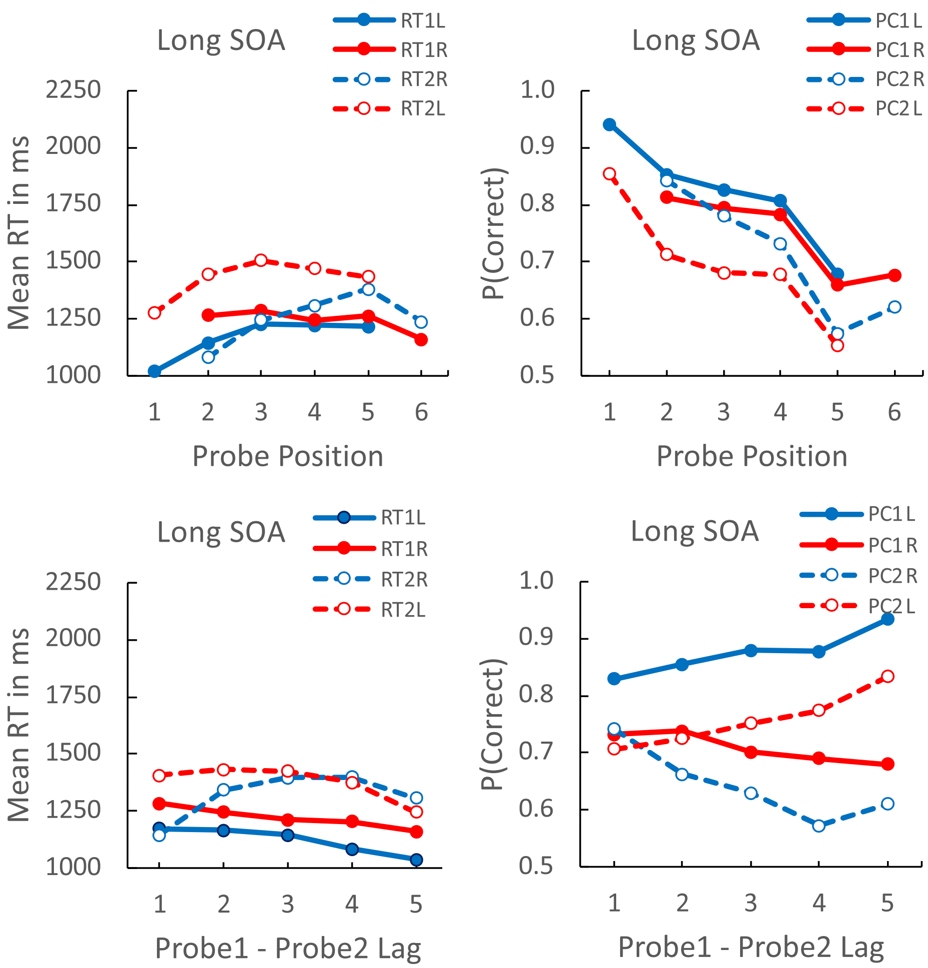

Fig. B2. Position and Lag Effects with Long SOAs. Note: Interactions between direction (LR, RL) and probe position (top row) and direction (*forward* = L then R = blue; *backward* = R then L = red) and lag (bottom row) in the long SOA experiment. L and R refer to the relative positions of the cues in the list. Left column: Mean response time (RT). Right column: Accuracy (P(Correct)).

Appendix C. Position × Response × Direction

Table C1 contains the results of linear contrasts with weights {-2—1 0 1 2} for positions 1–5 (or 2–6), which tested for accessing the list from the beginning (positive slope) or the end (negative slope), and quadratic contrasts with weights {-2 1 2 1—2} for positions 1–5 (or 2–6), which tested for accessing the list from the nearest end.

Table C1
Position Effects *Contrasts assessing linear and quadratic trends for RT1 and RT2 as a function of position for each combination of response (R1* vs. *R2) and direction (LR* vs. *RL) in each experiment.*

		t	df	MSe	*p*	BF_{10}	N > 0
Horizontal S							
R1 LR	Linear	4.2637	29	125.2041	0.0002	142.4	26
	Quadratic	2.8138	29	83.9986	0.0087	5.067	20
R1 RL	Linear	−1.2929	29	149.4495	0.2059	0.4135	14
	Quadratic	1.3316	29	108.5609	0.1934	0.4324	20
R2 LR	Linear	11.2229	30	77.6274	0.0000	2.89×10^{9}	30
	Quadratic	9.7816	30	149.5252	0.0000	129,784,081	31
R2 RL	Linear	0.0552	29	98.2388	0.9564	0.1947	13
	Quadratic	8.3140	29	24.9244	0.0000	3,354,379	27
Horizontal P							
R1 LR	Linear	3.8795	31	109.8694	0.0005	59.2	22
	Quadratic	5.1418	31	78.6025	0.0000	1,506	27
R1 RL	Linear	−4.7716	31	112.8670	0.0000	571.6	8
	Quadratic	0.4377	31	93.6277	0.6648	0.2064	15
R2 LR	Linear	8.9564	31	87.6100	0.0000	26,080,568	30
	Quadratic	10.3845	31	154.9528	0.0000	704,089,366	32
R2 RL	Linear	−0.7909	31	114.8673	0.4350	0.252	10
	Quadratic	10.3221	31	22.7122	0.0000	612,680,982	31
Vertical							
R1 LR	Linear	4.8051	31	120.9840	0.0000	623.6	26
	Quadratic	5.3114	31	79.9204	0.0000	2,353	27
R1 RL	Linear	−3.8097	30	105.3902	0.0006	48.61	8
	Quadratic	2.9875	30	106.2981	0.0056	7.348	20
R2 LR	Linear	8.6996	31	91.6274	0.0000	14,064,560	30
	Quadratic	11.6891	31	115.1202	0.0000	1.164×10^{10}	31
R2 RL	Linear	−1.1123	30	109.1746	0.2746	0.3367	14
	Quadratic	9.4476	30	24.9708	0.0000	61,105,402	30
Sequential							
R1 LR	Linear	8.0575	31	162.0551	0.0000	2,908,768	30
	Quadratic	1.6072	31	97.0144	0.1181	0.06005	21
R1 RL	Linear	3.2581	31	114.1289	0.0027	13.5163	23
	Quadratic	7.0658	31	97.2641	0.0000	235,076	29
R2 LR	Linear	12.7559	31	86.5352	0.0000	1.0044×10^{11}	31
	Quadratic	11.0440	31	116.3750	0.0000	2,978,728,057	30
R2 RL	Linear	1.0617	31	171.1835	0.2966	0.3163	18
	Quadratic	6.4567	31	29.7966	0.0000	48,189	28
Perceptual H							
R1 LR	Linear	−4.6911	29	33.1562	0.0001	413.2	5
	Quadratic	−6.7707	29	34.6314	0.0000	79,782	5
R1 RL	Linear	1.1475	29	43.1316	0.2606	0.3535	16
	Quadratic	−10.3571	29	31.1253	0.0058	317,657,140	0
R2 LR	Linear	−0.3173	29	40.5445	0.7532	0.2037	16
	Quadratic	−2.0037	29	35.8359	0.5802	1.117	12
R2 RL	Linear	0.0177	29	63.6554	0.9860	0.1944	18
	Quadratic	−2.4073	29	12.9046	0.1060	2.272	9
Perceptual V							
R1 LR	Linear	0.9598	31	35.7669	0.3446	0.2882	16
	Quadratic	−6.7707	31	61.2034	0.0000	109,418	5
R1 RL	Linear	11.5801	31	26.7988	0.0000	9.278×10^{9}	32
	Quadratic	−10.3571	31	84.2581	0.0058	662,419,313	10
R2 LR	Linear	3.5335	31	39.1425	0.0013	25.65	23
	Quadratic	−2.0037	31	76.9870	0.5802	1.099	13
R2 RL	Linear	2.3017	31	36.6839	0.0282	1.853	22
	Quadratic	−2.4073	31	28.4635	0.106	2.257	9

(*continued on next page*)

Table C1 (*continued*)

		t	df	MSe	*p*	BF_{10}	N > 0
Long SOA							
R1 LR	Linear	4.6228	31	100.5924	0.0001	388.5	24
	Quadratic	5.1639	31	61.2034	0.0000	1,596	27
R1 RL	Linear	−2.7649	31	84.0002	0.0095	4.601	13
	Quadratic	2.2537	31	84.2581	0.0314	1.697	19
R2 LR	Linear	6.2307	31	79.0240	0.0000	26,621	27
	Quadratic	9.7124	31	76.9870	0.0000	153,749,833	29
R2 RL	Linear	2.9489	31	117.4530	0.0060	6.798	21
	Quadratic	5.3941	31	28.4635	0.0000	2,927	28

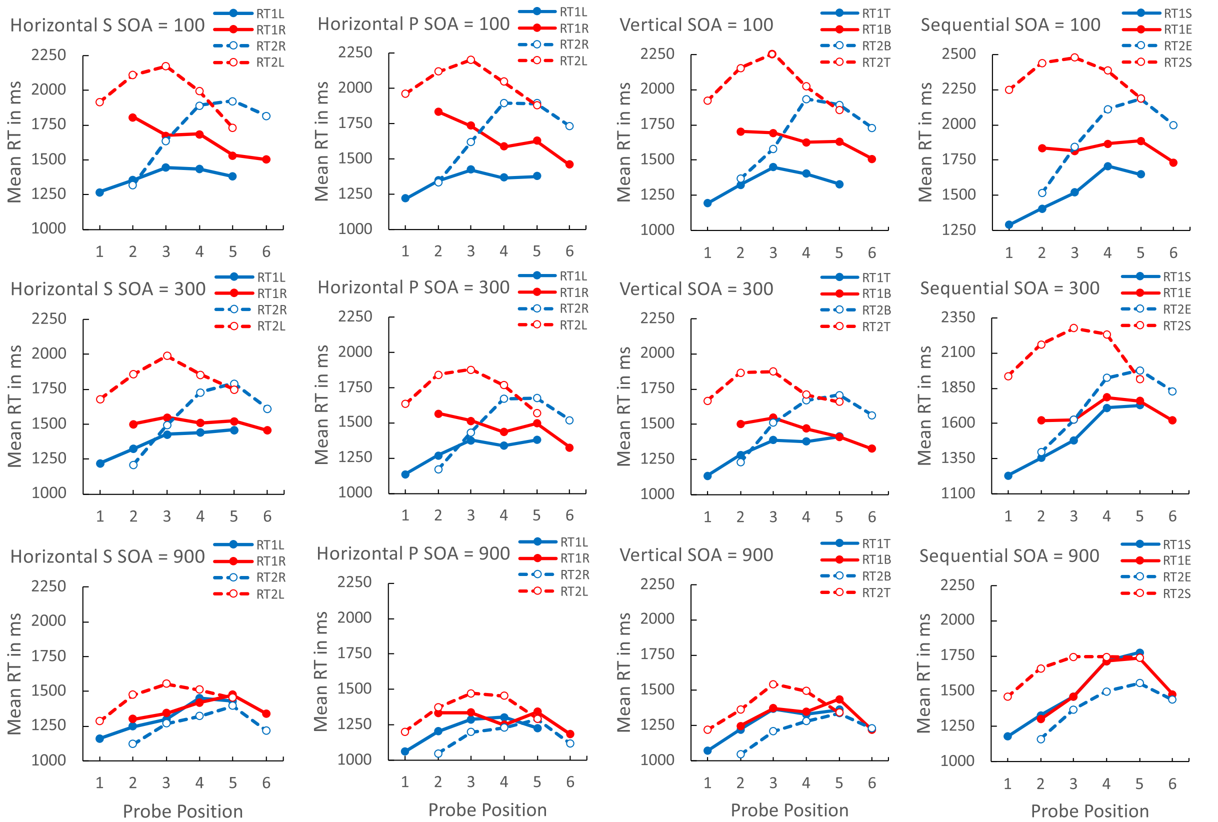

Fig. C1. Position × Direction at Each SOA Experiments 1–4. Note: Interactions between direction (*forward* = L then R = blue; *backward* = R then L = red) and response (RT1 vs. RT2) as a function of probe position in Experiments 1–4. L, R (horizontal), T, B (vertical), and S, E (sequential) refer to the relative positions of the cues in the list. Top, middle, and bottom rows present data from stimulus onset asynchrony (SOA) = 100, 300, and 900 ms, respectively.

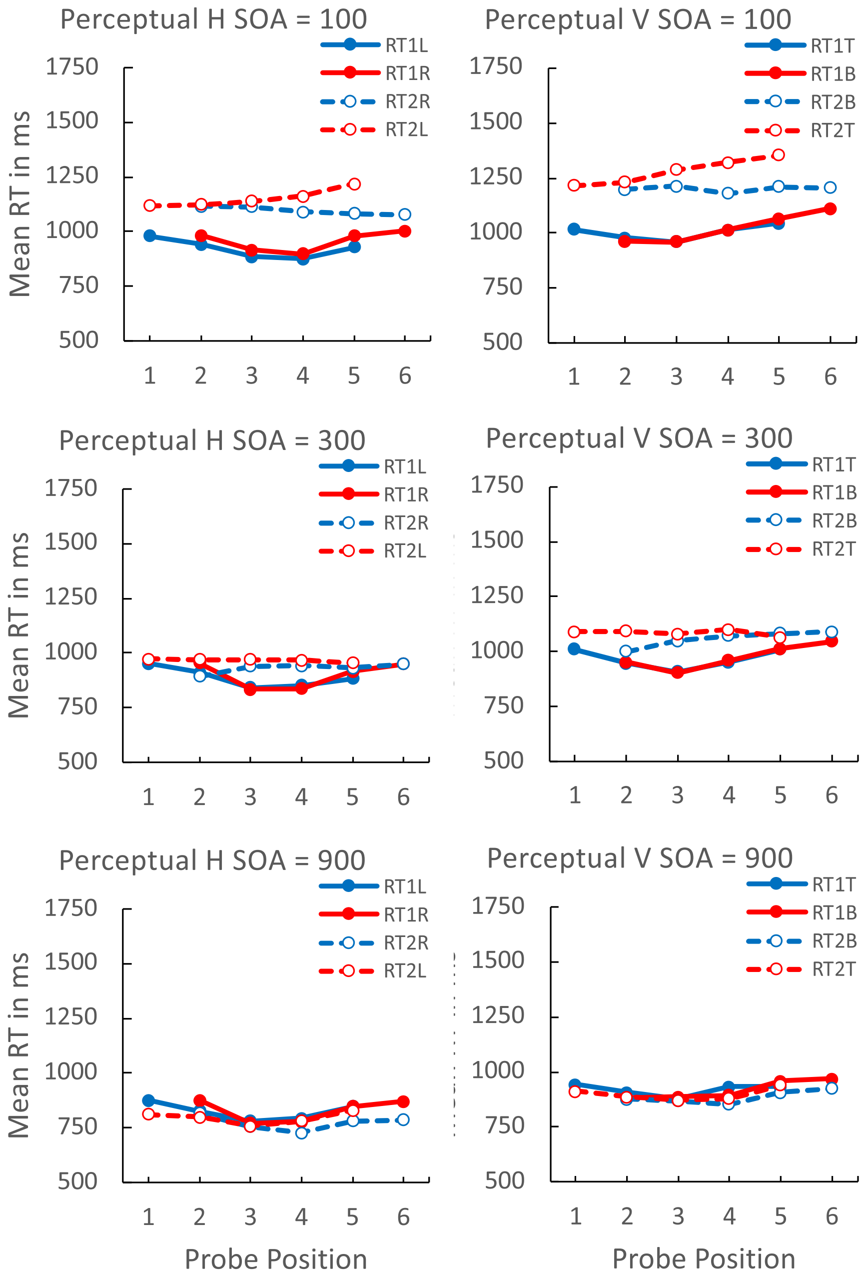

Fig. C2. Position × Direction at Each SOA Experiments 5–6. Note: Interactions between direction (*forward* = L then R = blue; *backward* = R then L = red) and response (RT1 vs. RT2) as a function of probe position in Experiments 5–6. L, R (horizontal), T, B (vertical), and S, E (sequential) refer to the relative positions of the cues in the list. Top, middle, and bottom rows present data from stimulus onset asynchrony (SOA) = 100, 300, and 900 ms, respectively.

Appendix D. Lag 1 sparing and SOA × Lag

Table D1 contains the results of contrasts assessing lag 1 sparing in backward and forward directions in each experiment. Table D2 contains summary tables for 3 (SOA) × 5 (lag) ANOVAs on RT (RT1, RT2) and accuracy (PC1, PC2). Fig. D1 shows interactions between lag and SOA for Experiments 1–4. Fig. D2 shows interactions between lag and SOA for Experiments 5–6.

Table D1
Lag Effects *Contrasts assessing linear component of lag effects on RT1 and RT2 for lags of 2–4 in Experiments 1–6.*

Experiment	*t*	df	MSE	*p*	BF_{10}	*N* > 0
RT1 LR						
Horizontal S	−3.7306	29	11.3063	0.0008	39.1881	8
Horizontal P	−5.0306	31	10.5354	0.0000	1124.515	7
Vertical	−4.1568	30	9.1723	0.0002	113.8387	7
Sequential	−9.3374	30	7.6668	0.0000	47,523,671	2
Perceptual H	5.3512	31	3.1915	0.0000	2613.642	27
Perceptual V	−0.3300	31	5.0895	0.7436	0.1986	14
RT1 RL						
Horizontal S	−3.1455	29	11.1592	0.0038	10.2810	23
Horizontal P	−1.9709	31	9.7742	0.0577	1.0415	19
Vertical	−3.6310	30	9.9158	0.0010	31.6951	17
Sequential	−0.2960	30	10.6215	0.7693	0.1995	15
Perceptual H	4.5522	31	3.3946	0.0001	323.7402	28
Perceptual V	2.8469	31	4.5187	0.0078	5.4654	21
RT2 LR						
Horizontal S	3.7891	29	11.2847	0.0007	45.0243	8
Horizontal P	1.5087	31	14.4154	0.1415	0.5258	11
Vertical	0.7312	30	13.5253	0.4703	0.2451	8
Sequential	−0.6240	30	9.9997	0.5373	0.2293	12
Perceptual H	4.4575	31	3.2182	0.0001	253.7509	26
Perceptual V	2.3573	31	4.4827	0.0249	2.0539	24
RT2 RL						
Horizontal S	−3.8956	29	12.3497	0.0005	58.0833	6
Horizontal P	−1.9370	31	13.8565	0.0619	0.9857	10
Vertical	−2.6429	30	14.9386	0.0129	3.5832	9
Sequential	−0.8236	30	15.4181	0.4167	0.2617	10
Perceptual H	1.6058	31	3.3064	0.1185	0.5993	21
Perceptual V	0.0347	31	4.5578	0.0347	0.1889	20

Table D2
Lag 1 Sparing *Contrasts assessing lag 1 sparing in RT and accuracy for each direction (forward, backward) and differences between forward and backward in each experiment.*

Experiment	*t*	df	MSe	*p*	BF_{10}	N > 0
RT Forward						
Horizontal S	13.4011	29	19.5377	0.0000	1.182×10^{11}	30
Horizontal P	10.5530	31	22.6608	0.0000	1.023×10^{9}	30
Vertical	17.0820	30	17.1161	0.0000	9.963×10^{13}	31
Sequential	16.8517	30	21.2304	0.0000	6.984×10^{13}	31
Perceptual H	5.7054	31	6.3071	0.0000	6,659	26
Perceptual V	5.4643	31	6.5293	0.0000	3,522	30
Long SOA	10.2829	30	19.8833	0.0000	392,362,898	31
RT Backward						
Horizontal S	8.3166	29	15.2049	0.0000	3,374,881	27
Horizontal P	6.3777	31	22.3851	0.0000	39,172	28
Vertical	6.6392	30	26.2200	0.0000	66,992	28
Sequential	5.3189	30	43.8778	0.0000	2,210	30
Perceptual H	4.2128	31	6.5538	0.0002	136	24
Perceptual V	3.4959	31	7.1531	0.0014	23.47	26
Long SOA	2.7889	30	21.7687	0.0091	4.827	23
RT Forward – Backward						
Horizontal S	5.3698	29	25.2101	0.0000	2,308	25
Horizontal P	2.9759	31	32.3852	0.0056	7.208	19
Vertical	4.7365	30	24.9755	0.0000	492.3	28
Sequential	2.5348	30	49.0709	0.0167	2.893	26
Perceptual H	0.9072	31	9.2317	0.3713	0.2757	18
Perceptual V	1.2680	31	8.4164	0.2142	0.3921	19

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Table D2 (*continued*)

Experiment	*t*	df	MSe	*p*	BF_{10}	N > 0
Long SOA	5.1545	30	27.888	0.0000	1,444	25
PC Forward						
Horizontal S	2.5585	29	0.0163	0.0160	3.034	18
Horizontal P	3.4934	31	0.0152	0.0015	23.33	25
Vertical	3.7700	30	0.0179	0.0007	44.17	26
Sequential	3.3700	30	0.0153	0.0020	17.24	25
Perceptual H	0.2970	31	0.0058	0.7684	0.1967	19
Perceptual V	0.9360	31	0.0041	0.3565	0.2824	13
Long SOA	5.1273	30	0.0204	0.0000	1,346	25
PC Backward						
Horizontal S	0.5147	29	0.0146	0.6107	0.2197	19
Horizontal P	0.4467	31	0.0152	0.6582	0.2072	15
Vertical	2.7240	30	0.0167	0.0105	4.223	23
Sequential	1.9659	30	0.0117	0.0583	1.042	12
Perceptual H	0.3305	31	0.0050	0.7432	0.1987	15
Perceptual V	1.3055	31	0.0046	0.2013	0.4092	13
Long SOA	0.6299	30	0.0190	0.5334	0.2301	19
PC Forward – Backward						
Horizontal S	2.0253	29	0.0168	0.0521	1.157	19
Horizontal P	2.8915	31	0.0160	0.0069	6.009	20
Vertical	1.2503	30	0.0176	0.2205	0.3892	15
Sequential	4.2563	30	0.0175	0.0002	145.9	25
Perceptual H	0.6663	31	0.0051	0.5102	0.2319	17
Perceptual V	0.3395	31	0.0064	0.7365	0.1992	17
Long SOA	4.3369	30	0.0214	0.0001	178.6	25

Table D3
Lag × SOA *Summary tables for 3 (SOA) × 5 (lag) ANOVAs on RT (RT1, RT2) and accuracy (PC1, PC2) data for Experiments 1–6.*

Effect	*F*	df	MSe	*p*	η_p^2
RT1 – Horizontal S					
SOA	16.8203	2,62	29806.1418	0.0000	0.3517
Lag	31.5056	4,124	16254.0009	0.0000	0.5040
SOA × Lag	3.3088	8,248	7926.2290	0.0013	0.0964
RT1 – Horizontal P					
SOA	35.3150	2,62	43273.3521	0.0000	0.5325
Lag	37.8240	4,124	17269.7208	0.0000	0.5496
SOA × Lag	1.3301	8,248	10257.4086	0.2289	0.0411
RT1 – Vertical					
SOA	19.1803	2,62	42151.7526	0.0000	0.3822
Lag	44.0294	4,124	16763.2099	0.0000	0.5868
SOA × Lag	2.7069	8,248	6758.8511	0.0071	0.0803
RT1 – Sequential					
SOA	6.0778	2,62	58173.3484	0.0039	0.1639
Lag	64.8727	4,124	13221.5494	0.0000	0.6767
SOA × Lag	1.2203	8,248	9171.7613	0.2874	0.0379
RT1 – Perceptual H					
SOA	13.0704	2,62	38365.4084	0.0000	0.2966
Lag	11.5534	4,124	2253.1979	0.0000	0.2715
SOA × Lag	2.5704	8,248	1749.4226	0.0104	0.0766
RT1 – Perceptual V					
SOA	14.2276	2,62	22461.7464	0.0000	0.3146
Lag	8.8723	4,124	2574.1947	0.0000	0.2225
SOA × Lag	2.2652	8,248	2965.9402	0.0236	0.0681
RT1 – Long SOA					
SOA	1.2922	2,62	114880.5247	0.2820	0.0400
Lag	51.4713	4,124	6493.6807	0.0000	0.6241
SOA × Lag	3.4645	8,248	6965.5912	0.0000	0.1005
RT2 – Horizontal S					
SOA	436.6753	2,62	29163.4836	0.0000	0.9337
Lag	37.5419	4,124	28279.9091	0.0000	0.5477
SOA × Lag	4.9851	8, 248	12009.4628	0.0000	0.1385
RT2 – Horizontal P					
SOA	635.7885	2,62	25933.6974	0.0000	0.9535

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Table D3 (*continued*)

Effect	*F*	df	MSe	*p*	η_p^2
Lag	40.6655	4,124	24825.8716	0.0000	0.5674
SOA × Lag	2.7167	8,248	12212.8052	0.0069	0.0806
RT2 – Vertical					
SOA	640.8971	2,62	23450.5336	0.0000	0.9539
Lag	44.1007	4,124	25926.4617	0.0000	0.5872
SOA × Lag	3.7061	8,248	11705.6211	0.0000	0.1068
RT2 – Sequential					
SOA	329.8317	2,62	47122.2543	0.0000	0.9141
Lag	107.7596	4,124	16768.7384	0.0000	0.7766
SOA × Lag	5.8016	8,248	10124.7930	0.0000	0.1576
RT2 – Perceptual H					
SOA	249.9603	2,62	17601.2577	0.0000	0.8897
Lag	9.9449	4,124	2749.6994	0.0000	0.2429
SOA × Lag	1.5420	8,248	1930.9031	0.1432	0.0474
RT2- Perceptual V					
SOA	266.7613	2,62	16742.2437	0.0000	0.8959
Lag	23.3791	4,124	2409.2694	0.0000	0.4299
SOA × Lag	3.6199	8,248	2453.2968	0.0000	0.1046
RT2 – Long SOA					
SOA	515.1565	2,62	26652.9237	0.0000	0.9432
Lag	31.3305	4,124	14827.9643	0.0000	0.5027
SOA × Lag	4.7588	8,248	6834.0193	0.0000	0.1331
PC1 – Horizontal S					
SOA	46.5476	2,62	0.0171	0.0000	0.6002
Lag	2.5595	4,124	0.0084	0.0419	0.0763
SOA × Lag	1.0633	8,248	0.0050	0.3895	0.0332
PC1 – Horizontal P					
SOA	21.7348	2,62	0.0129	0.0000	0.4122
Lag	4.4031	4,124	0.0082	0.0023	0.1244
SOA × Lag	1.4844	8,248	0.0062	0.1632	0.0457
PC1 – Vertical					
SOA	42.6406	2,62	0.0095	0.0000	0.5790
Lag	1.2207	4,124	0.0096	0.3054	0.0379
SOA × Lag	0.4470	8,248	0.0046	0.8918	0.0142
PC1 – Sequential					
SOA	35.5893	2,62	0.0197	0.0000	0.5345
Lag	16.3190	4,124	0.0065	0.0000	0.3449
SOA × Lag	1.0925	8,248	0.0049	0.3689	0.0340
PC1 – Perceptual H					
SOA	5.3606	2,62	0.0008	0.0071	0.1474
Lag	2.7945	4,124	0.0007	0.0291	0.0827
SOA × Lag	1.9118	8,248	0.0009	0.0588	0.0581
PC1 – Perceptual V					
SOA	3.4646	2,62	0.0049	0.0375	0.1005
Lag	1.4489	4,124	0.0013	0.2219	0.0447
SOA × Lag	1.6960	8,248	0.0011	0.0998	0.0519
PC1 – Long SOA					
SOA	20.7201	2,62	0.0060	0.0000	0.4006
Lag	1.4749	4,124	0.0071	0.2138	0.0454
SOA × Lag	1.7515	8,248	0.0041	0.0873	0.0535
PC2 – Horizontal S					
SOA	37.4641	2,62	0.0169	0.0000	0.5472
Lag	2.5481	4,124	0.0080	0.0426	0.0760
SOA × Lag	1.8075	8,248	0.0063	0.0761	0.0551
PC2 – Horizontal P					
SOA	28.7027	2,62	0.0116	0.0000	0.4808
Lag	4.9017	4,124	0.0142	0.0011	0.1365
SOA × Lag	0.2651	8,248	0.0062	0.9765	0.0085
PC2 – Vertical					
SOA	20.7600	2,62	0.0109	0.0000	0.4011
Lag	1.2962	4,124	0.0115	0.2752	0.0401

(*continued on next page*)

Table D3 (*continued*)

Effect	*F*	df	MSe	*p*	η_p^2
SOA × Lag	1.3867	8,248	0.0050	0.2027	0.0428
PC2 – Sequential					
SOA	28.4128	2,62	0.0199	0.0000	0.4782
Lag	10.0264	4,124	0.0094	0.0000	0.2444
SOA × Lag	0.4304	8,248	0.0063	0.9022	0.0137
PC2 – Perceptual H					
SOA	3.0587	2,62	0.0017	0.0541	0.0898
Lag	2.8584	4,124	0.0016	0.0263	0.0844
SOA × Lag	1.0302	8,248	0.0019	0.4137	0.0322
PC2 – Perceptual V					
SOA	6.9148	2,62	0.0044	0.0019	0.1824
Lag	0.0940	4,124	0.0019	0.9842	0.0030
SOA × Lag	1.0727	8,248	0.0016	0.3828	0.0334
PC2 – Long SOA					
SOA	3.1538	2,62	0.0079	0.0496	0.0923
Lag	3.1758	4,124	0.0146	0.0160	0.0929
SOA × Lag	0.3402	8,248	0.0064	0.9496	0.0109

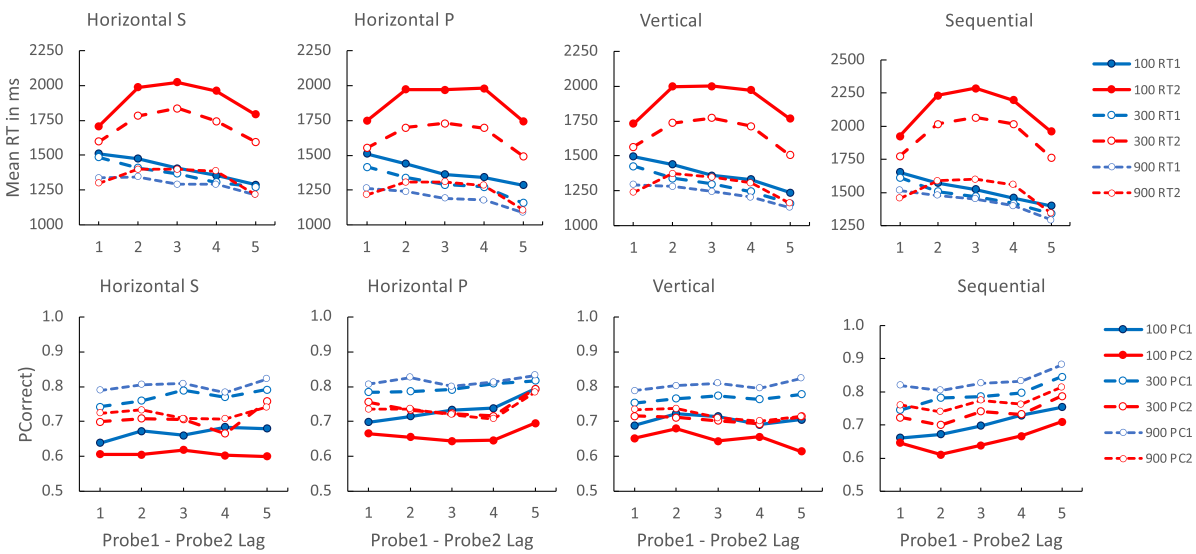

Fig. D1. SOA × Lag Experiments 1–4. Note: Interactions between direction (*forward* = LR, TB, SE = blue; *backward* = RL, BT, ES = red) and response (RT1 vs. RT2) as a function of lag and stimulus onset asynchrony (SOA = 100, 300, 900 ms) in Experiments 1–4. Top row: RT; bottom row: accuracy.

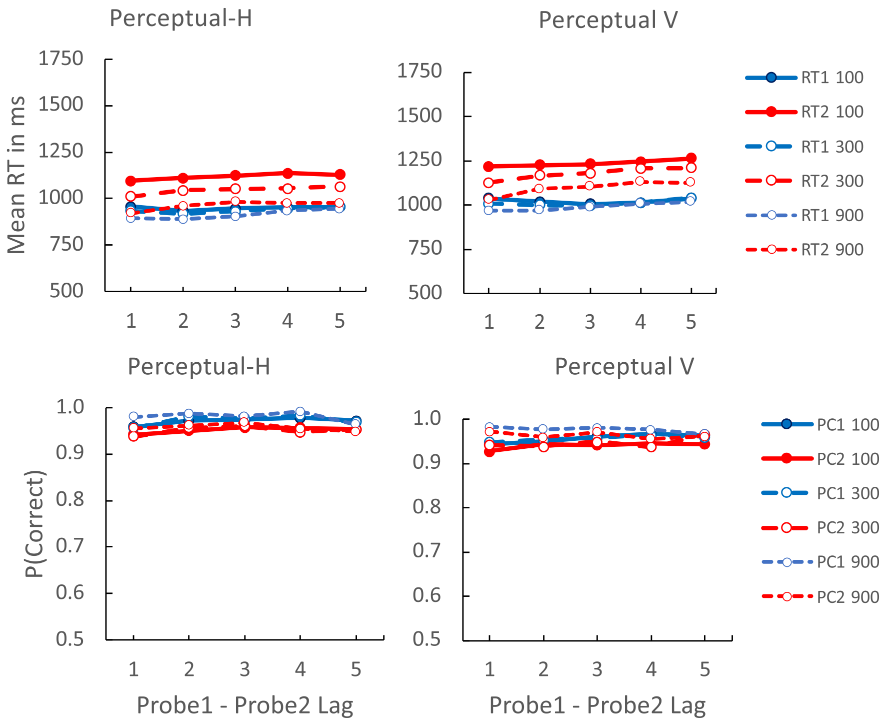

Fig. D2. SOA × Lag Experiments 5–6. Note: Interactions between stimulus onset asynchrony (SOA = 100, 300, 900 ms) and response (RT1 vs. RT2) as a function of lag between the first and second probes in Experiments 5–6. Top row: RT; bottom row: accuracy.

Appendix E. Error analysis

Table E1 contains contrasts evaluating transpositions, intrusions and response reversals as functions of SOA. Table E1 contains contrasts evaluating transpositions as a function of response and direction. Table E2 contains contrasts evaluating position-specific prior list intrusions.

Table E1

Transpositions, Intrusions and Response Reversals × SOA *Contrasts assessing linear trend relating the probability of transpositions, intrusions, and response reversals to SOA in RT1 and RT2 and the difference in linear trend between RT1 and RT2 in each experiment.*

	t	df	MSe	*p*	BF_{10}	N > 0
Transpositions × SOA R1						
Horizontal S	7.1861	31	38.5812	0.0000	320,461	31
Horizontal P	6.0469	31	31.6485	0.0000	16,405	27
Vertical	6.5899	31	32.5118	0.0000	68,286	31
Sequential	7.7038	31	36.9539	0.0000	1,198,590	31
Perceptual H	3.6383	31	6.2357	0.0010	32.94	24
Perceptual V	2.0655	31	5.9309	0.0473	1.22	21
Long SOA	4.3781	31	18.6868	0.0001	207.1	25
Transpositions × SOA R2						
Horizontal S	6.3193	31	36.1886	0.0000	33,603	31
Horizontal P	5.9952	31	26.323	0.0000	14,314	29
Vertical	5.5907	31	25.6453	0.0000	4,918	30
Sequential	6.8555	31	38.035	0.0000	136,397	30
Perceptual H	4.4074	31	6.8067	0.0001	223.2	24
Perceptual V	0.4145	31	6.4842	0.6814	0.2045	24
Long SOA	0.8185	31	17.5627	0.4193	0.2571	17
Intrusions × SOA R1						
Horizontal S	0.3954	31	9.1689	0.6953	0.2030	15
Horizontal P	0.6080	31	11.5126	0.5476	0.2241	16
Vertical	1.3141	31	10.606	0.1985	0.4133	14
Sequential	0.7796	31	7.7764	0.4415	0.2499	14

(continued on next page)

Table E1 (*continued*)

	t	df	MSe	*p*	BF_{10}	N > 0
Perceptual H	1.2192	31	3.4859	0.232	0.3715	10
Perceptual V	2.0655	31	5.9309	0.0473	1.2200	9
Long SOA	0.4771	31	11.659	0.6366	0.2099	16
Intrusions × SOA R2						
Horizontal S	0.6186	31	15.2567	0.5407	0.2254	15
Horizontal P	2.4985	31	12.4825	0.018	2.6900	8
Vertical	0.4140	31	10.7196	0.6818	0.2045	13
Sequential	1.5881	31	11.1377	0.1224	0.5849	13
Perceptual H	6.0807	31	13.5265	0.0000	17,934	19
Perceptual V	0.4145	31	6.4842	0.6814	0.2045	14
Long SOA	3.5788	31	16.0669	0.0012	28.57	8
R1-R2 Reversals × LR × SOA						
Horizontal S	5.6569	31	31.0572	0.0000	5,858	30
Horizontal P	3.748	31	24.6464	0.0007	42.93	26
Vertical	4.536	31	27.7363	0.0001	310.5	27
Sequential	6.1333	31	29.7963	0.0000	20,600	32
Perceptual H	3.7312	31	4.7907	0.0008	41.21	22
Perceptual V	2.4274	31	15.1137	0.0212	2.345	24
Long SOA	3.1879	31	5.4111	0.0033	11.53	22
Lag 1 Transpositions R1 vs R2						
Horizontal S	5.5262	31	4.8632	0.0000	4,148	29
Horizontal P	4.8020	31	3.1563	0.0000	618.6	25
Vertical	4.1352	31	5.4713	0.0003	111.9	25
Sequential	4.5866	31	7.1608	0.0001	353.8	28
Perceptual H	2.0331	31	0.8761	0.0507	1.155	14
Perceptual V	2.6933	31	1.4851	0.0113	3.97	19
Long SOA	2.1666	31	2.7837	0.0381	1.452	22
Lag 1 Transpositions LR vs RL						
Horizontal S	1.5086	31	1.5329	0.1415	0.5258	12
Horizontal P	1.6931	31	1.9012	0.1005	0.6783	17
Vertical	1.1618	31	1.4525	0.2542	0.3495	11
Sequential	1.4340	31	2.0267	0.1616	0.4777	12
Perceptual H	2.5911	31	0.4704	0.0145	3.229	20
Perceptual V	2.0108	31	0.3730	0.0531	1.112	16
Long SOA	0.4587	31	1.8394	0.6496	0.2082	14

Table E2

Transpositions *Contrasts comparing immediate forward (+1) and backward (-1) transpositions in the first versus the second response (top) and for the left-to-right versus right-to-left direction (bottom) in each experiment.*

	t	df	MSe	*p*	BF_{10}	N > 0
Response (R1,R2)						
Horizontal S	5.5262	31	4.8632	0.0000	4,148	29
Horizontal P	4.802	31	3.1563	0.0000	618.6	25
Vertical	4.1352	31	5.4713	0.0003	111.9	25
Sequential	4.5866	31	7.1608	0.0001	353.8	28
Perceptual H	2.0331	31	0.8761	0.0507	1.155	14
Perceptual V	2.6933	31	1.4851	0.0113	3.97	19
Long SOA	2.1666	31	2.7837	0.0381	1.452	22
Direction (LR,RL)						
Horizontal S	1.5086	31	1.5329	0.1415	0.5258	12
Horizontal P	1.6931	31	1.9012	0.1005	0.6783	17
Vertical	1.1618	31	1.4525	0.2542	0.3495	11
Sequential	1.434	31	2.0267	0.1616	0.4777	12
Perceptual H	2.5911	31	0.4704	0.0145	3.229	20
Perceptual V	2.0108	31	0.3730	0.0531	1.112	16
Long SOA	0.4587	31	1.8394	0.6496	0.2082	14

Table E3
Prior List Intrusions *Contrasts assessing the probability of a position-specific prior list intrusion in Experiments 1–6. Contrast weights = {-1 2—1} for lags {−1 0 1}, respectively.*

Experiment	*t*	df	*MSe*	*p*	BF_{10}	*N* > 0
R1						
Horizontal S	6.6014	31	0.9042	0.0000	70369.01	28
Horizontal P	3.8380	31	1.0911	0.0006	53.47	23
Vertical	4.6123	31	1.2738	0.0001	378.09	25
Sequential	4.8919	31	0.6580	0.0000	782.14	23
Perceptual H	−0.5837	31	0.2142	0.5637	0.2211	3
Perceptual V	1.0218	31	0.2141	0.3148	0.3047	9
R2						
Horizontal S	7.1552	31	1.3801	0.0000	295977.90	31
Horizontal P	6.7295	31	1.4071	0.0000	98289.52	27
Vertical	7.2476	31	1.0736	0.0000	375292.70	28
Sequential	4.8415	31	1.0134	0.0000	685.72	25
Perceptual H	−2.0612	31	0.2729	0.0478	1.2107	5
Perceptual V	−1.0865	31	0.2589	0.2856	1.2107	6

Appendix F. Comparing IRI and IKSI

Table F1 contains the results of contrasts comparing the IRIs at the 100 ms SOA with the IKSIs from the typing test.

Table F1
Contrasts comparing inter-response intervals at the 100 ms SOA with inter-keystroke intervals in the typing test for each experiment.

Experiment	*t*	df	*SEM*	*p*	BF_{10}	*N* > 0
Horizontal S	17.7822	30	17.5215	0.0000	2.87×10^{14}	31
Horizontal P	16.1959	31	21.3027	0.0000	4.91×10^{13}	32
Vertical	16.0273	31	273.934	0.0000	3.71×10^{13}	32
Sequential	17.4401	31	27.0224	0.0000	3.61×10^{14}	32
Perceptual H	6.6499	31	12.1093	0.0000	79869.19	29
Perceptual V	7.4022	31	15.9321	0.0000	557423.9	30

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