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Temporal Position Priming: Memory Traces of Recent Experience Bias the Allocation of Attention in Time

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Explicit expectations can guide attention toward the time at which an upcoming target is likely to appear. However, in real-life situations, explicit preknowledge of upcoming events' temporal occurrence is rarely provided. We investigated whether implicit memory traces can guide attention in time, as they guide attention to recently attended features and locations (priming of pop-out and priming of location; V. Maljkovic & K. Nakayama, 1994, Priming of pop-out: I. Role of features, *Memory & Cognition*, Vol. 22, pp. 657–672; V. Maljkovic & K. Nakayama, 1996, Priming of pop-out: II. The role of position, *Perception & Psychophysics*, Vol. 58, pp. 977–991). Using a rapid serial visual presentation task, we show a temporal position priming (TPP) effect by which search performance is speeded when the target temporal position within the visual stream happens to repeat on consecutive trials. We show that such repetition priming is one of the mechanisms that underlie the much-studied sequential effect of the foreperiod. We further demonstrate that the learned association that gives rise to TPP does not require the selection or execution of a motor response and that it affects perceptual stages of visual processing. The relations between these findings and existing accounts of the sequential effect as well as with other intertrial priming effects in visual search are discussed.

Keywords: attention, intertrial priming, time assessment, rapid serial visual presentation (RSVP), sequential effect

Time is a fundamental dimension of mental life. It is crucial to our ability to distinguish between different objects and events; to assess quantity, movement, and speed; to control our motor actions; and to appreciate art and music. Time is also important for selective attention. Whether we wait at a traffic light, prepare to catch a ball, or search for defective items in a production line, our expectations about when a critical event will occur substantially affect our actions and performance. Although our understanding of how time is perceived and represented has greatly advanced over the past 2 decades (see Buhusi & Meck, 2005, for review), research on its role in guiding visual attention still lags behind research pertaining to the role of space. Indeed, most of the research on attention has focused on the ability to select locations in space and the objects that occupy them. By contrast, the ability to select moments in time and the events that unfold over them has mostly been investigated indirectly, as a means to uncover the temporal limitations of attention (e.g., Raymond, Shapiro, & Arnell, 1992; Shih & Sperling, 2002).

The few studies that have addressed the question of how temporal information guides the allocation of attention in time have

typically used a temporal adaptation of Posner's spatial orienting task (e.g., Posner, Snyder, & Davidson, 1980). For instance, Coull and Nobre (1998) presented one of two symbolic cues that predicted with high validity the time interval at which the target stimulus would occur. They found improved performance for targets appearing at the predicted time interval. This finding illustrates that, similar to spatial information, temporal information can guide attention via top-down control (see also Kristjánsson, Eyjólfsson, Jónsdóttir, & Arnkelsson, 2010).¹

A growing body of research has demonstrated that implicit memory traces also play a central role in guiding visual attention in space by showing that deployments of focal attention and eye movements are facilitated toward recently attended features and locations (see Chun & Nakayama, 2000; Kristjánsson & Campana, 2010, for reviews). In particular, Maljkovic and Nakayama (1994, 1996) showed that in spatial search for a color singleton, performance is faster when either the target color or its location happens to repeat on successive trials. These intertrial priming effects are often referred to as *priming of pop-out* (PoP) of feature and position, respectively, and recent research (e.g., Lamy, Yashar, & Ruderman, 2010; Yashar & Lamy, 2011) suggests that they affect

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¹ Using a spatial cuing paradigm, Kristjánsson and colleagues (2010) varied the time interval between a cue and target displays. Their results showed that spatial validity effects increased when cue-to-target intervals were constant over several consecutive trials. This finding demonstrates that temporal information has an important role on the allocation of spatial transient attention. However, it is noteworthy that such effects could reflect the operation of top-down temporal expectations rather than automatic repetition effects because, in this study, cue-to-target intervals were significantly more likely to remain the same than to change on successive trials (and were completely predictable in one experiment).

both perceptual/attentional processing (e.g., Sigurdardottir, Kristjánsson, & Driver, 2008; Yashar & Lamy, 2010a) as well as response-related processing (Töllner, Gramann, Müller, Kiss, & Eimer, 2008; Yashar & Lamy, 2011), albeit only when search is difficult (Ásgeirsson & Kristjánsson, 2011; Lamy, Zivony, & Yashar, 2011).

Temporal Position Priming

In a recent study, we extended intertrial priming from the spatial to the temporal domain (Yashar & Lamy, 2010b). Observers searched for a target defined as the uniquely colored digit within a rapid serial visual presentation (RSVP) stream of uniformly colored digits presented at fixation. Thus, whereas the target location was known, the observers did not know when it would appear within the stream. This study yielded three main findings that underscore the similarities between attentional selection in space and in time. (1) Reaction times (RTs) were faster when the target color happened to repeat on two consecutive trials. (2) This intertrial priming effect was also found to transfer from the temporal search task to a spatial search task when these tasks were interleaved, suggesting that the representations that are modulated by recent attentional history are common to allocation of attention in space and in time. (3) Repeating the target position in the RSVP sequence—that is, its position in time—also speeded RTs.

The latter effect was the focus of the present study. It appears to be the temporal analogue of the spatial priming effect reported by Maljkovic and Nakayama (1996), as it also showed a distance effect, that is, it became smaller as the distance (in time) between target positions on successive trials increased. Based on this analogy, we may assume that similar mechanisms underlie this novel temporal position (TPP) priming effect and other intertrial priming effects. Specifically, we may infer that the relative temporal position at which a target is selected within a certain frame of reference (here, the time interval in which the RSVP stream unfolds) is stored in implicit short-term memory (STM), such that target selection a few moments later is speeded when the target appears at a similar relative temporal position. In situations in which visual stimuli are scanned following a certain rhythm (e.g., during reading), such implicit priming mechanisms may spare the need to explicitly and intentionally allocate attention in time. The present study investigated such implicit temporal priming mechanisms to uncover the stage(s) of processing at which they operate.

Foreperiod and the Sequential Effect

Research on temporal attention has focused on explicit allocation of attention in time (e.g., Coull & Nobre, 1998). However, there has been considerable research on the effects of *implicit* time assessment on performance since the early days of cognitive psychology within the field of “nonspecific preparation” (Woodrow, 1914; Wundt, 1904), which has recently sparked renewed interest (see Los, 2010, for a review). In a nutshell, RTs are faster when a stimulus that must be responded to as fast as possible (imperative stimulus or IS) is preceded by a warning signal (WS). The WS does not supply any information about either the characteristics of the IS or the required response but merely signals that the IS is impending. The interval between the WS and the IS or foreperiod (FP) strongly influences performance speed on such a

simple task (see Niemi & Näätänen, 1981, for review). In particular, when the FP duration varies randomly from trial to trial (variable FP condition), mean RTs become faster as FP duration increases (henceforth, the FP-RT function).

Crucially, for the present purposes, Woodrow (1914) also reported intertrial effects of FP duration, known as *sequential effects*. He showed “. . . that the RT to any interval is shortened when preceded by an interval of nearly the same or shorter length, and that it is lengthened when preceded by a considerably longer interval” (p. 46). In other words, this asymmetric intertrial effect, which has been replicated many times since this first report (e.g., Baumeister & Joubert, 1969; Klemmer, 1956; Possamai, Granjon, Requin, & Reynard, 1973; see Los, 2010, for a review), refers to an interaction between FP on the previous trial and FP on the current trial.

Comparison of the Sequential and TPP Effects

The interaction that underlies the sequential effect is conceptually similar to the interaction that is at the root of the TPP effect (Yashar & Lamy, 2010b) described in the previous section. Indeed, if the onset of the first stimulus within the RSVP stream is relabeled as the WS and the temporal position of the target within the RSVP stream as the FP, the TPP effect refers to the finding that the effects of the FP durations on the previous and current trial interact. However, different analyses have been used to describe the two effects. To measure TPP, Yashar and Lamy (2010b) examined performance as a function of the distance in time between successive targets (i.e., the absolute difference between FPs on the current vs. the previous trial) across FPs. Thus, for instance, FPs of 200 ms and 300 ms on the previous and current trials, respectively, corresponded to a distance of 100 ms, as did FPs of 400 ms and 300 ms on the previous and current trials, respectively. Accordingly, both types of trial sequence belonged to the same 100-ms distance condition. By contrast, studies of the sequential effects (e.g., Los & Agter, 2005) have typically measured performance for each FP in the current trial (FP_n) as a function of each FP in the previous trial (FP_{n-1}). Therefore, our analyses lacked the resolution necessary to detect the asymmetry that has been shown to be a crucial feature of the sequential effect. Specifically, TPP as measured in our original study was not sensitive to whether the FP on the current trial was longer or shorter than the FP on the previous trial, a variable that is at the heart of the sequential effect. Our analyses did not therefore allow us to determine whether the TPP and the sequential effects might indeed be emanations of the same underlying mechanism.

Linking these two lines of work is important for two reasons. On the one hand, relying on the rich literature on nonspecific preparation may allow us to more fully characterize the boundary conditions and underlying mechanisms of TPP. On the other hand, previous work on intertrial priming effects has delineated the stage(s) of processing at which they occur (e.g., Huang, Holcombe, & Pashler, 2004; Lamy et al., 2010; Yashar & Lamy, 2010a, 2011), whereas, as pointed out by Los (2010), the sequential effect of FP is often described as being related to *temporal preparation*, a general term that is noncommittal as to whether such preparation pertains to motor response processes or to earlier processes such as attention allocation. Thus, linking TPP to FP effects may deepen our understanding of the mechanisms underlying sequential FP

effects by shedding light on whether benefits of nonspecific preparation may, at least partially, result from facilitation of early perceptual/attentional processing.

Despite the apparent similarities between the two effects, there is a notable difference in the conditions in which they have been demonstrated: Whereas we demonstrated TPP in an RSVP task in which the observers had to select the target defined by its unique color among distractors in the stream, the sequential effect has typically been reported in studies in which the WS and IS were separated by an empty interval of time. There are three main consequences to this difference. First, repetition of the FP on two successive trials in the RSVP paradigm is confounded with repetition of the serial position of the target, that is, with the number of items that appeared in the stream prior to the target. By contrast, the sequential effect can only rely on encoding of the time interval between the WS and the IS. Second, time estimation is easier when the time interval between the WS and the target is subdivided into shorter intervals of equal length (as is the case in the RSVP paradigm in which distractors appear at a regular pace) than when it is empty (as in the FP paradigm), although it has been shown that sequential effects are unaffected by the addition of regularly presented time markers such as auditory clicks (see Niemi & Näätänen, 1981). Finally, unlike TPP, there is no uncertainty as to which stimulus is the target in the FP paradigm that yields the sequential effect, and observers are therefore not required to select the IS among to-be-ignored distractors. Accordingly, we interpreted the TPP as an effect of implicit STM on visual search that is similar to previously reported effects such as feature and location PoP (Maljkovic & Nakayama, 1994, 1996). That is, we suggested that repeating any attribute of the target that is uniquely associated with it—be it its defining feature, its location, or the time at which it occurs—enhances the observer’s ability to reselect it.

Objectives of the Present Study

The objectives of the present study were twofold. First, we set out to clarify the relationship between the TPP effect (Yashar & Lamy, 2010b) and the asymmetric sequential effects of FP (e.g., Los, 2010; Niemi & Näätänen, 1981; Vallesi, Shallice, & Walsh, 2007). In Experiment 1, we sought to determine whether sequential effects of FP are observed with Yashar and Lamy’s (2010b) RSVP paradigm using finer grained analyses. In Experiment 2, we tested whether this effect is best described in terms of TPP or in terms of an asymmetric sequential effect.

Second, we aimed at characterizing the mechanisms underlying these effects, namely, at determining whether they reflect selection- or response-based processes. In Experiment 3, we investigated whether the association that must be learned for TPP to occur requires selection/execution of a motor response or only attentional selection of the target. In Experiment 4, we tested whether repeated temporal position of the target speeds perceptual/attentional or response-based processes.

Experiment 1

The objective of this experiment was to replicate Yashar and Lamy’s (2010b) TPP finding and to determine whether the asymmetry that is characteristic of the sequential effect as demonstrated

in FP experiments also emerges using the RSVP paradigm with the appropriate analyses. Accordingly, participants searched for a target defined as the uniquely colored digit within an RSVP stream of uniformly colored digits. The target could appear at five possible temporal positions relative to fixation display offset (480, 600, 720, 840, or 960 ms). The TPP effect refers to the effect on performance of repeating the target temporal position on successive trials. The distance effect provides more detailed information and refers to the effect of the absolute difference between the FPs on successive trials. Thus, if the target appeared at a 600-ms FP on the current trial, distance would be 120 ms if the target on the previous trial had appeared at either a 480-ms or a 720-ms FP on the previous trial. The sequential effect refers to the effect of the FP on the previous trial (henceforth, FP_{n-1}) on performance as a function of the FP on the current trial (henceforth, FP_n).

Method

Subjects. Participants were 11 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected visual acuity and normal color vision.

Apparatus. An Intel Core 2 Duo computer was attached to a 17-in. CRT monitor, using $768 \times 1,024$ resolution and 85-Hz refresh rate graphics mode. The experiments were programmed with E-prime (Schneider, Eschman, & Zuccolotto, 2002). Responses were collected via the computer keyboard. A chin rest was used to set viewing distance at 50 cm from the monitor.

Stimuli and procedure. Sample stimulus displays are presented in Figure 1a. Each trial began with presentation of a fixation display, a gray $0.2^\circ \times 0.2^\circ$ sign (+) in the center of a black background, for 500 ms. It was followed by an RSVP stream consisting of 12 successively presented colored digits randomly selected among 2 to 9, with the restriction that no two consecutive digits were the same. Each digit was presented for 60 ms and separated from the next digit by an empty 60-ms interval, resulting in a stimulus onset asynchrony of 120 ms. Each RSVP stream contained one digit with a unique color, the target, and 11 digits in a different color, the distractors. On each trial, the target and the distractor colors were randomly drawn from four possible colors: red (CIE coordinates 0.586/0.329, 25.6 cd/m²), blue (CIE coordinates 0.181/0.185, 21.4 cd/m²), green (CIE coordinates 0.308/0.544, 43.2 cd/m²), and yellow (CIE coordinates 0.428/0.464, 70.6 cd/m²). The target position in time was randomly selected between the fifth and the ninth positions within the stream, corresponding to FPs of 480, 600, 720, 840, or 960 ms from RSVP onset. A blank screen followed the RSVP stream for 5 s or until the participant responded.

Participants were instructed to report whether the target was an odd or an even number by pressing designated keys (3 with the right hand for an even number and z with the left hand for an odd number) as accurately and quickly as possible. A blank screen was presented for 500 ms before the next trial began. Error trials were followed by a 500-ms feedback beep sound. Eye movements were not monitored, but participants were explicitly requested to maintain fixation throughout each trial.

The experiment began with a block of 20 practice trials, followed by 560 experimental trials divided into eight blocks. Participants were allowed a short rest after each block.

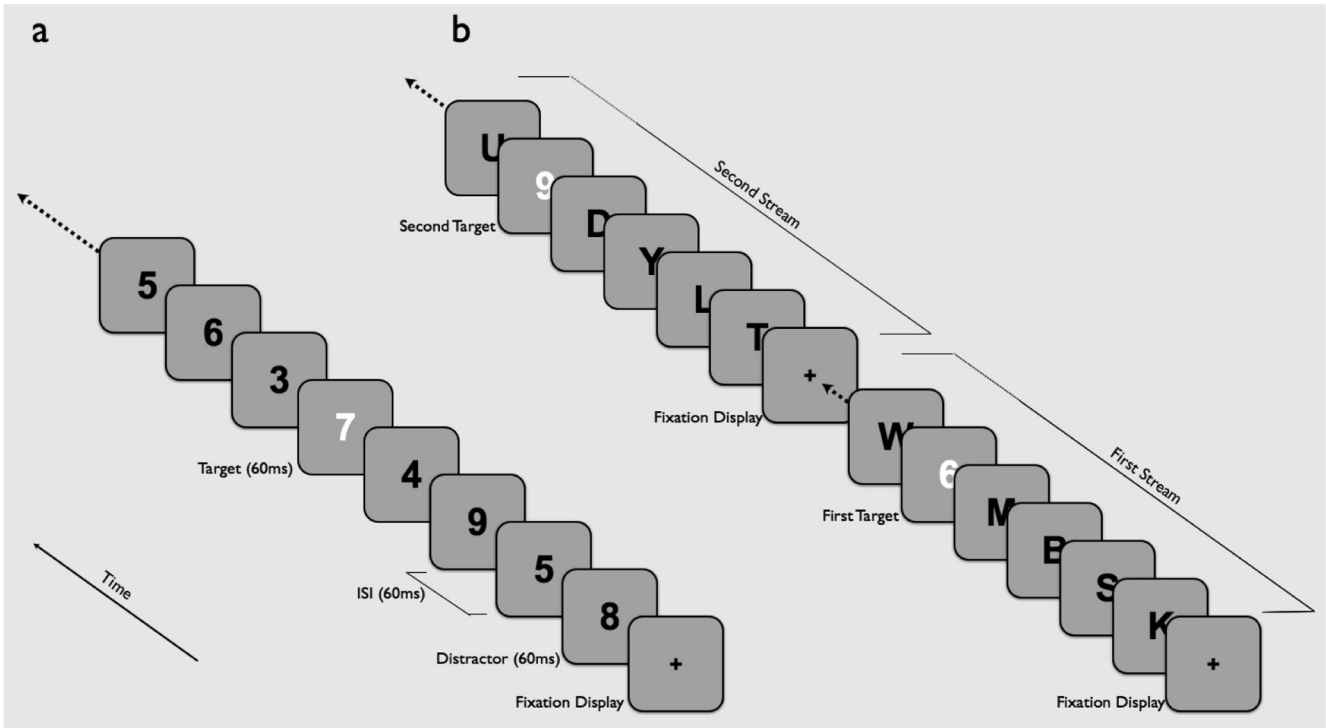


Figure 1. Illustration of the sequence of events in Experiments 1, 2 (Panel a), and 3 (Panel b). (a) In Experiments 1 and 2, observers had to report whether the color singleton target was an odd or an even number. (b) In Experiment 3, each trial included two streams and observers had to determine whether or not the target in the second stream was the same as the target in the first stream. The stimuli were displayed against a black background, shown here in gray. On a given trial, all the distractors were in one color, and the target was in a different color. Possible colors were red, green, blue, and yellow. In the illustration, the distractors are shown in black, and the target digit is shown in white.

Results and Discussion

The data from two participants were discarded because their error rates exceeded the group's mean by more than 2 standard deviations. Error trials (10% of all trials) and trials that followed an error trial were removed from all RT analyses. In all experiments, trials in which the RT exceeded the mean of its cell (resulting from crossing FP_n and FP_{n-1} conditions) by more than 2.5 standard deviations were also excluded from all RT analyses.

TPP. Following Yashar and Lamy's study (2010b), we measured the effect of the relative distance between the temporal positions (or FPs) of the current and previous targets. Distance was calculated as the absolute value of the difference between the temporal position of the target on the current trial (t_n) and the temporal position of the target on the previous trial (t_{n-1}), $d = |t_n - t_{n-1}|$. Thus, the minimum distance was 0 ms, which indicated that the target temporal position repeated on two consecutive trials. The distance increased by steps of 120 ms, with a maximum distance of 480 ms, corresponding to a 4-lag difference. Mean RTs are depicted in Figure 2 (bottom panel). An analysis of variance (ANOVA) was conducted with distance as the within-subject factor.

RTs. Mean RTs as a function of temporal distance are depicted in Figure 2 (bottom panel). The main effect of distance was significant, $F(4, 36) = 3.30$, $p < .03$, indicating that RTs increased

as the targets on consecutive trials were farther apart in time. It is noteworthy, however, that when all greater-than-zero distances were collapsed into a different-position condition, the effect of temporal position repetition (same vs. different position) was not significant, $t < 1$.

Previous studies have shown that intertrial priming effects are cumulative: They become larger as the number of successive repetitions increases (e.g., Maljkovic & Nakayama, 1994, 2000). To test whether TPP also shares this characteristic, here and in the following experiments, we measured the effect of successive repetitions up to a number that allowed for at least 20 trials per cell. Because in all experiments the target serial position was randomly set, the number of repetitions that matched this criterion was two. An ANOVA was conducted with number of repetitions (zero, one, or two) as a within-subject factor and revealed no significant effect, $F(2, 18) = 1.18$, $p > .1$, with mean RTs of 736 ms, 729 ms, and 749 ms for zero, one, and two repetitions, respectively.

Accuracy. The accuracy data mirrored the RT data. The main effect of distance approached significance, $F(4, 36) = 2.27$, $p = .08$, with lower accuracy as the distance in time between two consecutive targets increased. The effect of temporal position repetition (same vs. different position) did not reach significance, $t(9) = 2.99$, $p > .1$. The effect of successive

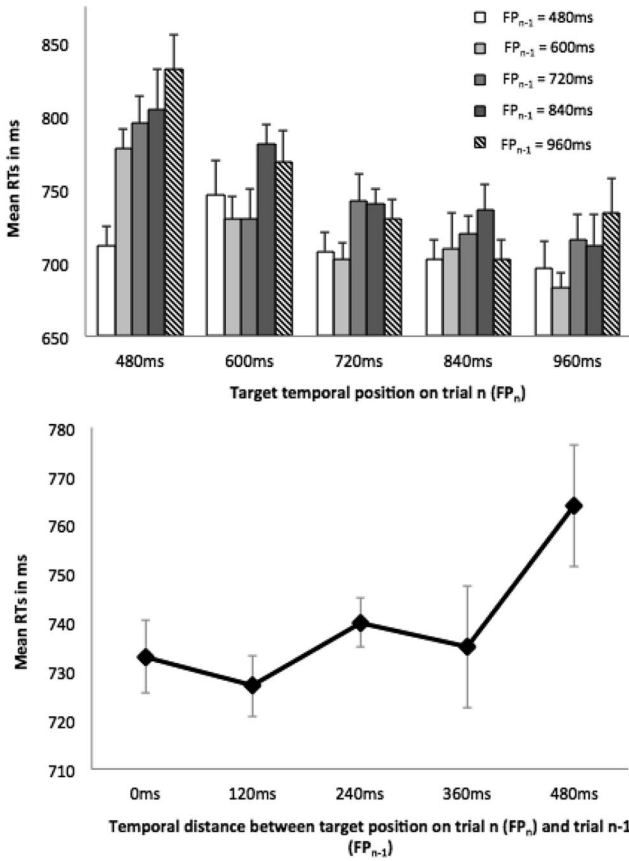


Figure 2. Mean reaction times (RTs) on correct-response trials in Experiment 1. Top panel: Temporal position priming (TPP) and sequential effect. Mean RTs for each target temporal position on trial n (FP_n) as a function of target temporal position on trial $n-1$ (FP_{n-1}). TPP is indicated by faster RTs when FP_n is the same as FP_{n-1} relative to when it is different. The sequential effect is indicated by slower RTs when FP_{n-1} is longer than FP_n . Bottom panel: Mean RTs as a function of the distance between the FP_n and FP_{n-1} ($d = |FP_n - FP_{n-1}|$). Error bars represent within-subject standard errors (Morey, 2008).

repetitions was not significant, $F < 1$, with mean accuracy rates of 11%, 9%, and 10% for zero, one, and two repetitions, respectively.

Sequential FP effects.

RTs. Next, we conducted a repeated measures ANOVA with FP_n and FP_{n-1} as within-subject factors, which is similar to the analysis that has typically been used in previous studies to demonstrate the sequential effect of the FP (e.g., Los, 2010). Mean RTs are depicted in Figure 2 (top panel) and accuracy scores are shown in Table 1. The main effect of FP_n was significant, $F(4, 36) = 13.30, p < .0001$, indicating that RTs became faster the later the target appeared in the RSVP stream. The main effect of FP_{n-1} was also significant, showing that RTs on trial n became slower the later in the stream the target had appeared on the previous trial. The interaction between the two factors was significant, $F(16, 144) = 2.23, p < .01$. As Figure 2 shows, RTs were slower when FP_n was shorter than FP_{n-1} , thus replicating the traditional sequential effect.

Accuracy. The main effect of FP_n was significant, $F(4, 36) = 8.80, p < .0001$, with fewer errors as the FP became longer. No other effect approached significance, $ps > .3$.

The results from Experiment 1 show that, using an RSVP task that required selection of the target among distractors, we replicated the distance effect of target temporal position reported by Yashar and Lamy (2010b) as well as the asymmetric sequential effect that has been repeatedly reported in tasks in which an empty interval separated the WS from the unique IS (e.g., Los, 2010). However, we failed to replicate the main effect of TPP reported by Yashar and Lamy (2010b).

TPP effect for each FP_n . The analysis of the effect of FP_n as a function of FP_{n-1} allowed us to look at the TPP effect separately for each temporal position of the target on the current trial (FP_n). This inspection shows that TPP is obtained when the target appears early in the stream, FP_n s of 480 and 600 ms, $t(9) = 41.55, p < .000$, and $t(9) = 4.26, p = .064$, respectively, but not with later FP_n s ($ps > .1$). No significant effect was observed on accuracy ($ps > .1$).

Based on these results, it appears that TPP (i.e., faster RTs when FP repeats from the previous trial; Yashar & Lamy, 2010b) and asymmetric sequential effects (i.e., slower RTs when FP_{n-1} is longer than FP_n ; e.g., Los, 2010) reflect the same phenomenon. Yet, these results also suggest that intertrial effects of target temporal position (or FP) are better described in terms of asym-

Table 1

Mean Percentage of Errors in Experiments 1, 2, and 3 for Each Target Temporal Position in Trial n (FP_n) as a Function of Target Temporal Position in Trial $n-1$ (FP_{n-1})

FP_n (ms)	FP_{n-1} (ms)	Experiment 1	Experiment 2	Experiment 3
480	480	15.0 (3.1)	9.7 (1.8)	4.3 (1.2)
	600	12.8 (1.9)		
	720	18.1 (3.6)	9.3 (1.5)	4.1 (1.2)
	840	19.4 (3.3)		
	960	15.0 (3.8)	9.7 (1.7)	5.8 (1.4)
600	0		6.7 (1.1)	
	480	6.6 (3.0)		
	600	8.3 (1.6)		
	720	7.4 (2.5)		
	840	12.2 (2.8)		
720	960	11.9 (3.3)		
	480	7.6 (2.0)	6.7 (2.0)	4.5 (1.5)
	600	8.8 (2.0)		
	720	7.7 (2.9)	7.6 (1.7)	2.6 (1.2)
	840	7.0 (1.8)		
840	960	10.5 (2.1)	5.8 (2.0)	1.6 (1.1)
	0		6.7 (1.0)	
	480	10.0 (4.0)		
	600	7.6 (2.8)		
	720	6.0 (2.0)		
960	840	6.7 (1.9)		
	960	9.5 (3.1)		
	480	9.6 (3.5)	9.4 (2.3)	5.0 (2.0)
	600	6.8 (2.1)		
	720	11.5 (3.1)	5.0 (2.9)	3.2 (1.5)
0	840	9.4 (1.9)		
	960	7.0 (3.6)	2.0 (2.3)	2.2 (1.7)
	0		5.9 (1.2)	

Note. $FP_{n-1} = 0$ represents the condition in which the target was absent on the previous trial ($n-1$). Within-subject standard errors (Morey, 2008) are given in parentheses.

metric sequential effects than in terms of TPP: Whereas the former description accounts for behavior for all FPs, the latter holds only for early FPs.

However, in addition to the influence of FP_{n-1} , the pattern of results observed in this experiment should also reflect the fact that the conditional probability of the occurrence of the target increases as its temporal position approaches the latest possible position (Niemi & Näätänen, 1981): As one moves forward in the trial without the target appearing, it becomes more and more likely that the target will appear soon, with this probability reaching 100% for the last possible FP in the trial. Accordingly, observers' expectations increase with increasing FP_n and RTs therefore become faster. Such expectation effects may mask the influence of TPP at later FPs because of floor effects.

The objective of Experiment 2 was to reevaluate the TPP interpretation of the sequential effect when expectation effects are eliminated.

Experiment 2

Several studies have demonstrated that when nonaging distributions of the FPs are used, such that at each candidate target temporal position (FP) within a trial the probability of target occurrence is the same for all remaining FPs, the FP-RT function no longer shows the characteristic pattern of RTs becoming faster as FP increases (e.g., Los & Agter, 2005; Mowbray, 1964; Näätänen, 1970; Trillenber, Verleger, Wascher, Wauschkuhn, & Wessel, 2000). This finding suggests that the increasing probability of the target appearing as time unfolds indeed accounts for the FP-RT function (but see Los & Agter, 2005, for an alternative account).

In the present experiment, we used a nonaging distribution of the target temporal positions to eliminate expectations related to the conditional probability of the target occurrence during the trial. If TPP effects were indeed masked by floor effects due to increasing expectations for later FPs in Experiment 1, then they should now become apparent. Namely, at the longest FP, we expected RTs to be faster when the FP on the previous trial had also been longest. If instead sequential effects are inherently asymmetric, independent of target occurrence expectancy, no TPP effect should be observed at the latest FP.

To our knowledge, of all the studies that employed a nonaging function in an FP paradigm, only Los and Agter (2005) thoroughly analyzed the interaction between the target's temporal position on the previous and current trials. Three main findings arose from their results. First, at the longest FP, RTs were faster when the FP on the previous trial had also been longest (a finding that the authors had difficulty accounting for within the asymmetric view of the sequential effect), and at the shortest FP, RTs were faster when the FP on the previous trial had also been shortest. These findings closely match our predictions. Second, RTs were not affected by FP_{n-1} for the intermediate FP. Finally, RTs were slower when following a target-absent trial relative to a target-present trial. The latter two findings do not directly follow from our account and are discussed later. An additional objective of the present experiment was to determine whether the pattern of results obtained using the FP paradigm could be replicated using the RSVP paradigm.

Method

Subjects. Participants were 11 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected visual acuity and normal color vision.

Apparatus, stimuli, procedure, and design. The apparatus, stimuli, and procedure were the same as those in Experiment 1 except for the following changes. Only three possible target serial positions (5, 7, and 9, that is, 480, 720, and 960 ms after fixation offset) were used instead of five. In addition, target-absent trials were introduced, in which participants had to withhold their response. The probabilities for the three target positions were determined by the function $p_n = 1/3 \times (1 - 1/3)^{(n-1)}$, where n designates the target serial position. Thus, target occurrence rates were 33% for $FP = 480$ ms, 22% for $FP = 720$ ms, 14% for $FP = 960$ ms, and 33% for no occurrence (i.e., target-absent trials). Thus, expectation of target occurrence remained constant across the three temporal positions. The experiment included 20 practice trials, followed by 720 trials divided into 18 blocks of 40 trials each.

Results and Discussion

Error trials (6% of all trials), trials that followed an error trial, and RT outliers (fewer than 4% of all correct trials) were removed from all RT analyses. The data from two participants were discarded because either their accuracy rates (one participant) or their mean RTs (one participant) exceeded the group's mean by more than 2 standard deviations. Target-absent trials and trials that were preceded by a target-absent trial were removed from analysis. Mean RTs are depicted in Figure 3 and accuracy data are shown in Table 1.

The following analyses included only trials that followed target-present trials, thus allowing for a direct comparison with the results from Experiment 1.

TPP. An ANOVA was conducted with number of repetitions (zero, one, or two) as the within-subject factor. The main effect of

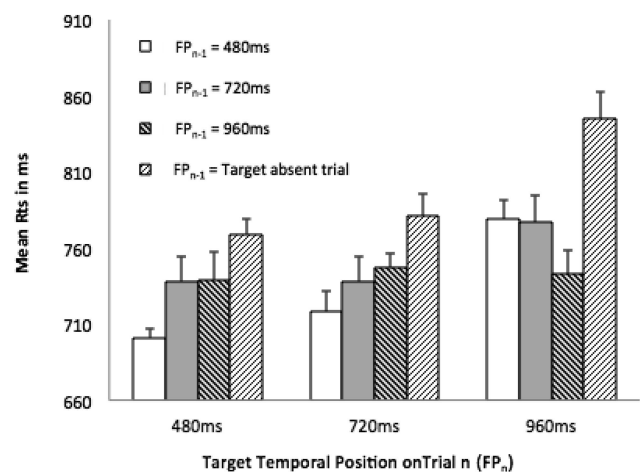


Figure 3. Temporal position priming (TPP) and sequential effect in Experiment 2. Mean reaction times (RTs) on correct-response trials for each target temporal position on trial n (FP_n) as a function of target temporal position on trial $n-1$ (FP_{n-1}). Error bars represent within-subject standard errors (Morey, 2008).

repetition was significant on RTs, $F(2, 16) = 16.49, p > .0001$, with mean RTs of 744 ms, 720 ms, and 709 ms for zero, one, and two repetitions, respectively, but not on accuracy, $F(2, 16) = 1.87, p > .1$, with 7.3%, 7.4%, and 10.0% of errors for zero, one, and two repetitions, respectively.

TPP effect for each FP_n .

RTs. The results are compatible with an interpretation of the data in terms of TPP: RTs were faster when target temporal positions on successive trials were the same than when they were different. Corroborating this conclusion, planned comparisons showed a significant repetition effect for the shortest (480 ms) and for the longest (960 ms) target temporal positions, $t(8) = 13.96, p < .01$, and $t(8) = 7.3, p < .03$, respectively. There was no significant effect of repetition for the intermediary target temporal position (720 ms), $t < 1$.

Accuracy. TPP was significant only for the longest FP (960 ms), $t(8) = 11.18, p < .01$, but not for the early and intermediate temporal positions (480 ms and 720 ms), $t_s < 1$.

Sequential FP effects. A repeated measures ANOVA was conducted with FP_n and FP_{n-1} as within-subject factors.

RTs. The main effect of FP_n was significant, $F(2, 16) = 9.96, p < .01$, but followed a pattern opposite to that observed in Experiment 1: RTs became slower as FP_n became longer. The main effect of FP_{n-1} was not significant, $F(2, 16) = 1.99, p > .1$. The interaction between the two factors was significant, $F(4, 32) = 5.55, p < .01$. The effect of FP_{n-1} was similar to that observed in Experiment 1 for the early and intermediate FPs. Namely, (a) for the 480-ms FP, RTs were significantly slower when FP_{n-1} had been longer than FP_n , $F(2, 16) = 4.36, p < .04$; and (b) for the 720-ms FP, the effect did not reach significance, $F(2, 16) = 2.64, p > .1$. However, for the longest FP_n (960 ms), the pattern differed from that of Experiment 1 and no longer matched the asymmetric sequential effect description: RTs were significantly faster when the FP_n was shorter than the FP_{n-1} , $F(2, 16) = 4.38, p < .04$ (see Figure 3).

Accuracy. The main effect of FP_n was significant, $F(2, 16) = 4.52, p < .01$, but in the opposite direction to that observed in the RT analysis, thus revealing a speed-accuracy trade-off. The main effect of FP_{n-1} approached significance, $F(2, 16) = 3.02, p < .07$. The interaction between the two factors was also significant, $F(4, 32) = 3.18, p < .01$, and showed a pattern numerically similar to the RT pattern. The effect of FP_{n-1} was significant only for the 960-ms FP_n , $F(2, 16) = 6.65, p < .001$, but not for 480-ms and 780-ms FP_n s, $F_s < 1$.

Target presence/absence. Next, to complete the comparison with Los and Agter's (2005) findings, we included trials following target-absent trials and conducted an ANOVA with target presence in the previous trial (present vs. absent) and FP_n as within-subject factors.

RTs. Trials following target-absent trials were slower than trials following target-present trials, $F(1, 8) = 41.76, p < .001$ (799 ms vs. 741 ms, respectively). The interaction between target presence in the previous trial and FP_n was not significant, $F(2, 16) = 2.19, p > .1$.

Accuracy. No effect was significant, $p_s > .1$.

The findings of Experiment 2 closely replicated the pattern of results reported by Los and Agter (2005), reinforcing the conclusion that TPP demonstrated using the RSVP paradigm and the sequential effect demonstrated using the FP paradigm reflect the

same effect. Crucially, the pattern of results in this experiment cannot be satisfactorily described in terms of asymmetric sequential effects: For the shorter FP, the RTs were indeed slower when FP_{n-1} was longer than FP_n , whereas at the latest FP, RTs were actually slower when FP_{n-1} was shorter than FP_n , thus violating the traditional description of the sequential effect (e.g., Woodrow, 1914). In terms of the TPP effect, RTs were faster when the target position repeated for both the shortest and the longest target positions. In addition, the intertrial priming effect gradually increased over two repetitions, showing the cumulative effect that is characteristic of feature and location intertrial priming (Maljkovic & Nakayama, 1994, 1996). As in Los and Agter's study, FP repetition did not affect performance for the intermediate target position (720 ms), an issue we address in the General Discussion.

The results are consistent with the idea that sequential effects of the FP reflect the joint influence of two factors: (1) expectation of the target occurrence within the trial and (2) intertrial repetition priming of the target position. Indeed, when the conditional probability of target appearance was equated for all three possible target positions in time, RTs no longer decreased with longer FPs.

It is noteworthy that RTs actually increased with longer FPs (but there was a speed-accuracy trade-off: Accuracy increased with longer FPs). This finding may be explained by the fact that to keep the conditional probability of target occurrence constant across potential target temporal positions within the stream, the proportion of trials for each FP decreased as FP increased. As expectancies are driven by the subjective probability of target occurrence (Niemi & Näätänen, 1981), if participants were sensitive to both the conditioned probability distribution and the actual proportion of trials for each target temporal position, their subjective expectations may have been higher for shorter FPs. An alternative, or perhaps complementary, explanation for this finding may be that as the proportion of target-absent trials increased with longer FP_n s, participants may have increasingly prepared to withhold their response—as required on target-absent trials. In other words, the more they progressed within the trial without a target appearing, the more strongly the tendency to refrain from responding competed with the tendency to produce a response, thereby leading to delayed responses. This account may also explain the slower RTs observed following target-absent versus target-present trials: Withholding one's response on the previous trial may have enhanced the tendency to withhold one's response on the current trial.

In the following experiments, our main objective was to determine whether TPP is related to perceptual or to motor processes. We investigated this question by addressing two different issues. In Experiment 3, we focused on the events that occur during encoding of the target onset time. We attempted to determine whether selecting/executing a motor response to the target is a necessary condition for the association that is critical for TPP to be formed. In Experiment 4, we focused on the stage of processing that is affected by repetition of the target temporal position. We investigated whether TPP speeds perceptual/attentional processes during search or later response-related processes.

Experiment 3

The findings from the previous experiment suggest that when a target is selected at time t and subsequently responded to within a certain frame of reference (here, within the RSVP stream), a target

that appears at the same relative temporal position is responded to faster and more accurately than a target that appears at a different time (irrespective of whether it appears earlier or later). Both sequential effects and short-term implicit memory effects such as PoP, and by extension, TPP, have been described in terms of reinforcement learning. For instance, Los (2010, p. 9) suggested that the conditioned strength associated with a candidate temporal position increases when the target is presented and responded to (reinforcement). In the same vein, Nakayama and Martini (2011) suggested that fluctuations in attentional weights related to feature repetitions have much in common with fluctuations in motivational salience induced by rewards.

In Experiment 3, we asked whether selecting/executing a motor response to the target is a necessary condition for the association that is critical for TPP to be formed. We designed a task in which the encoding trial (i.e., trial $n-1$) did not entail responding to the target. On each trial, subjects were presented with pairs of RSVP streams, each stream in a pair containing a color singleton target, as in the previous experiments. However, they were required to report whether the targets in the first and second RSVP streams (henceforth, T1 and T2, respectively) were the same or different digits. Thus, subjects had to attend to the first target but responded only after attending to the second target. Note that subjects did not simply refrain from responding to the first target: There was no response associated it. We reverted to a uniform distribution of target position (as in Experiment 1) to increase power.

If the learned association on trial $n-1$ that gives rise to TPP includes the execution/selection of a motor response, then we should no longer expect to find an intertrial repetition effect of the target temporal position in this experiment. Conversely, if the learned association is tied to earlier responses, such as selecting the target and engaging attention in it, then the interaction between target positions in the first and second streams should again be observed. That is, the findings of Experiment 1 should be replicated.

Method

Subjects. Participants were 13 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected visual acuity and normal color vision.

Apparatus, stimuli, procedure, and design. Sample stimulus displays are presented in Figure 1b. The apparatus, stimuli procedure, and design were similar to those of Experiment 1 except for the following changes. Instead of digits, Latin letters, randomly selected from the Latin alphabet (all Latin letters except for the letters *I*, *O*, and *X*) served as distractors. The target was again a color singleton but on each trial, target color and distractor color were randomly selected from three possible colors: red (CIE coordinates 0.586/0.329, 25.6 cd/m²), blue (CIE coordinates 0.181/0.185, 21.4 cd/m²), and green (CIE coordinates 0.308/0.544, 43.2 cd/m²). The target digit was randomly either 6 or 9. The possible target temporal positions were the same as in Experiment 2 (480, 720, or 960 ms from fixation display offset) but in the present experiment, they were equiprobable.

Each trial consisted of two consecutive RSVP streams separated by a 500-ms blank screen. Each RSVP stream was similar to those of Experiments 1 and 2 except for the differences noted above. Observers were instructed to report whether the targets in the first and in the

second RSVP streams were the same (T1 = 6 and T2 = 6 or T1 = 9 and T2 = 9) or different (T1 = 6 and T2 = 9 or T1 = 9 and T2 = 6) by pressing designated keys, counterbalanced between subjects. The experiment began with a block of 20 practice trials, followed by 560 experimental trials divided into eight blocks of 70 trials each.

Results and Discussion

Error trials (4% of all trials) as well as outliers (about 2% of all correct trials) were removed from all RT analyses. The data from two participants were discarded because their accuracy rate (one participant) or RTs (one participant) exceeded the group's mean by more than 2 standard deviations. Mean RTs are depicted in Figure 4 and mean accuracy scores are shown in Table 1.

TPP. In this experiment, we measured temporal repetition between two RSVP streams within a single trial. RTs were significantly faster when the temporal position repeated than when it did not, $t(10) = 7.4$, $p < .03$, 574 ms versus 584 ms, respectively. The effect of accuracy was not significant, $t(10) = 2.37$, $p > .1$.

TPP effect for each FP_n .

RTs. Planned analyses of TPP for each temporal position of the target showed that RTs were faster when the target position repeated from the first to the second stream for the earliest target position, $t(10) = 10.07$, $p < .01$, but not for the intermediate position, $t(10) = 1.70$, $p > .2$. For the latest target position, the effect only approached significance, $t(10) = 3.95$, $p = .07$.

Accuracy. Temporal position priming did not reach significance, $t(10) = 2.16$, $p > .1$, for the longest FP (960 ms), and $t_s < 1$ for the short and intermediate FPs.

Sequential FP effects. A repeated measures ANOVA was conducted with target position in the first stream and target position in the second stream as within-subject factors.

RTs. The results closely replicated the findings of Experiment 1. The main effect of temporal position of the second target was significant, $F(2, 20) = 5.45$, $p < .02$, indicating that RTs became faster the later the target appeared in the RSVP stream. There was no main effect of the temporal position of the first target, $F(2, 20) = 1.42$, $p > .2$. The interaction between the two factors was significant, $F(4, 40) = 4.65$, $p < .01$. Again, RTs were slower

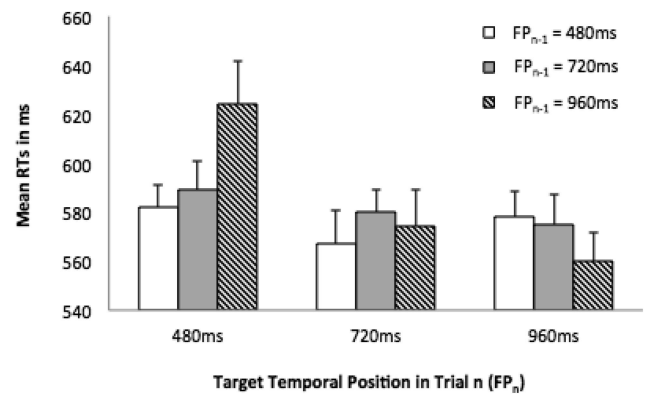


Figure 4. Temporal position priming (TPP) and sequential effect in Experiment 3. Mean reaction times (RTs) on correct-response trials for each target temporal position in the second stream (FP_n) as a function of target temporal position in first stream (FP_{n-1}). Error bars represent within-subject standard errors (Morey, 2008).

when the target appeared earlier in the second stream than it did in the first stream (see Figure 4).

Accuracy. The main effect of temporal position of the second target approached significance, $F(2, 20) = 3.04$, $p < .07$. Neither the main effect of target position in the first stream nor its interaction with target position in the second stream was significant, $ps > .2$.

The effect of TPP was replicated despite the fact that no response to the first target was required. This finding indicates that attending to the first target at a certain time within the RSVP stream sufficed to facilitate response to a second target that occurred at the same time within a subsequent RSVP stream. Although this finding does not preclude the possibility that response-related processes might also contribute to TPP, it strongly suggests that the learned association that is critical for TPP is related to target selection rather than to response processes.

Experiment 4

In the previous experiment, we showed that it is not necessary to associate a motor response with a first target event to benefit from repetition of the temporal position of a second target event a few moments later. Although this finding suggests that the learned association in TPP pertains to processes that unfold before motor response selection and/or execution, it is not informative as to which processes are affected by TPP.

In the present experiment, we relied on the idea that RTs with extended viewing times index both perceptual and postperceptual stages, whereas accuracy under data-limited conditions measures only processing during perceptual stages (e.g., Huang & Pashler,

2005; Moore & Egeth, 1998; Yashar & Lamy, 2010a). To create data-limited conditions, we presented the target very briefly and had it followed by a mask. Participants were required to extract the task-relevant information before the mask replaced the target and to respond under no speed stress. We reasoned that if TPP affects early stages of perceptual processing, then it should improve the perceptual quality of the target (which is indexed by response accuracy) when it happens to appear at the same temporal position as the target on the previous trial.

This experiment was similar to Experiment 1 except for the following changes. First, a mask followed the target. The target and mask were presented for 12 ms each and the interval between them was set individually so as to yield an accuracy rate ranging between 40% and 60% (with a chance level of 16.6%). Second, the task was to report the digit with the unique color rather than classifying it as an odd or an even number. Third, the digits 1, 7, and 8 were removed from the digit set. Finally, there were only three possible target temporal positions (360, 720, and 1,080 ms).

Method

Subjects. Participants were 11 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, stimuli, procedure, and design. The apparatus and stimuli were the same as those in Experiment 1 except for the following changes. To facilitate masking, rather than using text digits, we created digits by deleting selected segments from a box (made up of seven line segments; see Figure 5). Each line segment subtended

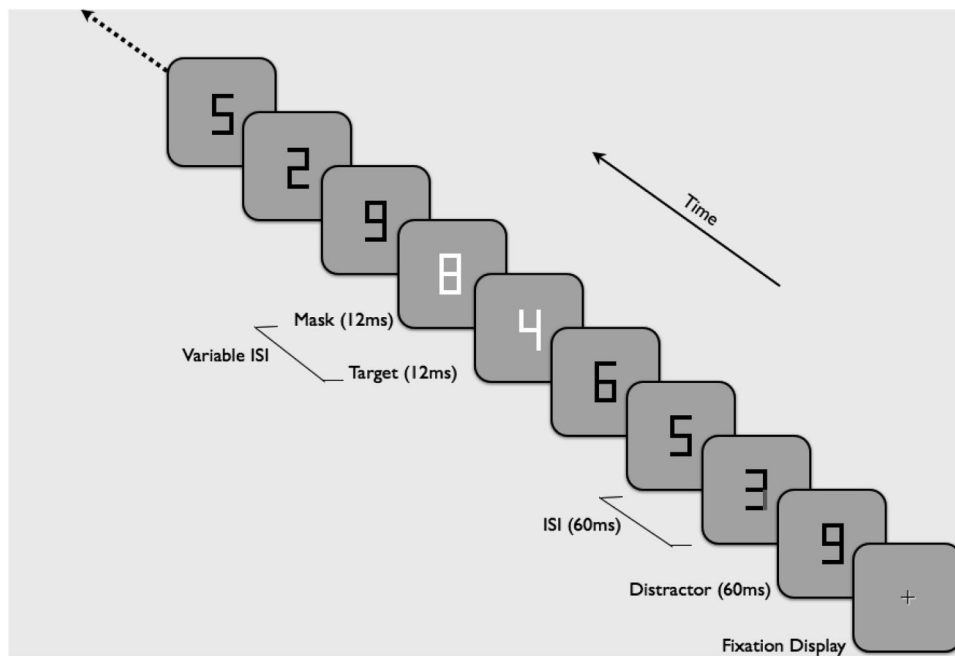


Figure 5. Illustration of the sequence of events in Experiment 4. The target was followed by a mask display after an interstimulus interval that varied as a function of performance. The stimuli were displayed against a black background, shown here in gray. On a given trial, all the distractors were in one color, and the target was in a different color. Possible colors were red, green, blue, and yellow. In the illustration, the distractors are shown in black, and the target digit is shown in white.

0.37° in length and was drawn with a 1-pixel stroke. The digit 8 served as a mask, which completely overlapped the line segments of all the other digits. It was always of the same color as the digit it followed (and masked).

The procedure and design were the same as those in Experiment 1 except for the following changes. Each stream included 13 digits instead of just 12. Each digit in the stream was randomly selected out of a digit set including 2, 3, 4, 5, 6, and 9, with the restriction that two successive digits were never the same. Within each RSVP stream, the target temporal position was randomly selected to be 460, 720, or 1,080 ms. On each trial, the target was followed by the mask, and the distractors were presented for the same duration as in the previous experiments and were not masked. The target and the mask were presented for 12 ms each. During practice, the time interval between target and mask (interstimulus interval [ISI]) was 108 ms in the first 10 trials, 84 ms in the following 10 trials, and 60 ms in the last 10 trials. During the experiment, ISI varied as a function of task performance, using a staircase procedure. It was set at 60 ms in the first block of trials and recalibrated after each block: To keep the average accuracy rate between 40% and 60% (given that chance-level accuracy was 16.6%), we increased or decreased ISI by 12 ms if the average accuracy rate had been below 40% or above 60% during the last block of trials, respectively.

Observers were required to report the target number by pressing the corresponding key on the numeric keypad. Observers were encouraged to maximize accuracy and were under no speed pressure.

The experiment began with a block of 30 practice trials, followed by 540 experimental trials divided into 18 blocks. Participants were allowed a short rest after each block.

Results and Discussion

Mean accuracy scores are depicted in Figure 6.

TPP. An ANOVA with number of repetitions (zero, one, or two) as a within-subject factor was conducted. The main effect of repetition approached significance, $F(2, 20) = 2.68, p > .09$, with 49%, 45%, and 46% error rates for zero, one, and two repetitions, respectively. Paired comparisons showed that one repetition improved performance, $t(10) = 15.30, p < .01$, with no additional benefit for the second repetition, $t < 1$.

TPP effect for each FP_n . Planned analysis of TPP for each temporal position of the target showed that accuracy was higher when the target's temporal position repeated on successive trials for the earliest and middle target positions, $t(10) = 16.89, p < .001$, and $t(10) = 5.01, p < .05$, respectively, but not for the latest target position, $t < 1$.

Sequential FP effects. A repeated measures ANOVA was conducted on accuracy data with target position on the current trial (FP_n) and target position on the previous trial (FP_{n-1}) as within-subject factors. The results paralleled the RT findings from Experiments 1 and 3. The main effect of FP_n was significant, $F(2, 20) = 22.23, p < .0001$, with accuracy improving as FP increased. There was no main effect of FP_{n-1} , $F(2, 20) = 1.32, p > .2$. The interaction between the two factors was significant, $F(4, 40) = 7.27, p < .001$, indicating that accuracy was lower when FP_n was shorter than FP_{n-1} (see Figure 6).

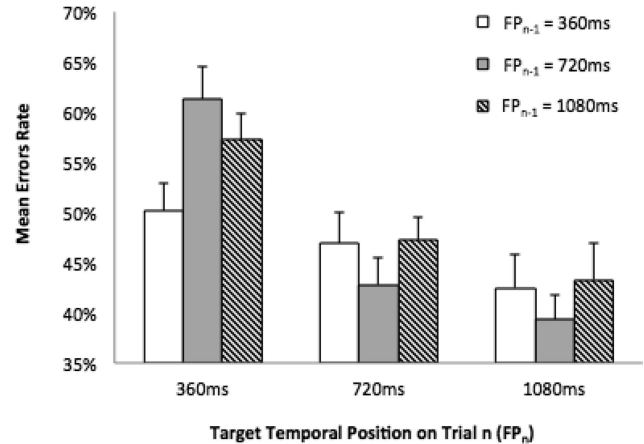


Figure 6. Mean error rates in Experiment 4. Temporal position priming (TPP) and sequential effect. Mean error rates for each target temporal position on trial n (FP_n) as a function of target temporal position on trial $n-1$ (FP_{n-1}). Error bars represent within-subject standard errors (Morey, 2008).

The results of this experiment show that TPP affects perceptual processes, as has been shown for other intertrial priming effects (e.g., PoP; Lamy et al., 2010; Yashar & Lamy, 2011; and dimension priming; Töllner et al., 2008), although it is important to note that they do not exclude the possibility that TPP may also affect response-related processes. In addition, the main effect of FP_n suggests that expectations regarding the time at which the target is most likely to appear also affect perceptual processes.

General Discussion

Summary of the Findings

We undertook this study with two open questions. First, we asked whether the TPP effect that we recently reported in RSVP search for a color singleton (Yashar & Lamy, 2010b) might in fact reflect the same mechanism as the well-documented sequential effect of FP (e.g., Los, 2010) and if so, whether this mechanism is best described as a repetition effect or as an asymmetric sequential effect. The results provide clear answers. We found that when the appropriate analyses were conducted, the asymmetric pattern that is characteristic of the sequential effect was observed in our RSVP search task (Experiment 1), suggesting that the two paradigms tap the same phenomenon. In addition, when we equated the conditional probabilities of target occurrence at all candidate temporal positions within a trial, the asymmetric pattern disappeared and the results conformed to what is expected from a temporal repetition effect (Experiment 2). We therefore suggest that the sequential effect reflects the joint influence of conditional probability of target occurrence and repetition of the target's temporal position.

Second, we asked whether this temporal repetition effect is related to perceptual or to response-related processes. We addressed two different aspects of this question: (1) We asked whether responding to the target with a motor response is necessary for the association that is critical for TPP to be formed. We found that TPP is observed even when no response is associated

with the target on the previous trial, which suggests that the learned association is tied to earlier responses, such as selecting the target and engaging attention in it. (2) We asked whether TPP affects perceptual processing of the target or only later, postperceptual processes. We found that when accuracy is measured with masked displays so as to tap only effects on perceptual processing, TPP is again observed.

Perceptual Versus Response-Related Mechanisms

Our results show that in the processing chain from input to response, both the conditional probability of target occurrence (which gives rise to the FP-RT function by modulating temporal uncertainty) and the repetition of the target's temporal position (or TPP) affect perceptual processes. The finding that variations in temporal uncertainty affect perception has been reported in earlier studies with regard to FP effects (e.g., Bausenhardt, Rolke, & Ulrich, 2007; Lasley & Cohn, 1981; Vangkilde, Coull, & Bundesen, 2012; Westheimer & Ley, 1996), temporal cuing effects (e.g., Correa, Lupianez, & Tudela, 2006; Martens & Johnson, 2005), and exogenous spatial cuing effects (i.e., transient shift of attention; Kristjánsson et al., 2010). However, the present study is the first report that sequential temporal effects also affect perception in a way that cannot be attributed to top-down expectations.

This finding is in line with previous research showing that other intertrial repetition priming effects affect perceptual stages of processing (e.g., Lamy et al., 2010; Sigurdardottir et al., 2008; Töllner et al., 2008; Yashar & Lamy, 2010a). As previous studies have demonstrated that intertrial priming also influences processes related to motor response selection/execution (e.g., Huang et al., 2004; Lamy et al., 2010; Yashar & Lamy, 2011), we speculate that it may also be the case for TPP, although the present study does not provide any direct evidence on this issue.

Determinants of the Sequential Effect

We have argued that the sequential effect is mainly determined by two separate factors: the conditional probability of target occurrence and TPP. These seem to provide a parsimonious account of the results of Experiments 1 and 4: On the one hand, RTs became faster as the FP became longer (and temporal uncertainty therefore became lower); on the other hand, a TPP effect was observed for early FPs and disappeared for the later FPs. We interpret this pattern as resulting from floor effects: TPP died out as soon as the FP effect reached its asymptote.

However, our results showed a singular pattern for the intermediate target position in Experiments 2 and 3, which cannot be readily explained by temporal uncertainty and TPP alone. When we eliminated within-trial variations of the conditional probability of target occurrence by using an exponential nonaging FP distribution (Experiment 2), TPP effects showed a V-shaped pattern: They were observed for the first and for the last FP, but not for the middle temporal position. This result does not appear to be spurious because Los and Agter (2005) also reported it under similar conditions. The same V-shaped pattern was observed in Experiment 3 despite the fact that we reverted to a uniform FP distribution, thus reinstating expectations that should have favored the latest target temporal positions.

What might account for the absence of TPP in the middle FP? Näätänen (1970) used a variable FP paradigm with a nonaging

distribution of the possible FPs and reported that RTs were fastest at the intermediate FP, an effect that he attributed to "increased expectancy in the middle of the foreperiod range" (p. 414),² or to the subjective distribution of FPs, which translates into "overrepresentation of the middle FPs in the range" (Niemi & Näätänen, 1981). Such increased expectancy for the middle FP may render the measurement of TPP less sensitive because of floor effects. Consistent with this possibility, RTs were indeed fastest for the middle position in Experiment 3, yet not in Experiment 2, in which it is noteworthy that by contrast with the results reported by Näätänen the RT slopes were positive rather than flat. Thus, although absence of TPP in the middle FP may be related to increased expectancy for this FP, further research is clearly needed to provide a full account for this finding.

Current Theoretical Accounts of the Sequential Effect

Our findings suggest that the TPP effect and the sequential effect reflect the same phenomenon. Three main models have been proposed to account for the sequential effect: the strategic view, the trace-conditioning view, and the dual-process view (see Los, 2010; Vallesi et al., 2007, for detailed descriptions). Although the objective of this study was not to test these models against each other, it should be useful to compare our account of the sequential effect with previous accounts.

According to the strategic view (e.g., Alegria, 1975; Baumeister & Joubert, 1969; Karlin, 1959; Thomas, 1967), a single mechanism underlies the FP-RT function and the sequential effect. Both the FP-RT function and the sequential effect are considered to be essentially related intentional preparation. The strategic view stipulates that observers intentionally prepare for the same FP as on the previous trial and maintain this preparation state if the FP on the current trial is longer than on the previous trial, which explains both the asymmetric pattern of the sequential effects as a function of FP and the FP-RT function.

The dual-process view put forward by Vallesi and colleagues (2007) also suggests that the FP-RT function and sequential effects reflect different mechanisms that can be dissociated. This account differs from the strategic view in that it proposes that the sequential effect itself is not intrinsically asymmetric: It interacts with temporal expectancy effects that account for the FP-RT function, and this interaction is responsible for the asymmetric pattern of the sequential effect that is typically observed. They based this conclusion on the finding that applying transcranial magnetic stimulation (TMS) pulses on the right dorsolateral prefrontal cortex both flattened the FP-RT function (i.e., eliminated the effects of temporal uncertainty on behavior) and revealed symmetric sequential effects: The shorter the FP on the previous trial, the faster the RTs

²Lamy (2005) reported a conceptually similar effect in a series of experiments investigating attentional capture. She showed that subjects are better able to resist attentional capture by an irrelevant cue when this cue appears at a fixed interval before the target, demonstrating the influence of temporal expectancies on attentional allocation. In addition and more important for the present purposes, she also showed that when the cue-to-target time interval varied randomly, attentional capture was observed for the shorter and for the longer intervals but not for the intermediate interval. This effect was not tied to a specific cue-to-target interval as it was replicated for the intermediate intervals of different time ranges. Lamy concluded that observers prepare for the middle interval.

they observed, irrespective of the FP on the current trial. They interpreted this result as reflecting higher arousal when the target had appeared earlier on the previous trial.

Finally, the trace-conditioning view (e.g., Los, 2010; Los & Van Den Heuvel, 2001) explains both the FP-RT function and the sequential effect in terms of classical conditioned learning. Each possible FP is associated with a certain conditioned strength, which is determined as follows: It is increased when the IS is responded to at that FP, decreased for possible FPs that elapse before the IS occurs (extinction), and does not change for FPs that come after response to the IS (persistence). The higher conditioned strength is, the shorter the RT to the IS. In its most recent version (e.g., Los, 2010; Los & Agter, 2005), the trace-conditioning model also stipulates that when some FPs are more frequent than others (i.e., when FP distribution is not uniform), an additional mechanism related to “temporal orienting” determines the sequential effect: Observers prepare for the most frequent FP in the distribution.

Comparison of the TPP Account With Current Models of the Sequential Effect

Our account shares several features with the existing models. Similar to the strategic view, we postulate that the sequential effect essentially reflects increased preparation for the same target position as on the previous trial. However, whereas the strategic model stipulates that the peak state of preparation reached when the FP is the same as on the previous trial is strategically controlled, we posit that TPP reflects the operation of short-term implicit memory, as do other repetition effects such as PoP (e.g., Maljkovic & Nakayama, 2000), although we have not directly addressed this issue here. This conjecture is in line with other evidence, reported by Los and Agter (2005), which challenges the notion that the sequential effect reflects intentional processes (see also Olson & Chun, 2001, for a demonstration of implicit effects of temporal context on attentional selection).

In addition, we do not invoke an additional mechanism of maintained preparation to explain the asymmetry of the sequential effect. Instead, we suggest that this asymmetry results from an interaction between a “pure” sequential effect and effects of conditional probability. However, our account differs from the dual-process account with regard to the mechanism that underlies this pure sequential effect. We describe it as an implicit STM effect that enhances processing of the target when it occurs at the same position on consecutive trials, whereas Valessi and colleagues (2007) propose that it reflects higher arousal levels on trials in which the target had appeared at an early versus a late temporal position on the previous trial. This divergence is a consequence of diverging findings. Our study and theirs used different procedures to eliminate FP-RT function negative acceleration: We used a nonaging function as in Experiment 2 (see also Los & Agter, 2005; Näätänen, 1970), whereas Vallesi et al. used TMS on the prefrontal cortex. We found RTs to be fastest when the target position repeated, whereas they found that RTs were fastest when the previous target position had been earliest, irrespective of the current FP. As these studies differed in many respects, further research is needed to integrate their findings into a common theoretical framework.

Finally, in line with the trace-conditioning view, we consider the sequential effect as an instance of implicit reward learning (see Nakayama & Martini, 2011, for a detailed argumentation of this idea with regard to other implicit intertrial priming effects). With Los (2010), we suggest that the conditioned strength associated with a candidate target temporal position increases when the target is presented (and attended) at that moment, which explains the temporal repetition effect. However, Los suggested that additional rules govern conditioned strength variations (namely, extinction and persistence) in order to account for the asymmetric pattern of sequential effects, which we explained by invoking an interaction with conditional probability effects.

Implications for Our Understanding of Time Encoding and Temporal Attention

The results from the present study suggest that the time at which selection occurs relative to a certain point of reference is encoded in STM. On subsequent events, such temporal memory traces facilitate attentional selection at the same relative point in time. This finding has several important implications for our understanding of how we encode time and direct our attention in time.

First, our findings imply that the passage of time can be accurately estimated and memorized, down to a resolution of fractions of a second. Although the neural structures that underlie the representations involved in repetitions effects pertaining to other object properties, such as location, color, orientation, or size, are well understood, there is no consensus as to what representations and mechanisms underlie our ability to measure time (see (Los, 2010; Nobre, Correa, & Coull, 2007). The characteristics of the temporal position priming effect described here may constrain models of time representations. For instance, although motor brain areas have been implicated in temporal prediction (see Nobre & Coull, 2010, for a review), our findings show effects of temporal encoding that are unrelated to motor processes, thereby suggesting that time must be represented in nonmotor areas. The robustness and simplicity of the TPP effect should make it a useful tool for investigating the neural underpinnings of time representation.

In particular, it can serve as a tool for understanding how representations of time and space interact during basic perceptual tasks. TPP can be considered as an analogue in the temporal domain of priming of location (PoL) in the spatial domain. In both cases, repetition of the attribute for which there is uncertainty (the time at which the target occurs in temporal search and the location of the target in spatial search) enhances perception. Moreover, both show cumulative effects over streaks of repetitions. Cognitive neuroscientists have suggested that the same brain and cognitive mechanisms underlie assessment of time, space, and magnitude (Walsh, 2003). We recently showed that PoL is contingent on temporal priming (Lechak, Yashar, Leber, & Lamy, 2012): Repetition of the target’s spatial position facilitated search only when its temporal position also repeated, but not vice versa. This finding suggests that for purposes of attentional allocation, temporal and spatial information interact and may be hierarchically organized (see also Kristjánsson et al., 2010).

Second, whereas previous studies have focused on the role of explicit, goal-directed temporal information in attentional guidance, our study underscores the role of implicit guidance of atten-

tion: We tend to engage our attention following the same “rhythm” as on previous events, despite no explicit incentive to do so. The present findings thereby provide additional evidence for the notion that our perceptual system seems to assume predictability even when there is none. Phenomena such as PoP, PoL, and TPP teach us that the default rule that our attentional system implicitly adopts is that any aspect that characterizes an object that has been recently found of interest and attended to should be more readily selected than other objects on a next encounter, even if in probabilistic terms, the repeated feature is no more likely than any of the other possible features to characterize the target. Such an implicit prediction mechanism may be implemented by associating a high motivational value to the characteristics defining the object of a successful search. This mechanism should be particularly useful in the temporal domain because, as we seem to have no specific organ that registers time, explicit information about the timing of events is usually unavailable.

Conclusion

Total randomness is rarely encountered in natural environments (see Nakayama & Martini, 2011, for a more detailed discussion) and repetitive or cyclical events are ubiquitous. Moreover, many basic tasks involve repetitive actions that we tend to perform following a certain rhythm—whether we pick berries from a bush or read a text. Thus, speculating on the functional role of the TPP effect, we suggest that our visual system takes advantage of the rhythmic nature of events and anticipates their timing to facilitate perception.

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