The Time-Event Correlation Effect Is Due to Temporal Expectancy, Not to Partial Transition Costs

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Humans are sensitive to temporal redundancies in their environment. When the identity of a target stimulus is correlated with the duration of the preceding interval, performance is better for frequent than for infrequent combinations of target and interval. This effect has been demonstrated several times in current timing research. However, it can be accounted for by 2 starkly contrasting explanations. The standard account has explained it in terms of learning associations between intervals and stimulus-response events. But, alternatively the effect might be due to partial trial transition costs, because infrequent time-event combinations are proportionally more often partial transitions (i.e., transitions of either interval, or target). We conducted 3 choice response time experiments to distinguish between both explanations. The results clearly show that the time-event correlation effect is due to learning, not to partial transition costs.

Keywords: temporal expectancy, time-event correlation effect, partial transition cost, feature binding, associative learning

Human behavior is to a large degree anticipative. A precondition of anticipative behavior is the formation of expectancy about predictable cognitive affordances. Based on such expectancies about future affordances, self-regulatory cognitive systems gain behavioral advantages by modulating themselves in a way that probable affordances are better processed than improbable ones (Gilbert & Wilson, 2007). Previous research on expectancy has distinguished between two main kinds of expectancy: event expectancy and time expectancy.

Event expectancy means anticipating *what* will happen, in the sense of estimating, based on the current situation, which perceptual, emotional, motivational, cognitive, motor, communicative, or control requirement will occur next. There is abundant empirical evidence that humans adapt with considerable speed and precision to the predictability of such requirements (e.g., Bubic, von Cramon, & Schubotz, 2010; Dreisbach & Haider, 2006; Posner, 1980; see Figure 1a).

Time expectancy, on the other hand, means expecting *when* something will happen, in the sense of adapting to the predictability of delays in interacting with the environment. The formation of time expectancy has been intensely investigated since the early times of cognitive psychology (cf. Lejeune & Wearden, 2009; Martius, 1891; Moore, 1904; cf. Surprenant & Neath, 1997; Vierordt, 1868), and currently receives ever-growing research interest (e.g., Coull, 2009; Coull, Frith, Büchel, & Nobre, 2000; Lange, 2009; Lange, Rösler, & Röder, 2003; Los & Horoufchin, 2011;

Steinborn & Langner, 2011). There is converging evidence that humans are highly sensitive to the distribution and probability of delays in their environment. When the length of the current delay in an interaction is predictable, processing capacities are scheduled to be optimally prepared after the most likely delay duration (Correa, Lupiáñez, Milliken, & Tudela, 2004; Kingstone, 1992; Seibold, Bausenhart, Rolke, & Ulrich, 2011; Seibold, Fiedler, & Rolke, 2011; see Figure 1b).

Previous theorizing on event expectancy and on time expectancy has sought to explain both phenomena by different functional cognitive models (e.g., Kok, Rahnev, Jehee, Lau, & de Lange, 2012; Simen, Balci, de Souza, Cohen, & Holmes, 2011). Likewise, empirical research has identified distinct functional neural networks for event expectancy and time expectancy (Davranche, Nazarian, Vidal, & Coull, 2011; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Hsu, Hamalainen, & Waszak, 2013).

However, during the last 4 years an integrative view of both kinds of expectancy (i.e., time based and event based) has emerged (Schröter, Birngruber, Bratzke, Miller, & Ulrich, 2014; Thomaschke & Dreisbach, 2013; Wagener & Hoffmann, 2010b; Wendt & Kiesel, 2011). There is accumulating evidence that both kinds of expectancy are inherently linked and heavily interact to enable humans to adapt to predictable environments. When, for example, launching a print job to our network printer, I am expecting paper in the output tray only after the typical response delay of the printer. When that interval has elapsed, I am expecting an error message, asking me to refill the printer with paper. Thus, event and time are not expected as such, but instead combinations of both (early paper output, *or* late error message).

This type of combined expectancy—mutually conditional expectancy of event and time—can be referred to as *time-event expectancy* (see Figure 1c). It has been claimed that
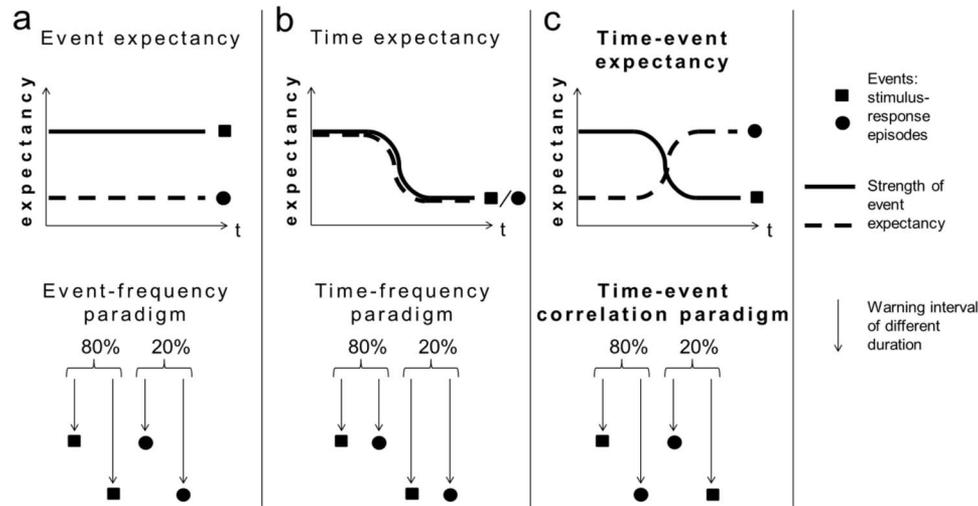
Figure 1. Schematic illustration of three types of expectancy with generating paradigms. The top panels show the strength of expectancy for two different stimulus-response events in dependence of time (measured from a noninformative warning cue, i.e., during the warning interval). The bottom panels show for each type of expectancy a typical behavioral paradigm which induced the respective expectancy. (a) Event expectancy refers to expecting one event more than the other, irrespective of their time of occurrence. It can be induced by presenting one target more often than the other (e.g., Hyman, 1953). (b) Time expectancy refers to expecting one time of occurrence (here the short interval) more than another, irrespective of the occurring event. It can be induced by presenting one warning interval more often than another (e.g., Zahn & Rosenthal, 1966). (c) Time-event expectancy refers to expecting events conditional upon times. It can be induced by presenting some combinations of interval and event more often than others (e.g., Wagener & Hoffmann, 2010b).

time-event expectancy is a fundamental principle of temporal cognition, because in most interactions with the environment the passage of time is informative about which event to expect (Thomaschke, Wagener, Kiesel, & Hoffmann, 2011b). There is growing evidence that humans do indeed automatically and precisely adapt to the predictability of time-event combinations. For instance, the duration of pauses in speech induces expectancies about the complexity (Watanabe, Hirose, Den, & Minematsu, 2008) or valence (Roberts & Francis, 2013; Roberts, Margutti, & Takano, 2011) of the following expression (see also MacGregor, Corley, & Donaldson, 2010), and computer users predict system responses based on preceding system delays (Shahar, Meyer, Hildebrandt, & Rafaely, 2012; Thomaschke & Haering, 2014). It is, however, not clear yet how previous theories, which model time expectancy and event expectancy as distinct systems, can account for this phenomenon.

Only recently some groups of researchers have attempted to investigate the functional principles and the underlying cognitive mechanism of time-event expectancy (Thomaschke, Kiesel, & Hoffmann, 2011; Wagener & Hoffmann, 2010b; Wendt & Kiesel, 2011). However, all previous studies on time-event expectancy have applied the same basic paradigm: the time-event correlation paradigm, first introduced by Wagener and Hoffmann (2010b). Participants give speeded responses to one of two possible target stimuli, preceded by one of two intervals. One target appears often after the long interval, the other one after the short interval. Participants are generally faster for frequent time-event combinations than for infrequent ones.

In all of these studies it has been taken for granted that findings with the time-event correlation paradigm provide direct evidence about time-event expectancy. Here, we question this view, in an initial argument step, by showing that all previous results from the time-event correlation paradigm can alternatively be interpreted as stemming from a process very different from any type of expectancy, namely partial trial transition costs. After explicating this perspective, we offer three experiments that allow us to distinguish clearly between both views of the time-event correlation paradigm. In the remainder of this introduction we will first describe in detail the time-event correlation paradigm. Second, we show how typical findings with this paradigm can be explained by partial trial transition costs. Third, we explicate the standard explanation in terms of time-event expectancy. Fourth, we juxtapose both accounts with regard to empirical predictions. Finally, we introduce the present experiments and explain how they can distinguish between these accounts.

Time-Event Correlation

Humans are highly sensitive to the frequency of events. This has been demonstrated abundantly for nontemporal, as well as for temporal aspects of events. With regard to nontemporal event frequency, Hyman (1953, Experiment 2, Conditions 3 and 4) showed that in binary choice response tasks with unbalanced stimulus probability, participants respond faster to the more frequent stimulus (see also, Broadbent & Gregory, 1965; Grossman, 1953; LaBerge & Tweedy, 1964; see Figure 1a).

The effects of temporal frequency on performance have typically been investigated by experiments with warning intervals[1] preceding target stimuli in simple or choice response tasks. The intervals vary in duration from trial to trial. Participants are sensitive to differences in the overall frequency of intervals (Della Valle, 1908; Los, Knol, & Boers, 2001; Schupp & Schlier, 1972). In particular, when one of two intervals occurs substantially more frequently than the other one, responses after the frequent one are faster (see Zahn & Rosenthal, 1966; for related findings see also Baumeister & Joubert, 1969; Bevan, Hardesty, & Avant, 1965; see Figure 1b).

Wagener and Hoffmann (2010b) recently introduced a new paradigm that manipulates the frequency of event-time *combinations*. In a speeded choice response task, they paired two target stimuli with preceding intervals of two different durations (600 ms and 1,400 ms). One of the stimuli occurred four times more often after the short duration than after the long duration. The other one was four times more likely after the long duration than after the short duration. Participants adapted to this regularity: Responses were faster and more accurate after the frequent than after the infrequent combinations of stimulus and warning interval duration. Wagener and Hoffmann interpreted this finding as evidence for time-event expectancy. They proposed that participants learned the associations between interval duration and stimulus, and scheduled their expectancy accordingly. Participants expected each stimulus after the interval that often preceded it in the past, and consequently responded faster and more correctly when this expectancy was met than when it was violated.

Note that the experimental design precluded expectancy for stimulus-response events as such, as well as for interval durations as such, because both stimuli appeared overall equally often, and both intervals occurred overall equally often. Only combinations of event and time differed in frequency and were thus predictable.

The paradigm introduced by Wagener and Hoffmann can be referred to as the time-event correlation paradigm, because the essential manipulation can be described as a correlation between the stimulus-response events and the interval durations. Since the introduction of the paradigm, the basic results have been replicated several times and different variations have been developed (Thomaschke, Kiesel et al., 2011; Thomaschke, Wagener, Kiesel, & Hoffmann, 2011a; Thomaschke, Wagener, et al., 2011b; Wagener & Hoffmann, 2010a; Wendt & Kiesel, 2011). Thomaschke, Wagener et al. (2011a, 2011b) used a version with a larger range of intervals. In this version, two intervals are strongly correlated with different stimuli, but at 13 other intervals both stimuli appear equally often. Thomaschke and Dreisbach (2013) and Thomaschke, Kiesel et al. (2011) employed versions of the time-event correlation paradigm which involved correlations between interval duration and only one particular aspect of a stimulus-response event (i.e., response or stimulus). Furthermore, Wendt and Kiesel (2011) manipulated the correlation between the duration of a warning interval and distractor interference. The typical finding in all those studies was that responses were significantly faster for frequent than for infrequent combinations of interval duration and aspects of an event. The same pattern was observed for error rates in most of the studies (Thomaschke, Kiesel, et al., 2011; Thomaschke, Wagener, et al., 2011a, 2011b; Wagener & Hoffmann, 2010b), except the studies by Thomaschke and Dreisbach (2013),

and by Wendt and Kiesel (2011) which showed no significant effect for error rates.

In the next sections, it will become clear that the improved performance for frequent relative to infrequent combinations in the time-event correlation paradigm can be explained in two fundamentally different ways, one drawing on binding and partial trial transition costs, and the other one drawing on time-event expectancies.

Partial Transition Costs

Binding. Many prominent theories in the areas of object perception and action control make the assumption that during the processing of perceptual and motor events the features of these events become temporarily connected via a *binding* process (Hommel, 2009; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Treisman, 1996). The connected features involve perceptual aspects of an object (Kahneman, Treisman, & Gibbs, 1992), motor features of actions (Bub, Masson, & Lin, 2013; Mattson & Fournier, 2008; Stoet & Hommel, 1999), perceptual features of anticipated action goals or action effects (James & Gauthier, 2009; Janczyk, Heinemann, & Pfister, 2012; Thomaschke, Hopkins, & Miall, 2012a), valences of actions (Eder & Klauer, 2007, 2009; Eder, Müsseler, & Hommel, 2012), as well as whether an action is successful or not (Hommel & Keizer, 2012). Cognitive theories have ascribed several functional roles to feature binding. One function is stabilizing a selected action plan in order to secure a coherent execution (Thomaschke, Hopkins, & Miall, 2012b). Another function might be to shield the features involved in a percept or an action plan from interference by competing cognitive processes (see Thomaschke, 2012 for a review). Furthermore, binding features might play a role in generating a unified conscious experience of an object, an action, or an action's goal (Zmigrod & Hommel, 2011).

A prominent and abundantly demonstrated consequence of binding is a behavioral pattern called *partial repetition costs*. Partial repetition costs stem from the inertness of feature binding over consecutive trials. Feature bindings evoked in one trial leave traces in the cognitive system, which affect binding in the following trial. These effects strongly depend on whether features are repeated or alternated in the current trial. If, for example, only one of two features is repeated from the previous trial, performance is usually worse than when both features are repeated (Kahneman et al., 1992), or if both features change (Hommel, 1998). We refer to trials where only one of two features changes, as *partial* transitions, and to trials where either both features change or both features repeat as *complete* transitions. From now on we refer to the former case as *partial* trial transition, and to the latter couple of cases as *complete* trial transitions. The performance benefits of complete transitions over partial ones are usually interpreted as stemming from the inertness of bindings (Colzato et al., 2012; Colzato, Zmigrod, & Hommel, in press; Dreisbach, Goschke, & Haider, 2006). When both features are repeated, the binding from the previous trial still persists to a degree in the following trial and can simply be renewed. Consequently, no interference between trials occurs. But, when only one of the features is repeated, this

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[1] Warning intervals are sometimes referred to as foreperiods (Niemi & Näätänen, 1981), or preparatory intervals (Zahn & Rosenthal, 1966).

feature needs to be released from the previous binding before it can be integrated into the present binding. This leads to an increase of error rate and response latency in the current trial. When, however, both features change, the new binding can also be established without any interference from the previous trial, because none of the features have to be released from previous bindings. Thus, the performance difference between complete and partial transitions is due to interference effects in partial transitions, not to benefits in complete transitions. Consequently, the effect is commonly referred to as partial repetition cost (e.g., Colzato & Hommel, 2008; Hommel, Kray, & Lindenberger, 2011; Zmigrod & Hommel, in press).

Binding time. Partial repetition costs have been demonstrated for various pairs of event features. They are present for auditory features (Zmigrod & Hommel, 2009), for visual features, for features from different modalities (Zmigrod, Spapé, & Hommel, 2009), and pairs of response and stimulus features (Colzato, Warrens, & Hommel, 2006; Dreisbach & Haider, 2008; Dreisbach & Wenke, 2011; Henson, Eckstein, Waszak, Frings, & Horner, 2014; Hommel, 1998; Zmigrod, de Sonneville, Colzato, Swaab, & Hommel, 2013). The time of occurrence of a stimulus or of a response has, however, not yet been demonstrated to be bound to other features. To our knowledge, no previous study has explicitly investigated this issue.

The potential of a point in time, or a temporal interval, to be bound with other features of an event is, however, pivotal to our explanation of the time-event correlation effect via trial transitions. Despite the lack of an explicit demonstration, there seems to be no a priori reason against the binding of time. Binding seems to be a universal principle of visuomotor cognition applying to almost every aspect of a stimulus-response episode; and its location in time (i.e., the duration of a preceding interval from a time marker) is an essential feature of an object or an action. Binding the time of their occurrence to other object or action features could be used to estimate their duration, or might assist temporal order judgments (e.g., Battelli, Pascual-Leone, & Cavanagh, 2007). We will come back to this issue in the General Discussion section.

Transition proportions. If time intervals are bound to targets in time-event correlation paradigms, the repeatedly observed time-event correlation effect could be explained without reference to any long-time learning or expectancy mechanism. In the time-event correlation paradigm stimulus-response events and intervals randomly vary from trial to trial (see above). Consequently, the paradigm involves trials with complete transitions, where event and interval are both alternated or are both repeated; but it also involves partial transitions, where either only the interval changes, or only the event changes (see Figure 2). Importantly for the current issue, partial and complete transitions are *not* distributed evenly over frequent and infrequent time-event combinations.

Specifically, in the time-event correlation paradigm there are two frequent and two infrequent combinations. The frequent combinations are typically overall four times as likely as the infrequent ones (e.g., Thomaschke, Wagener, et al., 2011a; Wagener & Hoffmann, 2010b). This means, when there is a frequent combination on trial n, it is only a complete transition when the combination on trial n-1 was also a frequent one. Consequently, frequent combinations are complete transitions with a probability of .8. When, on the other hand, trial n is an infrequent combination, it is a complete transition only when trial n-1 also was an
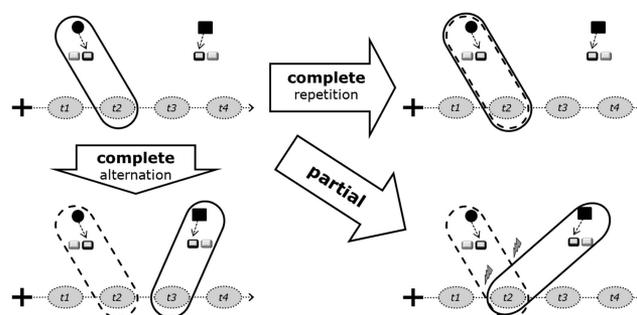
Figure 2. Binding effects in different types of trial transitions in the time-event correlation paradigm. Gray dotted ovals represent different points in time after onset of the fixation cross (labeled t1 to t4). The possible stimulus-response events are right key-presses to a circle or left presses to a square. Solid ovals represent the binding in the current trial. Broken ovals represent traces from the binding in the previous trial. In the example, a trial with the circle appearing at t2 (top left) is followed by three different types of trial transitions; two complete transitions (top right and bottom left), and one partial transition (bottom right). In the latter condition bindings interfere, because the representation of the repeated time of occurrence has to be released from the old stimulus-response event in order to be bound to the new one (lightening symbols).

infrequent combination. Consequently, infrequent combinations are complete transitions with a probability of .2.

Obviously, these proportions directly predict the time-event correlation effect: Performance in complete transitions is better than in partial transitions, and frequent combinations include 80% complete transitions, while infrequent combinations include only 20% complete transitions. Consequently, when averaging over transition types, performance in frequent combinations is better than performance in infrequent trials. Note that under this assumption, participants do not learn anything during the experiment. Frequent and infrequent trials are processed essentially in the same way throughout the experiment, and participants do not form any long-term expectancy concerning the next trial. Performance from this binding perspective would exclusively depend on the type of transition from the immediately preceding trial.

Specific Temporal Expectancy

The alternative and currently prevalent explanation of the time-event correlation effect assumes that participants build, throughout the experiment, temporally specific event expectancies. That means they learn to expect the occurrence of individual cognitive requirements specifically after those intervals these requirements frequently occurred after in the past. Expectancy selectively facilitates cognitive processing. Consequently participants' performance is superior when their expectancies are met (i.e., in trials with frequent combinations of interval and event), compared with when their expectancies are violated (i.e., in trials with infrequent combinations of interval and event; Thomaschke & Dreisbach, 2013; Thomaschke, Kunchulia, & Dreisbach, 2014; Wagener & Hoffmann, 2010b; Wendt & Kiesel, 2011).

The formulations of this account in previous sources have, however, been relatively vague or implicit, relative to our formulation of the binding account above (see Partial Transition Costs). It has not been specified yet what it means to "build specific

temporal expectancies," and how this can cognitively be achieved. In order to derive clear empirical predictions from the specific temporal expectancy account, we propose a simple model that shows explicitly how the time-event correlation effect can be predicted from specific temporal expectancy.

To this end, we break down the basic assumptions of the temporal expectancy account into a rudimentary working model. The model predicts empirically testable hypotheses that are in clear contradiction with predictions from the binding account.

The model. We assume that potential time markers (e.g., salient events, or own actions) trigger a temporally stable cascade of successive neural activation states. These activation states can be seen as "clock ticks," and we refer to them as *temporal states*. These temporal states have adjustably weighted connections to events which can be adapted by conditioning processes (see Figure 3). This basic architecture stems from a temporal conditioning model by Machado (1997). Machado's model has been used previously to explain how animals learn associations between intervals and behavior (Machado & Keen, 1999; Machado, Malheiro, & Erlhagen, 2009; Maia & Machado, 2009; Pinheiro de Carvalho & Machado, 2012). However, the dependent measures in those animal learning studies were response rates, not response time as in the time-event correlation paradigm.

Los, Knol and Boers (2001) adapted Machado's model for reaction time (RT) studies with human subjects. In their versions of the model, temporal states are associated with expectancy for cognitive processing,[2] and can, thus, shorten response time to stimuli after expected intervals (Los, 1996; Los & Heslenfeld, 2005; Steinborn & Langner, 2012; Steinborn, Rolke, Bratzke, & Ulrich, 2008, 2009, 2010). Los et al.'s version of the model has, however, only been applied to cases of time expectancy, where interval duration was *not* informative about the type of the upcoming event (see, however, Los, Kruijne, & Meeter, 2014, for a recent alternative model that would apply to time-event correlation designs).

We propose that a combination of Machado's and Los et al.'s accounts of temporal associative learning can serve as a cognitive foundation of specific temporal expectancy in humans, and can thus explain the time-event correlation effect. Specifically, we assume that the onset of the warning interval in the time-event correlation paradigm triggers a cascade of temporal states. We further assume that these temporal states project by adjustably weighted connections to expectancy-generating neural populations (as in the model by Los et al., 2001). These expectancy-generating populations are specific for individual cognitive events (as in the model by Machado, 1997), like for example translating a square stimulus into a left key press (see Footnote 2). Time-event associations are learned by a conditioning process. When a particular cognitive requirement occurs shortly after a certain temporal state has been passed, the connection between this temporal state and the neural population generating expectancy for this requirement is strengthened. Connections from this temporal state to other expectancy-generating populations are weakened at the same time. After some learning with time-event correlations, this should have the effect that traversing through the temporal states selectively activates event expectancies shortly before the moments the respective events have frequently occurred at in the past. As increased expectancy leads to selectively improved performance for processing the expected event, this would explain the time-event correlation effect.

Previous formulations of the cited models involved a precise quantitative description of the dynamic spread of activation through temporal states, as well as of the conditioning rules. Resulting quantitative predictions have successively been fitted to animal (Machado et al., 2009) and human (Los et al., 2001) experimental data. For the present purpose, however, a qualitative version is sufficient. It allows the specific temporal expectancy view to be contrasted with the trial transition view of the time-event correlation effect, because it is possible to derive qualitative predictions form the model, which are in direct opposition to the predictions of the trial transition account.

Binding, Expectancy, and the Time-Event Correlation Effect

The trial transition account and the specific temporal expectancy account explain the time-event correlation effect in very different ways. The former account ascribes the effect exclusively to differences in the processing of trial types, which are stable and inherent in the cognitive system's way of processing stimuli and responses. The latter account, on the contrary, claims that partic-
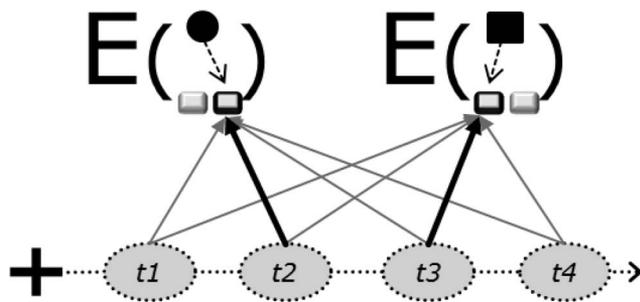
Figure 3. Illustration of the temporal expectancy model. Time markers (gray dotted ovals) have weighted associations (arrows) with expectancy-generating systems for both stimulus-response events. In the example, time point t2 is associated with expectancy for pressing the right key to a circle, and t3 is associated with pressing a left key to a square (thick arrows).

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[2] With "expectancy" we refer to a transient modulation of the cognitive system that leads to expected events being processed better than unexpected events. This meaning of expectancy included modulations of the perceptual system as well as modulations of the motor system (in the sense of expecting a response). This definition of expectancy is considerably broader than the term's use in some other areas of cognitive psychology. In perceptual science, for instance, expectancy refers—in contrast to "attention"—only to nonaction-relevant modulations of the system (Kok et al., 2012; Summerfield & Egner, 2009). In the older literature on temporal adaptation, expectancy had been used selectively for modulations of the perceptual system, in order to distinguish it from motor preparation (e.g., Mo & George, 1977; Thomas, 1974). For specific temporal expectancy, however, it is still under debate whether the effect is due to a perceptual or to a motor modulation. Both versions would be compatible with the specific temporal expectancy account as well as with the partial transition account. Consequently, we use the term expectancy here in a way that is neutral with regard to the perceptual/motor issue. This usage is in line with the current literature on temporal cognition, where expectancy, attention, and preparation are used in a mutually exchangeable way (see Los, 2010, for a discussion of this terminological development).

ipants acquire the behavioral pattern by an adaptive process throughout the experiment.

The purpose of the present study is to determine the contribution of partial transition costs and of time-event expectancy to the time-event correlation effect, by two means. First, we conduct classical time-event correlation experiments, but analyze the findings in a more fine-grained fashion. In contrast to the analyses applied in previous studies, our analysis will include not only the factor *frequency* of time-event combination, but also the factor *type* of transition (full vs. partial), allowing us to investigate the contribution of partial transition costs. We refer to this initial part of each experiment as the *acquisition phase*.

Second, we will introduce, following to the acquisition phase, a *transfer phase* with changed time-event correlations, in order to test whether potential learned time-event associations would transfer between experimental phases. A similar experimental logic in terms of transfer of learning has previously been employed in studies on visual attention (Rieth & Huber, 2013) and cognitive control processes (Torres-Quesada, Funes, & Lupiáñez, 2013). Rieth and Huber (2013), for instance, have trained participants on a deterministic analogue to the time-event correlation paradigm (i.e., the correlation was 100%) and have shown that learning was still effective when the correlation was abandoned.

Hypotheses. For the acquisition phase, the binding account would predict only a main effect for the type of transition, reflecting partial transition costs. The temporal expectancy account, on the other hand, would predict only a main effect of frequency of time-event combination.

With regard to the transfer phase, a binding account would predict that the time-event correlation effect cannot be affected by a previous experimental phase, because it is independent of any long-term learning. From the perspective of the binding account, the terms "acquisition phase" and "transfer phase" are actually misnomers, because no knowledge is acquired or transferred according to this account. An account in terms of specific temporal expectancy, on the other hand, would predict that performance in the transfer phase is affected by the time-event correlation learned in the preceding acquisition phase.

Experiment 1

Overview

The experiment consisted of two experimental phases. In an initial *acquisition* phase, we exposed participants to a classical time-event correlation paradigm. We analyzed results from this phase in a way that is sensitive to expectancy and to binding effects. In a following *transfer* phase, the correlation was abolished. For the test phase, the expectancy account predicts that performance is—at least in the beginning of the test phase—still better for the formerly frequent combinations of interval and target than for the formerly infrequent combinations. According to the binding account the time-event correlation effect should immediately disappear at the transition to the transfer phase, because according to this account it is independent of any learning.

Method

Participants. In this and all following experiments, participants were students of the University of Regensburg. They received course credit or 8 € for participation. Participants had normal or corrected to normal vision. In Experiment 1, 20 participants were tested. One participant was male, 19 were female. Their mean age was 22.70, $SD = 2.41$.

Apparatus and stimuli. Participants were sitting in a dimly lit room facing a computer screen (19" diagonal) at a viewing distance of approximately 50 cm. Responses were collected via the "y" and "m" keys of a standard QWERTZ keyboard, positioned centrally on the table in front of the participants. The experiment was run by the program E-Prime (Schneider, Eschman, & Zuccolotto, 2002), Version 2.

Target stimuli were a black filled square and a circle, measuring 1.5 cm $\times$ 1.5 cm, presented against a white background. The warning stimulus was the plus sign (font "Arial"), measuring 1 cm $\times$ 1 cm. Error messages were displayed in red. The background color was white throughout the entire experiment.

Procedure.

Trial. Each trial started with the presentation of the fixation cross. The fixation cross remained on the screen during the warning interval. The warning interval was either 600 ms or 1,800 ms long. After the warning interval, the fixation cross was substituted by the target stimulus. The participant had to respond to the target stimulus with a key press as fast and accurately as possible. After a variable intertrial interval, the next trial started with the next fixation cross. The intertrial intervals were randomly drawn from the following set of durations: 250 ms, 450 ms, 650 ms, 850 ms, 1,050 ms, and 1,250 ms.

Targets were assigned to keys according to a fixed mapping. The mapping was counterbalanced across participants. When participants responded too early (i.e., during the warning interval), too late (i.e., after 1,000 ms), or wrongly an appropriate error message appeared for 3 s.

Block. Each target and each interval appeared in half of the trials in a given block. Both targets were paired with both warning intervals, but, unbeknownst to participants, pairings differed in frequency in some of the blocks. The different interval-target combinations were presented in random order, so that participants could expect combinations only based on their frequency. In total there were 160 trials per block. After each block, participants had the opportunity to take a self-paced pause.

Full procedure. Participants received written instructions on the screen. They were not informed about the function of the warning intervals or about the purpose of the experiment. They were informed that there were five blocks in the experiment, but they were not informed that these blocks belonged to different experimental phases. Before beginning with the experiment they gave informed consent. Participants were instructed to respond as fast and accurately as possible.

The experiment started with an acquisition phase lasting for three blocks. In the acquisition phase, one of the targets was paired with the short (600 ms) warning interval in 80% of its occurrences. The other target was paired with the long (1,800 ms) interval in 80% of its occurrences.

In two further blocks, the correlation between warning interval and target was abolished. This means that each target occurred equally often after each of the intervals. Participants did not know that there were different phases in the experiment.

After completing the blocks, participants completed a postexperimental questionnaire, asking whether they had detected any regularity

during the procedure. In total, the experiments lasted for 40 min. Participants were debriefed after completing the questionnaire.

Data screening and analysis. The first block was considered practice, and, hence, excluded from analysis. The first two trials of each block might have been affected by restarting after the interblock pause, and have, consequently, also been excluded. We further excluded trials following errors. Error trials have been excluded from analyses of RTs. We accounted for outliers by ignoring trials with RTs more than three SDs away from their condition mean for each combination of block, frequency, type of transition, and participant (Bush, Hess, & Wolford, 1993). Collapsed over all experiments there were 1.25% outliers.

For direct estimations of the frequency effect in different conditions we provide, along with the reliability statistics, two versions of Cohen's d (see Figures 4 to 6). d_{BET} refers to the design independent effect size (Dunlap, Cortina, Vaslow, & Burke, 1996), which allows Cohen's small/medium/large classification to be applied (Cohen, 1977). d_{WIT} is corrected for subject variance (Gibbons, Hedeker, & Davis, 1993), and allows, thus, more precise comparisons with results from previous time-event correlation studies by potential meta-analyses. Both effect sizes have been bias corrected according to Hedges (1981) and Gibbons et al. (1993).

Results

Acquisition phase. With regard to the acquisition phase we calculated mean error rates and RTs for each combination of the factors' type of transition (complete vs. partial) and frequency (frequent vs. infrequent, see Figure 4).

Response times. As expected, a time-event correlation effect was observed in the acquisition blocks. Participants responded faster to frequent combinations of interval and target, $M = 397.50$, $SD = 43.74$, than to infrequent combinations, $M = 393.59$, $SD = 44.94$, $t(19) = 3.966$, $p = .001$, $d_{WIT} = 0.851$, $d_{BET} = 0.311$.

The 2×2 repeated measures ANOVA with the factors type of transition (complete vs. partial) and frequency of combination (frequent vs. infrequent) yielded no main effect for type of transition, $F(1,$ 19$) < .001$, $p = .989$, $\eta_p^2 < .001$, but a main effect for frequency of combination, $F(1, 19) = 12.189$, $p = .002$, $\eta_p^2 = .391$. The interaction was not significant, $F(1, 19) = 2.671$, $p = .119$, $\eta_p^2 = .123$ (see the Appendix for a more detailed analysis of the data).

Error rates. With regard to error rates participants did not respond significantly more correctly after frequent, $M = 1.722\%$, $SD = 1.18$, than after infrequent, $M = 2.315\%$, $SD = 3.28$, combinations of interval and stimulus, $t(19) = 0.993$, $p = .333$, $d_{WIT} = 0.213$, $d_{BET} = 0.182$. Despite that, we ran an ANOVA with the factors type of transition and frequency of combination, in order to check for potential speed–accuracy trade-off explanations for the RT results. No effect attained significance, $F < 2.697$, $p > 117$.

Transfer phase. We conducted 2×2 ANOVAs with the factors former frequency (formerly frequent vs. formerly infrequent) and block (4 and 5). The factor block was included to assess the stability of a potential transfer effect (see Figure 4).

Response times. The factor former frequency was marginally significant, $F(1, 19) = 3.534$, $p = .076$, $\eta_p^2 = .157$, with responses for formerly frequent combinations, $M = 371.64$, $SD = 42.79$, being faster than for formerly infrequent combinations, $M = 377.21$, $SD = 41.29$. The effect of block was not significant, $F(1, 19) = 1.453$, $p = .243$, $\eta_p^2 = .071$, and did not interact with frequency, $F(1, 19) = .060$, $p = .810$, $\eta_p^2 = .003$.

Errors. No main effect or interaction approached significance; all $F < 1$, all $p > .7$.

Postexperimental questionnaire. According to the postexperimental questionnaire, none of the participants recognized the time-event correlation in the experiment.

Discussion

Results from the acquisition and from the transfer phase clearly speak in favor of an expectancy based explanation of the time-event correlation effect. The expectancy explanation predicted a main effect for frequency of combination in the acquisition phase and a main effect for former frequency of combination in the transfer phase. Both predictions have been confirmed, with how-
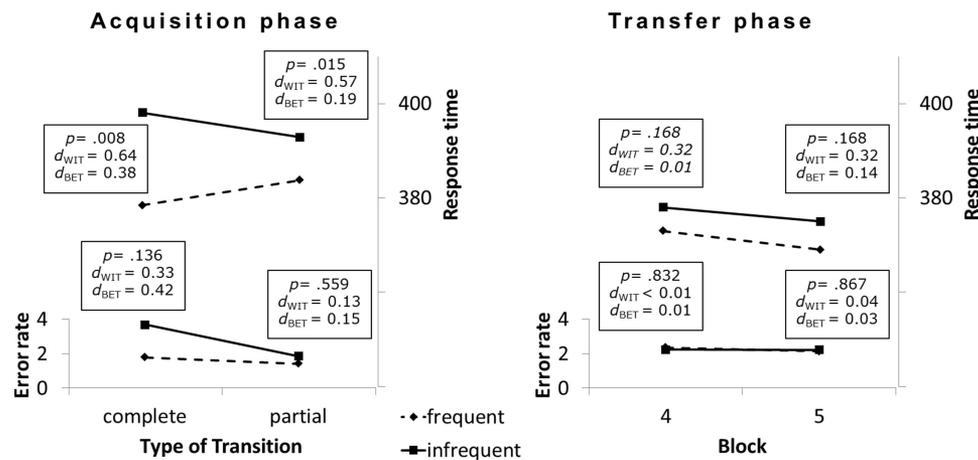
Figure 4. Mean response times and error rates for Experiment 1. Boxes refer to the significance and effect magnitudes of within subjects *t* tests for frequency of combination. For the left panel the lines refer to the current frequency of the time-event combination. For the right panel the lines refer to the former frequency of the time-event combination.

Acquisition phase

Transfer phase
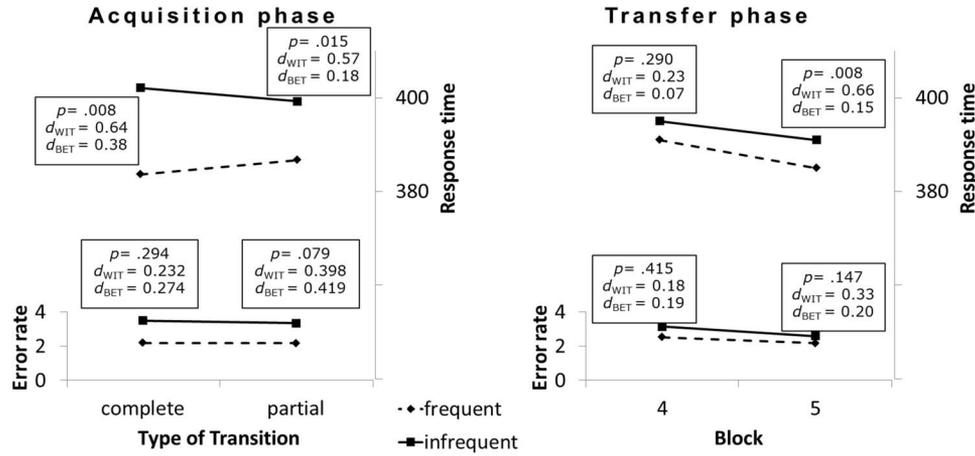
Figure 5. Mean error rates and response times for Experiment 2. The boxes show the significance and effect magnitudes of within subjects *t* tests for Frequency of combination. For the left panel the lines refer to the current frequency of the time-event combination. For the right panel the lines refer to the former frequency of the time-event combination.

ever, the main effect in the transfer phase being only marginally significant. We did not observe any effects for expectancy or binding in error rates. This is in line with previous studies in specific temporal expectancy (Thomaschke & Dreisbach, 2013; Thomaschke & Haering, 2014).

We did not observe any evidence for the binding account of the time-event correlation effect. This account would have predicted slower response times in partial transitions than in full transitions. This difference was not significant. Responses for full changes were even slower than responses for partial changes (see Appendix for a more detailed transition-specific analysis).

Experiment 2

Results from Experiment 1 have provided clear evidence for specific temporal expectancy and against binding in the time-event correlation effect. These findings could, however, have

been confounded by an aspect of the design which might seem negligible on first view. Following some of our earlier experiments with the time-event correlation paradigm (e.g., Thomaschke & Dreisbach, 2013), we chose the intertrial intervals to be variable in this initial experiment. Many previous studies with the time-event correlation paradigm have, however, applied constant intertrial intervals (Thomaschke, Kiesel, et al., 2011; Thomaschke, Wagener, et al., 2011a, 2011b; Wagener & Hoffmann, 2010b; Wendt & Kiesel, 2011).This difference might constrain the generalizability of our results, because temporal expectancy as well as binding is known to be sensitive to intertrial intervals.

With regard to general temporal expectancy Los and Schut (2008) showed that participants tend to form expectancies already during the intertrial intervals in cases where the warning interval is short (see also Bertelson, 1967). Effects from trial

Acquisition phase

Transfer phase
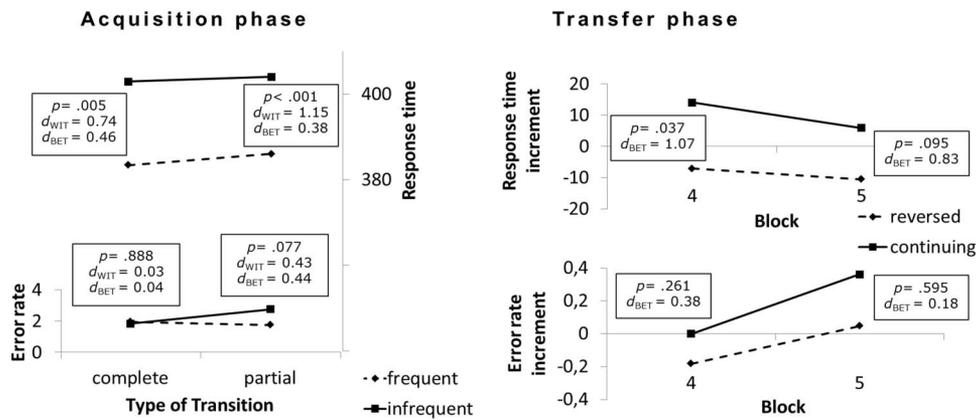
Figure 6. Mean error rates and response times for Experiment 3. In the left panel, the boxes show the significance and effect magnitudes of within-subjects *t* tests for frequency of combination. In the right panel the boxes refer to significance and effect magnitude of between-subjects *t* tests comparing the overall error/response time increment relative to the acquisition phase.

transitions are also sensitive to the duration of intertrial intervals. With relatively short intertrial intervals participants tend to expect repetitions rather than alternations (Bertelson, 1965; Rabbitt, 1968). But they develop a tendency away from response repetition toward response alternation when intertrial intervals are long (Kirby, 1980; Soetens, 1998; Soetens, Boer, & Hueting, 1985).

Importantly in the current context, the magnitude of partial transition costs can also be substantially affected by the duration of the intertrial interval (Kleinsorge, 1999, Experiment 2). Hommel and Colzato (2004) and Zmigrod and Hommel (2010) showed that binding effects decline, but do not completely vanish, when the intertrial interval is lengthened from 500 ms to 4,000 ms.

The variability of intertrial intervals in the present study included interval durations considerably longer (i.e., up to 1,250 ms) than the usual constant intervals from previous studies ($\approx$ 500 ms). One might argue that the inclusion of relatively long intertrial intervals in the present study could have impaired and abolished the binding process as such. In this case it would be possible that the time-event correlation effect, despite being caused by specific temporal expectancy in the present study, has been caused by binding in the previous studies.

Such a speculation would not devalue our conclusion that the time-event correlation effect in Experiment 1 was due to specific temporal expectancy, but it would undermine the generalizability of our conclusion about previous time-event correlation studies. In order to account for this problem we replicated Experiment 1 with a constant intertrial interval, very similar in length to previous studies.

Method

Participants. Twenty participants were tested. Four participants were male, 16 were female. Their mean age was 24.80, SD = 4.79. None of the participants took part in Experiment 1 before.

Procedure. The procedure mirrored that of Experiment 1 with the only exception that this time, throughout the experiment, the intertrial intervals were kept constant at a duration of 600 ms.

Results

Acquisition phase.

Response times. During the acquisition phase, a time-event correlation effect was observed (see Figure 5). Participants responded faster to frequent combinations of interval and target, M = 384.26, SD = 45.23, than to infrequent ones, M = 399.59, SD = 43.62, $t(19)$ = 4.815, p < .001, d_{WIT} = 1.034, d_{BET} = 0.337.

The 2 × 2 repeated measures ANOVA with the factors type of transition (complete vs. partial) and frequency of combination (frequent vs. infrequent) yielded no main effect for type of transition, $F(1, 19)$ = .001, p = .974, η_p^2 < .001, but a main effect for frequency of combination, $F(1, 19)$ = 19.842, p < .001, η_p^2 = .511. The interaction was not significant, $F(1, 19)$ = .570, p = .460, η_p^2 = .029.

Errors. With regard to error rates, participants responded more correctly after frequent, M = 2.172, SD = 1.59, than after infrequent, M = 3.371, SD = 3.33, combinations of target and interval. But the difference was only marginally significant, $t(19)$ = 1.862, p = .078, d_{WIT} = 0.400, d_{BET} = 0.406.

The 2 × 2 ANOVA with the factors type of transition and frequency of combination yielded no significant effect, all F < 2.873, all p > .106.

Transfer phase.

Response times. The factor former frequency was significant, $F(1, 19)$ = 5.500, p = .030, η_p^2 = .224. Responses for formerly frequent combinations, M = 388.28, SD = 45.65, were reliably faster than for formerly infrequent combinations, M = 393.26, SD = 44.06. Although the effect of block was not significant, $F(1, 19)$ = 1.667, p = .212, η_p^2 = .081, and did not interact with frequency, $F(1, 19)$ = .668, p = .424, η_p^2 = .034, it should be noted that an effect of frequency was significant only in the fifth block, not in the fourth one (see Figure 5).

Errors. An analogous ANOVA was conducted for error rates. The factor block attained no significance, $F(1, 19)$ = .1.567, p = .226, η_p^2 = .076. Although participants committed fewer errors in formerly frequent, M = 2.33, SD = 2.38, than in formerly infrequent, M = 2.85, SD = 2.52, trials, the factor former frequency was not significant, $F(1, 19)$ = 1.418, p = .248, η_p^2 = .069. The interaction between factors was also not significant, $F(1, 19)$ = 0.079, p = .782, η_p^2 = .004.

Postexperimental questionnaire. Analysis of the postexperimental questionnaire revealed that, again, none of the participants became aware of the correlation between interval duration and target.

Discussion

The results from both experimental phases replicate the findings from Experiment 1 perfectly. We found clear evidence for specific temporal expectancy. Predictions from the a binding account have not been confirmed. It thus follows that, even with a fixed and rather short intertrial interval, no indication of binding can be detected.

Experiment 3

The purpose of Experiment 3 was to confirm the finding of Experiments 1 and 2 by investigating the transfer of specific temporal expectancy via another heuristic strategy. In Experiments 1 and 2 we tested whether a mismatch with formerly acquired temporal expectancies can be detected by performance decrements in individual trials. Here we test, between subjects, whether a high increase of mismatches (between formerly acquired temporal expectancy and actual time-event combination) leads to an overall performance decrement. Instead of switching the time-event correlation to neutral, we now compare two groups with different time-event correlation in the transfer phase. In one group (*continuing group*) the correlation between target and interval in the transfer phase was identical to the correlation in the acquisition phase. For another group the correlation from the acquisition phase was exactly reversed in the transfer phase (*reversed group*). If expectancy was built up in the acquisition phase, this expectancy should have been violated very often in the reversed group, leading to poorer performance relative to the continuing group. According to the binding account, neither group should differ in performance in the transfer phase, because the proportions of trial transition types are identical between both groups.

The acquisition phase is a further exact replication of Experiments 1 and 2. As there was no important difference in the result

patterns of Experiments 1 and 2, we ran half of the participants in Experiment 3 with constant intertrial intervals, and the other half with variable intertrial intervals.

Method

Participants. Twenty participants were tested. Three participants were male, 17 were female. Their mean age was 23.00, $SD = 2.17$.

Procedure. Ten participants were run in the continuing group and 10 in the reversed group. In the continuing group, the blocks in the transfer phase were identical to the blocks in the acquisition phase. In the reversed group, the correlation between target and interval was reversed between acquisition and transfer phase. This means the target formerly paired in 80% of its occurrences with the short interval was now paired in 80% of its occurrences with the long interval. In both groups five participants were run with a constant intertrial interval of 600 ms (as in Experiment 2), and five participants were run with a variable intertrial interval randomly drawn from the same range as in Experiment 1. All other aspects were identical to both previous experiments.

Results

One participant from the continuing group was excluded from the analysis, due to an error rate exceeding 25%.

Acquisition phase.

Response times. Again we observed a substantial time-event correlation effect. Participants responded significantly faster after frequent combinations of target and interval, $M = 384$ ms, $SD = 41$, than after infrequent combinations, $M = 404$ ms, $SD = 47$; $t(18) = 5.007$, $p < .001$, $d_{WIT} = 1.10$, $d_{BET} = 0.416$.

In order to distinguish between expectancy and binding components of this effect, we conducted a 2×2 repeated measures ANOVA with the factors type of transition and frequency of combination. The effect of type of transition was not significant, $F(1, 18) = .450$, $p = .511$, $\eta_p^2 = .024$. As in the previous experiments, the main effect of frequency of combination was significant, $F(1, 18) = 20.482$, $p < .001$, $\eta_p^2 = .532$, but the interaction was not, $F(1, 18) = .081$, $p = .779$, $\eta_p^2 = .004$ (see Figure 6). Due to the procedural similarity between the acquisition phases of all three experiments, we performed an additional 2×2 ANOVA on data collated from all experiments together. The results were qualitatively identical to the single experiment analyses: A significant main effect for frequency of combination, but no significant main effect for type of transition, and for the interaction (see also Tables 11A and 12A in the Appendix for results of a more detailed analysis four factorial analysis).

Error rates. Participants committed on average fewer errors for frequent combinations of target and interval, $M = 1.90\%$, $SD = 1.06$, than for infrequent combinations, $M = 2.74\%$, $SD = 2.26$. This difference was, however, only marginally significant, $t(18) = 1.826$, $p = .084$, $d_{WIT} = 0.401$, $d_{BET} = 0.411$.

In a 2×2 repeated measures ANOVA, no effect attained significance, all $F < 1.258$, and all $p > .277$.

Transfer phase. We tested, between groups, whether the Reversed group had an overall performance disadvantage in the transfer phase from the larger number of expectancy violations. However, we did not compare the absolute response performance,

but the individual performance improvement, relative to the acquisition phase. This standardization of transfer phase performance removed the condition-independent performance differences between participant groups, and reduced thereby the probability of alpha and beta errors. Thus, for each transfer block and participant we subtracted the participant's average performance score from the acquisition phase (see Figure 6).

Response times. We conducted a mixed 2×2 ANOVA with the within-subjects factor block (4 vs. 5) and the between-subjects factor group (continuing vs. reversed). Block was not significant, $F(1, 17) = 1.153$, $p = .298$, $\eta_p^2 = .064$. Group, on the other hand yielded a significant main effect, $F(1, 17) = 6.135$, $p = .024$, $\eta_p^2 = .265$. The performance in the continuous group improved in the transfer phase, while performance deteriorated in the reversed group. Note, however, that the difference between groups was significant only in the fourth block, not in the fifth (see Figure 6). Yet this pattern was not reliable, as evidenced by a nonsignificant interaction, $F(1, 17) = 0.188$, $p = .670$, $\eta_p^2 = .011$.

Error rates. We conducted the same mixed 2×2 ANOVA for error rates. Neither the main effect for block, $F(1, 17) = 0.052$, $p = .823$, $\eta_p^2 = .003$, nor for group, $F(1, 17) = 1.132$, $p = .302$, $\eta_p^2 = .062$, nor the interaction was significant, $F(1, 17) = 0.199$, $p = .661$, $\eta_p^2 = .012$.

Postexperimental questionnaire. None of the participants reported having detected the correlation between interval and target.

Discussion

Results from the acquisition phase fully confirm the findings from Experiments 1 and 2. They provide clear evidence in favor of specific temporal expectancy, by a significant effect of frequency of combination.

Results from the transfer phase are in line with these findings. Overall performance improved when the previous time-event correlations were continued into the transfer phase, but it deteriorated when this correlation was reversed. This pattern was predicted by specific temporal expectancy, but is at odds with a binding account of the time-event correlation effect, because that latter account would have predicted no difference between groups.

General Discussion

The aim of the present study was to identify the cognitive mechanism responsible for the performance benefit for frequent time-event combinations in choice response tasks. Is the effect due to specific temporal expectancy? This would mean that participants learn to associate each point in time with its most frequent stimulus-response event, and schedule their temporal expectancies accordingly. Or is the effect due to time-event binding? Time-event binding would lead to better performance after complete than after partial transitions. The set of frequent time-event combinations necessarily includes a higher proportion of complete transitions than the set of infrequent combinations, explaining the overall benefit for frequent combinations.

To distinguish between these two alternatives we conducted three experiments. The results unequivocally speak against a binding account, and strongly in favor of an account in terms of specific temporal expectancy.

All experiments included an almost identical acquisition phase, in which participants were exposed to an interval-target correlation. In the acquisition phases of all experiments, a strong time-event correlation effect was observed, in the sense of significantly faster responses for frequent than for infrequent combinations of interval and target.

Furthermore, in none of the experiments did we observe significant effects from types of transition. Consequently, partial repetition costs (i.e., effects of time-event binding) did not contribute to the time-event correlation effect. Instead it can be fully explained by specific temporal expectancy.

These conclusions are supported by findings from a second experimental phase—the transfer phase. In Experiments 1 and 2, the correlation between interval and target turned to neutral in the transfer phase. In both experiments, participants responded significantly faster to formerly (i.e., in the preceding acquisition phase) frequent than to formerly infrequent combinations of interval and target. Transfer of learned time-event associations between experimental phases cannot be explained by binding, because binding is a momentary phenomenon that is only effective in the immediately following trial. Specific temporal expectancy explains perfectly the observed transfer of associations between experimental phases, because it relies on an associative learning mechanism.

In the transfer phase of Experiment 3 we compared a group with continuing interval-event correlations with a group with reversed interval-event correlations. The former group showed an overall response speed improvement relative to the acquisition phase, whereas the latter group showed slower response times relative to the acquisition phase. Again, this pattern can only be explained by a transfer of associative knowledge from the acquisition phase to the transfer phase, and consequently speaks against time-event binding, but in favor of specific temporal expectancies.

In summary, six independent analyses from three experiments unequivocally support a specific temporal expectancy explanation of the time-event correlation effect. To our knowledge, this is the first demonstration of specific temporal expectancy that cannot alternatively be explained by binding. We conclude that, first, humans can form temporally specific event expectancies, and that, second, the time-event correlation paradigm provides direct access to specific temporal expectancy. Thus, we recommend the time-event correlations paradigm for future research on this phenomenon.

Implications for Time-Event Binding

We have demonstrated that binding of time and other event features is not involved in bringing about the time-event correlation effect. Furthermore, we found no evidence for time-event binding in any of our experiments. Does this mean that time cannot, in principle, be bound into event files like other features (color, location, etc.) can? Not necessarily so. In the following, we offer two different interpretations.

On the one hand, it might be that the domain of possible features in event files is indeed restricted to nontemporal features. Given that binding has been demonstrated to be so universal that it involves almost any other type of feature, it might, at first sight, seem unlikely that duration is not among them. However, the reason for time not getting bound into event files could lie in the functional role of the very mechanisms of binding itself. Binding

of features in event files is largely responsible for temporally structuring experience and perceptual-motor cognition (Fournier & Gallimore, 2013). Features can change from one event to another over time, cognitively representing environmental dynamics. For fulfilling this function it is pivotal that event files are themselves situated in a continuous temporal frame. When time representations are themselves arbitrarily bound into event files, they cannot figure as cognitive reference frame for tracking the dynamic of objects and actions anymore. Thus, the temporal cognitive organization of binding precludes time representations as candidates for bound features.

On the other hand, our paradigm might simply have been insensitive to time-event binding. Partial transition costs are not the only behavioral manifestations of binding (see Zmigrod & Hommel, in press, for a review). It could be that temporal bindings are less tightly bound into action plans than other features, so that they are automatically released between consecutive trials. In that case, time-event binding should be observable only in paradigms which do not rely on trial-by-trial modulation. There are, for example, instances of temporal versions of stimulus-response compatibility experiments (Grosjean & Mordkoff, 2001; Kunde, 2003) which could be interpreted via binding of temporal features into action plans (Hommel, 2009).

A third possibility would be that temporal binding has temporally asymmetric behavioral effects, as unspecific time expectancy has (Los, 2010). When, for example partial transition costs would only be visible at the longer interval, but not at the shorter one, the overall effect might have been too weak to be detected in our analysis, which collapsed data over both intervals. However, in the Appendix we provide a more detailed analysis of the data that also includes Interval as a factor. This analysis, does not confirm a temporally asymmetric effect from binding.

Intentional Versus Nonintentional Temporal Expectancy

The distinction between intentional and nonintentional mechanisms is a prevalent topic in the current literature on temporal expectancy (e.g., Los, 2010; Vallesi, Arbula, & Bernardis, 2014; Vallesi & Shallice, 2007). In this literature, nonintentional processes are often equated with *exogenous* or *automatic* processes (Correa et al., 2004). Typical instances of nonintentional temporal expectancy are transient increases of general arousal caused by cues (see, e.g., Capizzi, Correa, & Sanabria, 2013, for a discussion; Coull, Nobre, & Frith, 2001; Hackley et al., 2009), or expectancy based on conditioning processes, as described above (e.g., Los & Van den Heuvel, 2001).

Intentional processes are commonly equated with *endogenous*, *strategic*, or *voluntary* expectancy (Los, 2010; Vallesi & Shallice, 2007). A typical instance of intentional temporal expectancy is temporal orienting (e.g., Correa, Cappucci, Nobre, & Lupiáñez, 2010; Correa, Lupiáñez, Madrid, & Tudela, 2006; Correa, Lupiáñez, & Tudela, 2005, 2006; Correa, Sanabria, Spence, Tudela, & Lupiáñez, 2006; Coull, Cheng, & Meck, 2011; Coull & Nobre, 1998, 2008), where participants adjust their temporal expectancy according to explicit cues or to instructions. It is currently under debate how intentional and nonintentional processes contribute to different temporal expectancy effects, like the sequential interval

effect, and the variable interval effect (see Los, 2010, for a review).

How is the distinction between intentional and nonintentional mechanisms of temporal expectancy related to the two accounts of the time-event correlation effect juxtaposed in the present article?

The binding account can clearly be classified as a nonintentional process, because the partial transition cost pattern fully relies on nonintentional trial-to-trial priming effects beyond voluntary control. The strength of binding itself can be modulated in a top down manner, for example by task representations (see Dreisbach, 2012, for a review), but its manifestation in the partial transition cost pattern is clearly not due to intentional strategic processes.

For the temporal expectancy account this classification is less straightforward. Based on the model of specific temporal expectancy which we suggested in the introduction, specific temporal expectancy can be regarded as a nonintentional process. According to our model, the temporal allocation of expectancy is determined by the conditioned weights of projections from temporal states to expectancy generative neural populations, which are not under strategic voluntary control.

However, an alternative model of specific temporal expectancy based on intentional processes is also possible. Such a model would assume that participants, once they detected the time-event correlation, chose to initially focus their expectancy to the event that is likely to occur after the short interval. When this interval is passed by, they voluntarily reorient their expectancy toward the event that is likely after the long interval. Such a model would also predict the data pattern observed in the present experiments.

Our choice for a model based on nonintentional processes is motivated by the observation that participants seem not to be aware of the correlation in time-event correlation studies (see, e.g., Thomaschke & Dreisbach, 2013). This was confirmed in the present study. None of the participants reported detection of the regularity in a postexperimental questionnaire.

However, given that first, a postexperimental questionnaire is not a perfect instrument to definitively detect awareness of a regularity (see Irvine, 2012; Overgaard & Sandberg, 2012; Reingold & Merikle, 1988; Sandberg, Timmermans, Overgaard, & Cleeremans, 2010, for discussions of this issue), and that second, conditioning processes do not in principle preclude awareness (see Clark, Manns, & Squire, 2002; Los & Van den Heuvel, 2001; Lovibond, Liu, Weidemann, & Mitchell, 2011; Lovibond & Shanks, 2002; Singh, Dawson, Schell, Courtney, & Payne, 2013, for discussions), we like to emphasize that our findings do not exclude an intentional model of specific temporal expectancy.

We rather suggest that future studies directly explore by more specialized empirical means whether specific temporal expectancy is due to intentional or to nonintentional processes, as it has been done previously for general time-expectancy.

What Is Expected in a Temporally Specific Manner?

Our study shows that specific temporal expectancy is responsible for the time-event correlation effect. The results do, however, not specify what exactly is expected in a temporally specific manner. The expectancies might equally well be motor expectancies, or be of perceptual nature, or be expectancies of

any other cognitive processes. The present experiments are not informative in this respect. As the stimulus-response mapping was fixed, stimulus-interval correlation was always accompanied by an analogous response-interval correlation. From the previous literature on time expectancy and on event expectancy, no clear hypotheses can be derived concerning this issue. Time expectancy has been demonstrated for visual processes (Bueti, Bahrami, Walsh, & Rees, 2010; Fischer, Plessow, & Ruge, 2013; Rolke, 2008; Rolke & Hofmann, 2007; Vangkilde, Coull, & Bundesen, 2012; Vangkilde, Petersen, & Bundesen, 2013) as well as for motor processes (Burle, Tandonnet, & Hasbroucq, 2010; Müller-Gethmann, Ulrich, & Rinkenauer, 2003; Tandonnet, Burle, Vidal, & Hasbroucq, 2006). Likewise, studies on event expectancy have provided evidence for motor expectancy (Leuthold & Jentzsch, 2011; Leuthold, Sommer, & Ulrich, 1996; Rosenbaum, 1980) as well as for visual expectancy (Posner, 1980). However, there are two previous studies that explicitly investigated the cognitive basis of specific temporal expectancy (Thomaschke & Dreisbach, 2013; Thomaschke, Kiesel, et al., 2011). These studies tested perceptual and motor expectancy independently of each other in different variations of the time-event correlation paradigm. The results suggest that specific temporal expectancy in the time-event correlation paradigm is motor expectancy, not perceptual expectancy. A study by Rieth and Huber (2013), on the other hand, found evidence for specific temporal expectancy for perceptual location (see also Wagener & Hoffmann, 2010b).

Note, however, that this issue is orthogonal to the research question dealt with in the present study. Partial transition costs have been reported for bindings between relevant stimulus features and irrelevant stimulus features as well as between responses and irrelevant stimulus features. Thus, interval duration, as an irrelevant stimulus feature, could have been bound to both, stimulus identity and responses.

Conclusion

Two independent analyses of a time-event correlation experiment have shown that the time-event correlation effect is caused by specific temporal expectancy. The effect is due to the frequency of time-event combinations, not to the type of transition. Furthermore, effects from previous time-event correlations are observable, even when the correlation is abandoned or reversed, clearly speaking in favor of an expectancy-based account. Our results do not, in principle, speak against the possibility that time is bound into event files, but they clearly show that such a mechanism is not involved in the time-event correlation effect.

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Appendix

Interval-Specific Data and Analyses

To allow a comprehensive view of the data, we conducted additional more fine grained ANOVAs, including additional factors which were not involved in the experimental hypotheses. For the acquisition phase of each experiment, we calculated mean RTs for each combination of the factors' interval (short vs. long), interval transition (repetition vs. change), target transition (repetition vs. change), and frequency of interval-target combination (frequent vs. infrequent, see Tables 1A, 5A, and 9A). Tables 2A, 6A, and 10A show the results of corresponding $2 \times 2 \times 2 \times 2$ repeated measures ANOVAs.

For the transfer phases of Experiments 1 and 2 we calculated the mean RTs for each combination of the factors block (4 vs. 5), interval (short vs. long), interval transition (repetition vs. change), target transition (repetition vs. change) and former frequency of combination (formerly frequent vs. formerly infrequent, see Tables 3A and 7A). Tables 4A and 8A show the results of a corresponding $2 \times 2 \times 2 \times 2 \times 2$ repeated measures ANOVA.

To increase statistical power for the analyses of the acquisition phase, we also provide a combined analysis where we collapsed data from the acquisition phases of all three experiments (see Tables 11A and 12A).

Table 1A

Experiment 1. Mean Response Times (M) in ms and Standard Deviations (SD) in the Acquisition Phase of Experiment 1 for Interval, Interval Transition, Target Transition, and Frequency of Interval–Target Combination

| | Frequent | | | | Infrequent | | | |
| | Interval repetition | | Interval change | | Interval repetition | | Interval change | |
Target	M	SD	M	SD	M	SD	M	SD
				Short interval				
Repetition	370	48	386	52	389	74	395	60
Change	396	54	403	44	397	55	422	67
				Long interval				
Repetition	366	45	364	55	385	67	382	45
Change	386	49	376	46	396	47	408	78

(*Appendix continues*)

Table 2A

Experiment 1. Results of a Repeated Measures ANOVA Over the Mean Response Times in the Acquisition Phase of Experiment 1

Factor	F	p	η_p^2
Interval	6.097	.023	.243
Interval transition	3.216	.089	.145
Target transition	11.291	.003	.373
Frequency	19.873	.001	.511
Interval × Interval Transition	2.812	.110	.129
Interval × Target Transition	0.067	.789	.004
Interval Transition × Target Transition	0.368	.551	.019
Interval × Frequency	0.400	.534	.021
Interval Transition × Frequency	1.046	.319	.052
Target Transition × Frequency	0.014	.909	.001
Interval × Interval Transition × Target Transition	0.009	.926	<.001
Interval × Interval Transition × Frequency	0.154	.699	.008
Interval × Target Transition × Frequency	0.119	.734	.006
Interval Transition × Target Transition × Frequency	4.975	.038	.208
Interval × Interval Transition × Target Transition × Frequency	0.028	.868	.001

Table 3A

Experiment 1. Mean Response Times in ms and Standard Deviations in the Transfer Phase of Experiment 1 for Block, Interval, Interval Transition, Target Transition, and Frequency of Interval–Target Combination

	Block 4								Block 5							
	Frequent				Infrequent				Frequent				Infrequent			
	Interval repetition		Interval change		Interval repetition		Interval change		Interval repetition		Interval change		Interval repetition		Interval change	
Target	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
							Short interval									
Repetition	363	48	360	50	361	48	378	53	360	60	364	48	367	48	374	51
Change	381	47	409	57	390	61	399	49	369	44	388	41	376	51	402	69
							Long interval									
Repetition	358	45	365	49	379	49	361	55	376	61	357	53	366	42	373	54
Change	381	54	371	52	389	52	381	49	378	54	376	60	381	44	379	59

(*Appendix continues*)

Table 4A

Experiment 1. Results of a Repeated Measures ANOVA Over the Mean Response Times in the Transfer Phase of Experiment 1

Factor	F	p	η_p^2
Block	1.042	.320	.052
Interval	3.166	.091	.118
Interval transition	2.533	.128	.118
Target transition	12.394	.002	.396
Frequency	5.794	.026	.234
Block × Interval	2.103	.163	.100
Block × Interval Transition	0.614	.443	.031
Block × Frequency	0.004	.951	<.001
Interval × Interval Transition	19.995	<.001	.513
Interval × Target Transition	8.090	.010	.299
Block × Target Transition	3.765	.067	.165
Interval Transition × Target Transition	2.486	.131	.116
Interval × Frequency	0.004	.950	<.001
Interval Transition × Frequency	0.288	.638	.012
Target Transition × Frequency	0.206	.665	.011
Block × Interval × Interval Transition	0.107	.748	.006
Block × Interval × Target Transition	0.914	.351	.046
Block × Interval Transition × Target Transition	0.556	.465	.028
Block × Interval × Frequency	2.237	.151	.105
Block × Interval Transition × Frequency	1.937	.180	.093
Block × Target Transition × Frequency	0.445	.508	.023
Interval × Interval Transition × Target Transition	2.009	.173	.096
Interval Transition × Target Transition × Frequency	1.166	.294	.058
Interval × Interval Transition × Frequency	0.069	.795	.004
Interval × Target Transition × Frequency	0.129	.666	.010
Block × Interval × Interval Transition × Target Transition	0.013	.910	.001
Block × Interval × Interval Transition × Frequency	2.266	.149	.107
Block × Interval × Target Transition × Frequency	0.681	.419	.035
Block × Interval Transition × Target Transition × Frequency	0.115	.738	.006
Interval × Interval Transition × Target Transition × Frequency	0.980	.335	.049
Block × Interval × Interval Transition × Target Transition × Frequency	6.544	.019	.256

Table 5A

Experiment 2. Mean Response Times in ms and Standard Deviations in the Acquisition Phase of Experiment 2 for Interval, Interval Transition, Target Transition, and Frequency of Interval–Target Combination

	Frequent				Infrequent			
	Interval repetition		Interval change		Interval repetition		Interval change	
Target	M	SD	M	SD	M	SD	M	SD
				Short interval				
Repetition	365	49	377	58	381	99	392	52
Change	411	53	408	48	406	60	434	91
				Long interval				
Repetition	369	46	365	51	370	88	382	39
Change	382	51	377	43	403	42	410	65

(*Appendix continues*)

Table 6A

Experiment 2. Results of a Repeated Measures ANOVA Over the Mean Response Times in the Acquisition Phase of Experiment 2

Factor	F	p	η_p^2
Interval	4.041	.060	.183
Interval transition	3.825	.066	.175
Target transition	20.634	<.001	.534
Frequency	12.980	.002	.419
Interval × Interval Transition	0.907	.354	.048
Interval × Target Transition	4.689	.044	.207
Interval Transition × Target Transition	0.044	.837	.002
Interval × Frequency	0.122	.731	.007
Interval Transition × Frequency	3.407	.081	.159
Target Transition × Frequency	0.502	.488	.027
Interval × Interval Transition × Target Transition	0.035	.854	.002
Interval × Interval Transition × Frequency	0.011	.916	.001
Interval × Target Transition × Frequency	1.328	.264	.069
Interval Transition × Target Transition × Frequency	0.544	.470	.029
Interval × Interval Transition × Target Transition × Frequency	0.934	.347	.049

Table 7A

Experiment 2. Mean Response Times in ms and Standard Deviations in the Transfer Phase of Experiment 2 for Block, Interval, Interval Transition, Target Transition, and Frequency of Interval–Target Combination

	Block 4								Block 5							
	Frequent				Infrequent				Frequent				Infrequent			
	Interval repetition		Interval change		Interval repetition		Interval change		Interval repetition		Interval change		Interval repetition		Interval change	
Target	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
							Short interval									
Repetition	382	69	395	74	378	62	390	63	374	51	395	66	370	52	389	49
Change	408	53	422	66	412	58	417	52	404	48	411	57	402	53	436	61
							Long interval									
Repetition	375	52	371	56	386	46	388	47	367	52	362	45	382	44	375	45
Change	393	50	390	53	402	60	392	49	395	54	374	46	398	59	389	49

(*Appendix continues*)

Table 8A

Experiment 2. Results of a Repeated Measures ANOVA Over the Mean Response Times in the Transfer Phase of Experiment 2

Factor	F	p	η_p^2
Block	1.476	.239	.072
Interval	17.457	.001	.479
Interval transition	4.069	.058	.176
Target transition	42.010	<.001	.689
Frequency	7.056	.016	.271
Block × Interval	0.886	.358	.045
Block × Interval Transition	0.288	.598	.015
Block × Frequency	0.884	.359	.044
Interval × Interval Transition	25.572	<.001	.574
Interval × Target Transition	5.874	.026	.236
Block × Target Transition	0.394	.537	.020
Interval Transition × Target Transition	1.149	.297	.057
Interval × Frequency	1.048	.319	.052
Interval Transition × Frequency	0.358	.557	.018
Target Transition × Frequency	0.137	.715	.007
Block × Interval × Interval Transition	3.380	.082	.151
Block × Interval × Target Transition	0.001	.975	<.001
Block × Interval Transition × Target Transition	0.005	.944	<.001
Block × Interval × Frequency	0.151	.702	.008
Block × Interval Transition × Frequency	1.985	.175	.095
Block × Target Transition × Frequency	1.396	.252	.068
Interval × Interval Transition × Target Transition	0.664	.425	.034
Interval Transition × Target Transition × Frequency	0.386	.542	.020
Interval × Interval Transition × Frequency	0.034	.855	.002
Interval × Target Transition × Frequency	1.260	.276	.062
Block × Interval × Interval Transition × Target Transition	0.409	.530	.021
Block × Interval × Interval Transition × Frequency	0.703	.412	.036
Block × Interval × Target Transition × Frequency	0.428	.521	.022
Block × Interval Transition × Target Transition × Frequency	2.864	.107	.131
Interval × Interval Transition × Target Transition × Frequency	0.412	.528	.021
Block × Interval × Interval Transition × Target Transition × Frequency	0.112	.741	.006

Table 9A

Experiment 3. Mean Response Times in ms and Standard Deviations in the Acquisition Phase of Experiment 3 for Interval, Interval Repetition, Target Repetition, and Frequency of Interval–Target Combination

	Frequent				Infrequent			
	Interval repetition		Interval change		Interval repetition		Interval change	
Target	M	SD	M	SD	M	SD	M	SD
				Short interval				
Repetition	378	63	385	76	390	61	398	51
Change	387	53	402	54	388	44	412	81
				Long interval				
Repetition	370	45	367	51	374	68	395	68
Change	397	38	376	28	399	45	403	77

(*Appendix continues*)

Table 10A

Experiment 3. Results of a Repeated Measures ANOVA Over the Mean Response Times in the Acquisition Phase of Experiment 3

Factor	F	p	η_p^2
Interval	2.240	.163	.169
Interval transition	1.167	.303	.096
Target transition	2.427	.148	.181
Frequency	6.130	.031	.358
Interval × Interval Transition	2.144	.171	.163
Interval × Target Transition	0.710	.418	.061
Interval Transition × Target Transition	0.267	.615	.024
Interval × Frequency	0.225	.645	.020
Interval Transition × Frequency	1.763	.214	.136
Target Transition × Frequency	0.119	.737	.011
Interval × Interval Transition × Target Transition	1.263	.258	.103
Interval × Interval Transition × Frequency	1.669	.223	.132
Interval × Target Transition × Frequency	0.176	.683	.016
Interval Transition × Target Transition × Frequency	0.122	.734	.011
Interval × Interval Transition × Target Transition × Frequency	0.071	.795	.006

Table 11A

Experiments Collapsed. Mean Response Times in ms and Standard Deviations in the Acquisition Phases of Experiments 1–3 for Interval, Interval Transition, Target Transition, and Frequency of Interval–Target Combination

	Frequent				Infrequent			
	Interval repetition		Interval change		Interval repetition		Interval change	
Target	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
			Short interval					
Repetition	370	51	382	59	386	80	395	54
Change	400	54	405	47	399	54	424	79
			Long interval					
Repetition	368	45	365	51	377	74	385	49
Change	387	47	376	40	399	44	408	72

(*Appendix continues*)

Table 12A
Experiments Collapsed. Results of a Repeated Measures ANOVA Over the Mean Response Times in the Acquisition Phase of Experiments 1–3 Collapsed

Factor	F	p	η_p^2
Interval	11.758	.001	.190
Interval transition	7.983	.007	.138
Target transition	30.651	<.001	.380
Frequency	39.051	<.001	.439
Interval × Interval Transition	5.297	.026	.096
Interval × Target Transition	0.899	.348	.018
Interval Transition × Target Transition	0.007	.933	<.001
Interval × Frequency	0.666	.418	.013
Interval Transition × Frequency	6.095	.017	.109
Target Transition × Frequency	0.059	.810	.001
Interval × Interval Transition × Target Transition	0.665	.419	.013
Interval × Interval Transition × Frequency	0.457	.502	.009
Interval × Target Transition × Frequency	1.331	.254	.026
Interval Transition × Target transition × Frequency	3.643	.062	.068
Interval × Interval Transition × Target Transition × Frequency	0.887	.351	.017