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Timing & Time Perception 4 (2016) 248–270

TIME

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Time-Based Expectancy for Task Relevant Stimulus Features

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Received 5 May 2016; accepted 16 August 2016

Abstract

When a particular target stimulus appears more frequently after a certain interval than after another one, participants adapt to such regularity, as evidenced by faster responses to frequent interval-target combinations than to infrequent ones. This phenomenon is known as time-based expectancy. Previous research has suggested that time-based expectancy is primarily motor-based, in the sense that participants learn to prepare a particular response after a specific interval. Perceptual time-based expectancy — in the sense of learning to perceive a certain stimulus after specific interval — has previously not been observed. We conducted a Two-Alternative-Forced-Choice experiment with four stimuli differing in shape and orientation. A subset of the stimuli was frequently paired with a certain interval, while the other subset was uncorrelated with interval. We varied the response relevance of the interval-correlated stimuli, and investigated under which conditions time-based expectancy transfers from trials with interval-correlated stimuli to trials with interval-uncorrelated stimuli. Transfer was observed only where transfer of perceptual expectancy and transfer of response expectancy predicted the same behavioral pattern, not when they predicted opposite patterns. The results indicate that participants formed time-based expectancy for stimuli as well as for responses. However, alternative interpretations are also discussed.

Keywords

Time-based expectancy, temporal attention, foreperiod, time-event correlation, temporal preparation, temporal expectancy

1. Introduction

In order to behave in a goal directed manner, it is important to anticipate *which* behaviorally relevant event will happen next (Bubic et al., 2010; Gilbert & Wilson, 2007; Summerfield & Egner, 2009) as well as to anticipate *when* it will happen

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DOI: 10.1163/22134468-00002069

(Coull & Nobre, 1998; Coull et al., 2000; Haering & Kiesel, 2012). For an athlete, for example, it is important to anticipate that the next command after 'ready', and 'steady' will be 'go'. But in order to show optimal behavior, she also benefits from an accurate estimate of *when* the 'go' will follow the 'steady' (i.e., instantaneously, after a second, or after a minute; see Correa, 2010).

Expectancy about when something will happen is usually referred to as *time expectancy* (TE) or *temporal expectancy* in the literature. The subject of TE has a long tradition in the cognitive sciences (Lejeune & Wearden, 2009; Martius, 1891; Moore, 1904; Surprenant & Neath, 1997; Vierordt, 1868) and is currently a heavily researched area (e.g., Los & Heslenfeld, 2005; Los & Horoufchin, 2011; Matthias et al., 2010; Pecenka & Keller, 2009; Rimmele et al., 2011). One of the most common research paradigms in TE is the foreperiod (FP) paradigm. In a FP paradigm, a target stimulus is announced by a preceding warning stimulus. FP refers to the interval between warning stimulus and target. When FPs are constant within an experimental block, the warning stimulus allows, in principle, an exact temporal prediction of target occurrence. However, the ability to prospectively estimate time intervals gets less accurate the longer the interval lasts (Buhusi & Meck, 2005; Gibbon, 1977; Gibbon et al., 1984; Grondin, 2010; Lewis & Miall, 2009; Piras & Coull, 2011; Wearden, 2016). This explains a common finding in the FP literature. Namely, variation of FPs between blocks leads to increased target response times (RTs) after longer FPs (Los & Schut, 2008; Posner et al., 1973; Rolke et al., in press; Seibold & Rolke, 2014b; Steinborn et al., in press; Wundt, 1874).

When FPs, on the other hand, vary unpredictably *within* a block of trials, one cannot anticipate the FP of a trial in advance. This leads to generally longer RTs than in constant FP designs (Awramoff, 1903; Cardoso-Leite et al., 2009). Although expectancy for a particular FP in advance of a trial is extremely difficult in variable FP designs, participants form TEs concerning target occurrence, and update these expectancies throughout the course of a trial, as evidenced by decreasing RTs with increasing FPs. Numerous examples of the variable FP effect are provided by Hickey and Los (2015); Langner et al. (2010); Lohmann et al. (2009); Los and Agter (2005); MacDonald and Meck (2008); Steinborn and Langner (2011, 2012); and Woodrow (1914). Moreover, the variable FP effect has typically been explained by a timing mechanism sensitive to the increase in conditional probability of an immediate target occurrence as time elapses during the FP (e.g., Elithorn & Lawrence, 1955; Janssen & Shadlen, 2005; MacDonald & Meck, 2004 — see, however, Los & Agter, 2005; Los & Van den Heuvel, 2001; Los et al., 2001; Shi et al., 2013; Steinborn et al., 2008, 2010 for alternative explanations of the variable FP effect).

Note that TE is — by definition — independent of event expectancy. Accordingly, TE has usually been investigated in scenarios were event expectancy was balanced. In these studies, the time of target occurrence is not informative regarding the event to occur. In simple response paradigms the target is constant over trials (e.g., Elliott, 1973; Frith & Done, 1986), and in forced-choice tasks, the targets are usually balanced across different FPs (e.g., Kingstone, 1992; Steinborn et al., 2009). In a study by Kingstone (1992), TE and event expectancy have both been manipulated in one design. He employed combined cues before FPs. One part of the cue predicted the duration of the FP, and the other part predicted the orientation of the target stimulus. He observed simultaneous expectancies for time and for the type of event (i.e., target orientation). However, both expectancies were induced independently of each other, in the sense that they were orthogonally manipulated: both FPs were equally often paired with both orientations. This means the flow of time did not change the event probabilities.

Thomaschke et al. (2011a) have argued that this pure form of TE rarely appears in real life (see also Gobel et al., 2011). Even the athlete in our introductory example has no pure time expectancy, independent from event expectancy. She probably has a strong time expectancy to hear something about a second after the 'steady' command. But it is not *any* auditory stimulus that she expects after that time. Her expectancy for the command 'go' after a second is likely to be much higher than her expectancy for another 'steady' after a second. We refer to this kind of expectancy with the term *time-based* expectancy (TBE). When a TBE was formed temporal expectancy is conditional on event expectancy, and event expectancy is conditional on temporal expectancy. Consequently, one expects neither an event per se, nor a point in time per se, but a combination of an event and a point in time.

Time-based expectancy is ubiquitous in everyday life, for instance in language processing (Brosy et al., 2016; MacGregor et al., 2010; Roberts & Francis, 2013; Roberts et al., 2011; Roberts & Norris, 2016; Watanabe et al., 2008) or human machine interaction (Shahar et al., 2012; Thomaschke & Haering, 2014). One of the most popular examples comes from football (Kuper & Szymanski, 2009). Before the European Champions League final in Moscow in 2008, one team's goalkeeper had been briefed by the Basque economist Ignacio Palacios-Huerta with the penalty kick statistics of all opponent players (Apesteguia & Palacios-Huerta, 2010; Palacios-Huerta, 2003). The pattern for the player Cristiano Ronaldo included temporal information: when he shoots a penalty kick immediately without hesitation, he chooses the left and right corner with equal probability. However, when he pauses shortly before the kick, he shoots to the right with 85% probability. Based on this information, the keeper had to build up TBE: he had to change his event expectancy conditional upon the flow of time. During a short initial interval he had to prepare for diving to both sides, while in the case of a prolonged interval he had to quickly change his expectancy to the right corner. Indeed Ronaldo was to do a penalty kick in the match. He paused his run-up to the ball, and shot — as predicted — to the right. The penalty kick was duly saved by the keeper Petr Cech (Kuper & Szymanski, 2009).

It is important to note at this point, that TBE is not another form of TE. It is no expectancy for time. The keeper in the example could not know in advance which time interval will happen. He could only know that if a certain time interval (e.g., a stop in the run-up) occurs, this implies a certain event (e.g., shooting to the right). TBE is expectancy for events, not for times, but the expectancy is *based* on time. While time is the expected entity in TE, it figures as an event cue in TBE. Note, also, that TE and event expectancy can well co-occur without any TBE, as long as times and events are not correlated with each other (e.g., Kingstone, 1992). Although ubiquitous in everyday life, TBE has been investigated empirically only by a few recent studies (Kunchulia & Thomaschke, 2016; Thomaschke & Dreisbach, 2015; Thomaschke et al., 2011b; Wagener & Hoffmann, 2010a, 2010b; Wendt & Kiesel, 2011).

Wagener and Hoffmann (2010b), for example, applied a Two-Alternative-Forced-Choice task with two FPs, which varied randomly from trial to trial. One of the two target stimuli appeared in 80% of its occurrences after one of the FPs, and the other stimulus appeared in 80% of its occurrences after the other FP. Participants showed a TBE effect, in the sense of responding faster to frequent FP–target combinations than to infrequent FP–target combinations. Thus, participants expected one stimulus-response event after the short FP and the other one after the long FP. Wagener and Hoffmann's results allow, however, no conclusion about which stage of cognitive processing does benefit from TBE. Was participants' perceptual processing facilitated for a specific stimulus after a particular FP? Or was the execution of a specific response facilitated after a particular FP? Both explanations would account for the observed TBE effect.[1]

In relation to TE, the issue of the cognitive locus of expectancy is currently intensely researched (Bausenhart et al., 2006; Correa et al., 2010; Lampar & Lange, 2011; Seifried et al., 2010). Researchers have identified TE effects on auditory (Bausenhart et al., 2007; Lange, 2009, 2010; Lange & Heil, 2008; Lange et al., 2003, 2006), tactile (Lange & Röder, 2006) and visual perception (Bueti et al., 2010; Correa et al., 2004, 2005, 2006a; Rolke, 2008; Seibold & Rolke, 2014a). Further, TE effects have also been shown for central response-selection processes (Fischer et al., 2012; Hackley & Valle-Inclán, 2003; Klein & Kerr, 1974) and for late motor processes (Boulinguez et al., 2008, 2009; Duclos et al., 2008a, b; Spijkers, 1990).

Yet, these findings cannot automatically be generalized to TBE. It might rather be that some cognitive processes benefit from TE, while other processes are facilitated by TBE. Knowing when something will happen might mobilize other

1 In earlier studies, the terms temporal *expectation* and temporal *preparation* were frequently used to differentiate between perceptual and motor-based explanations of FP effects (see, e.g., Mo & George, 1977). In that reading the term TBE would suggest a perceptual basis of the phenomenon. However, the current literature on temporal cognition uses the terms expectancy and preparation nearly interchangeably for behaviorally measurable effects of FPs (see Los, 2010, for a discussion of this terminology). We follow the current usage of 'expectancy', and do not imply any underlying mechanism by using the term TBE instead of 'time based *preparation*'.

cognitive resources, than does knowing — based on time — what will happen. For example, the athlete might form TE in the motor domain, in the sense of an event-independent increased motor-related arousal that would facilitate the execution of *any* motor action after one second, running, jumping, or fighting. But, at the same time she might have a TBE to perceptually process the 'go' signal after one second, in the sense that only processing of exactly that auditory stimulus is selectively facilitated at the time after one second. The aim of the present study is to identify the cognitive locus of TBE. Is the goalkeeper's visual system tuned to detect a shot to the right particularly well after a certain time interval, or does he already prepare to dive to the right after a certain time interval, or both?

Two previous studies (Thomaschke & Dreisbach, 2013; Thomaschke et al., 2011c) aimed at determining the cognitive locus of TBE. Thomaschke et al. (2011c) employed a Two-Alternative-Forced-Choice Task with two FPs varying randomly between trials. Four stimuli differed along two dimensions, namely shape and orientation (see Fig. 1). In different experiments, the correlation between FPs and stimuli has been varied, as well as the mapping from stimuli to responses. FPs predicted either shape, orientation, or combinations of shape and orientation. Likewise, responses were mapped to stimuli in different experiments, according to shape, orientation, or to a combination of shape and orientation. TBE effects were observed only when FP predicted both stimulus features and responses, but not when only stimulus features were predicted by FP. These results suggest that TBE affects mainly post-perceptual processing stages, like response selection or response execution.

In a related study (Thomaschke & Dreisbach, 2013) response keys were arranged in the form of a square such that the upper and lower keys on the left and right side had to be pressed with the middle (upper key) and the index (lower key) finger of the left and right hand. Participants had to switch back and forth between

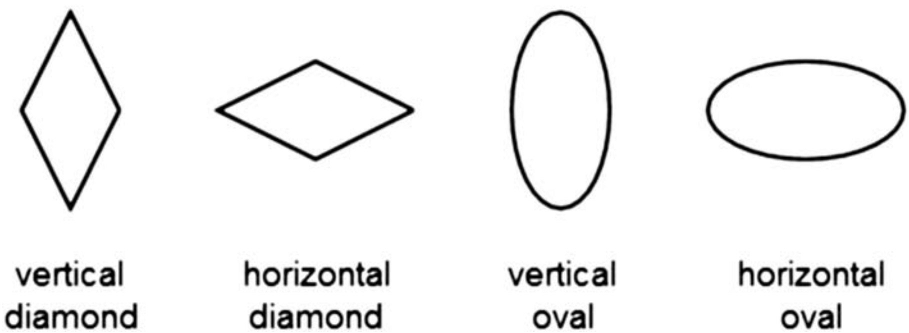

Figure 1. The four imperative stimuli adapted from Thomaschke et al. (2011c). The stimuli differed along the two dimensions form (oval vs. diamond) and orientation (horizontal vs. vertical). The diamond was a regular rhombus with the length of one diagonal half the length of the other diagonal. The oval was a regular ellipse with a conjugate diameter of half the length of the traverse diameter.

the left and right pair of keys from trial to trial. The imperative stimulus required to press either the upper or the lower one of the current pair of keys, respectively. On one of the key pairs the required key (upper or lower) was predictable by FP, on the other pair it was not. Participants formed TBE for the predictable key pair. Here the important question was whether they transferred this TBE to the unpredictable pair dependent on whether they operated the pairs bimanually (i.e., they switched hands from trial to trial) or unimanually (i.e., they moved one hand back and forth between trials). Transfer was only observed in the unimanual condition, but not in the bimanual condition. This means that TBE, in this paradigm, was specific to a certain hand, what suggests a post-perceptual locus of TBE. The conclusions from these studies are in line with previous evidence for effects from TE on motor processing (e.g., Davranche et al., 2007; Duque & Ivry, 2009; Duque et al., 2010; Tandonnet et al., 2003, 2006).

In sum, TBE has been observed when FPs predicted responses (Thomaschke & Dreisbach, 2013), but not when they predicted stimulus features (Thomaschke et al., 2011c). The standard conclusion from these studies has been that TBE primarily facilitates motor processing, not visual processing.

However, this conclusion might be premature. In the previous study that tested explicitly TBE for stimulus features, the predictable stimulus features were always task-irrelevant (Thomaschke, Kiesel, et al., 2011). In one experiment (Exp. 4a), for example, only stimulus shape was predictable by FPs, but responses were mapped to stimuli according to orientation. It might be that stimulus features could in principle benefit from TBE, but only when they are relevant to response selection. Processing of the irrelevant shape dimension might have been suppressed in favor of attending to orientation (see, e.g., Andersen & Müller, 2010; Polk et al., 2008; Wegener et al., 2008). Thus, no TBE was formed for it.

In the present study, we aimed to further test whether TBE might facilitate visual processing. In contrast to previous experiments, stimulus temporally predictable stimulus features are relevant for choosing the response. We developed a variant of the FP paradigm where TBE is induced in some trial types (inductive trials) and measured in other trial types (diagnostic trials, cf. Hoffmann & Sebald, 2005). The task was arranged in a way that potential TBE for stimulus features and potential TBE for responses would transfer to different diagnostic trials. We hypothesize that TBE for stimulus features will be observed in the present experiments, because the temporally predictable stimulus features are, in contrast to previous studies, task relevant.

2. Experiment

2.1. Overview

The design is illustrated in the top panel of Fig. 2. There were four different target stimuli differing along two different dimensions: shape (oval vs. diamond) and

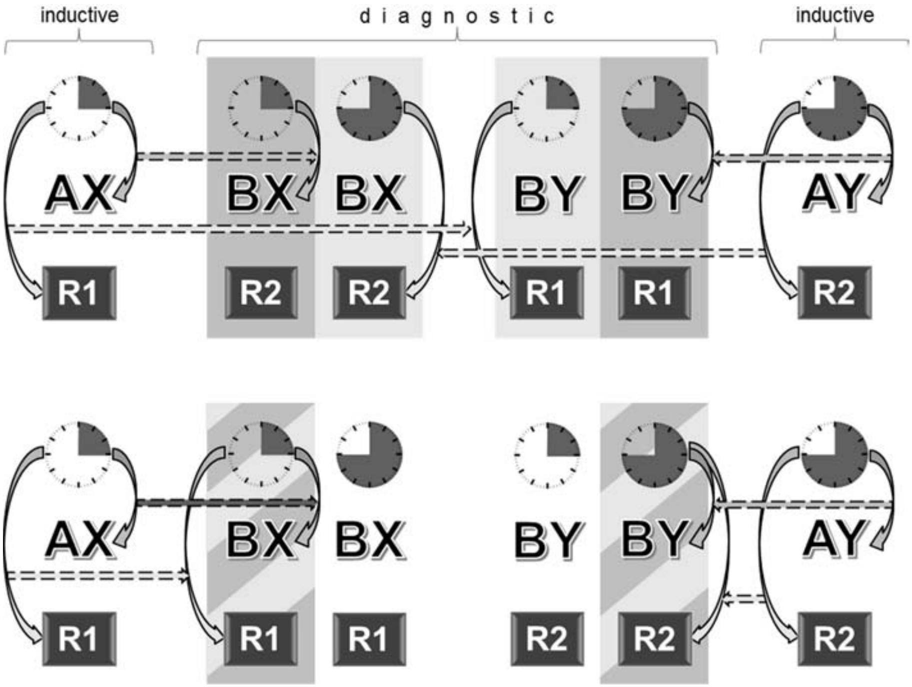

Figure 2. Potential TBE in Exp. 1A (top panel) and Exp. 1B (bottom panel). Each column represents a trial type. The top rows represent the trial type's FP. The middle rows represent the stimulus expressed as a combination of its features. The feature dimensions are A/B and X/Y. The A/B dimension is orientation and the X/Y dimension shape, or the other way around for half of the participants. There are four possible feature combinations, and hence four different stimuli (see Fig. 1). R1 and R2 are the two possible responses. Curved arrows represent potential TBE (short arrows for perceptual TBE, and long arrows for motor TBE). The straight broken arrows represent potential transfer of TBE from inductive to diagnostic trials (dark grey for perceptual TBE, and light grey for motor TBE). In Exp. 1A (top panel) motor TBE would transfer to different diagnostic trials than perceptual TBE (dark grey boxes for perceptual TBE, and light grey boxes for motor TBE). In Exp. 1B (bottom panel) perceptual TBE and motor TBE would transfer to the same diagnostic trials (striped boxes).

orientation (horizontal vs. vertical, see Fig. 1). One of the stimuli appeared only after the short, and another one only after the long, FP. These two stimuli were chosen in a way that the features on one of the dimensions were predictable by FP (the X/Y dimension in Fig. 2) but features on the other dimension were not (the A/B dimension in Fig. 2). We refer to trials containing either of these stimuli as *inductive* trials, because the temporal predictability of these trials should induce TBE.

Figure 3 illustrates an example. In this example, the inductive trials are trials with the vertical diamond and the vertical oval. The vertical diamond occurs only after the short and never after the long FP. The vertical oval, on the contrary, occurs only after the long and never after the short FP. This makes the feature 'shape' temporally predictable. Thus, the X/Y dimension is realized by the shape

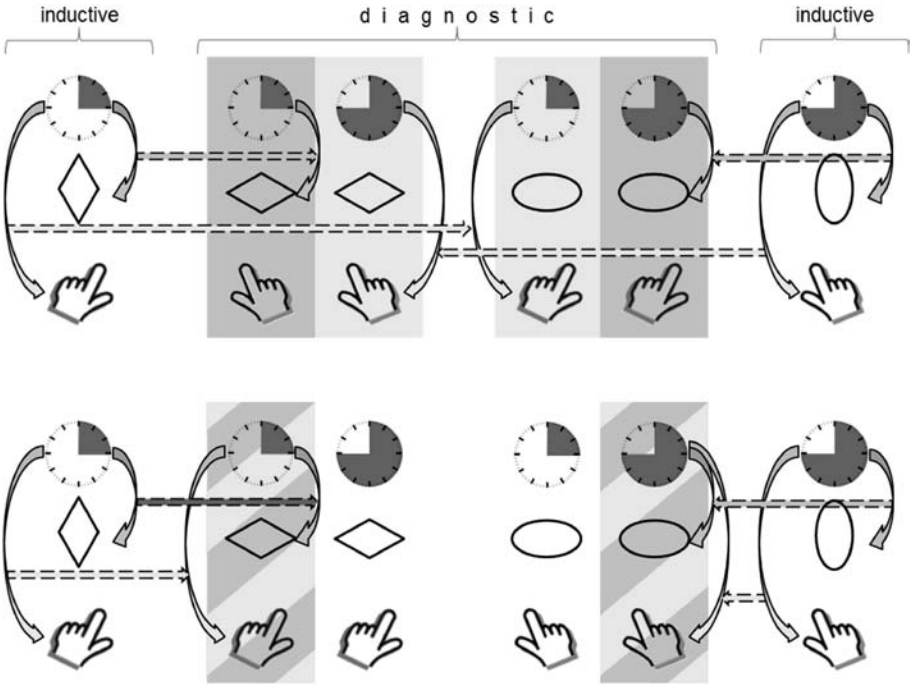

Figure 3. Illustration of an example stimulus-response mapping in Exp. 1A (top panel) and 1B (bottom panel). In this example, shape is temporally predictable, while orientation is not. In Exp. 1A, TBE for shape would predict faster responses to horizontal diamonds after short FPs and to horizontal ovals after long FPs. TBE for responses, on the contrary, would predict faster responses to the horizontal diamond after long FPs, and to the horizontal oval after short FPs. In Exp. 1B, TBE for shape and for responses would both predict faster responses to horizontal diamonds after short FPs, and to horizontal ovals after long FPs.

dimension, in this example. However, the orientation of the stimuli is not predictable by time, in this example. Thus, the A/B dimension is realized by orientation.

The other two stimuli appear equally often after the short as after the long interval. We refer to trials with these stimuli as *diagnostic* trials, because, due to the temporal unpredictability of these stimuli, TBE cannot be induced by these trials. However, they allow us to measure TBE that potentially has been formed in inductive trials and transferred to these diagnostic trials. TBE for the temporally predictable stimulus feature would lead to facilitated performance in only those diagnostic trials in which the feature appeared after its typical FP (dark grey boxes in Fig. 2).

In our example (see Fig. 3), the horizontal diamond and the horizontal oval figured as diagnostic trials. When participants formed TBE on the shape dimension, they should expect diamonds to appear early and ovals to appear late, as this is the regularity in inductive trials. For diagnostic trails, this would mean that responses to the horizontal diamond should be faster after a short than after a long FP, and responses to the horizontal oval should be faster after the long than after the short FP.

Stimuli were mapped to responses according to a feature-orthogonal classification rule. That means they were not classified along one of their feature dimensions (shape or orientation). Instead, one instance of each shape was mapped to the left and the other instance to the right key. Likewise, one instance of each orientation was mapped to the left and the other instance was mapped to the right key (see Fig. 2). This means, participants responded with one button to the vertical oval and to the horizontal diamond, and with the other button to the horizontal oval and to the vertical diamond. Thus two inductive trials involved different responses, and hence response was temporally predictable. Potential TBE for response would also transfer to diagnostic trials. TBE for responses would facilitate those diagnostic trials in which the responses appear after their typical FPs (light grey boxes in Fig. 2). The feature orthogonal stimulus-response mapping implies that TBE for stimulus features and TBE for responses would transfer to different diagnostic trials. When in diagnostic trials the response appears after its typical FP, than the predictable feature necessarily appears after its atypical FP. Conversely, when in diagnostic trials the predictable feature appears after its typical FP, then the response necessarily appears after its atypical FP.

In our example (see Fig. 3), participants could have learned in inductive trials that they have to respond with their left hand more often after short than after long FPs, and that they have to respond with their right hand more often after long than after short FPs. If this form of response-related TBE transfers to diagnostic trial, they should respond to the horizontal diamond faster after the long than after the short FP, because the horizontal diamond requires a right hand response. Conversely they should response faster to the horizontal oval after short FPs than after long FPs, because the horizontal oval requires a left hand response. This pattern is, however, opposite to the one predicted based on TBE for shape (see above).

When TBE selectively facilitates visual feature processing, participants should respond faster to trials where features are temporally predictable. When, on the contrary, TBE selectively facilitates response processing participants should respond faster in those diagnostic trials where responses are temporally predictable. When TBE facilitates feature processing and response processing we should observe a null effect between both types of diagnostic trials. The latter effect would, however, also be predicted when there is no transfer of TBE at all from inductive to diagnostic trials.

In order to disambiguate a potential null effect in Exp. 1A we conducted an analogous control Exp. 1B. The only difference to Exp. 1A was that responses were mapped to one of the stimulus features (e.g., horizontal → left, vertical → right) instead of a combination of both features. This entailed that potential TBE for the stimulus feature would enhance performance in the same type of diagnostic trials that would be enhanced by TBE for responses. Thus, a comparison between the diagnostic trials that would benefit from stimulus TBE and response TBE vs. the diagnostic trials that would benefit neither from stimulus TBE nor response TBE would show whether TBE is effective at all in this paradigm.

In our example (see Fig. 3), participants had to respond in Exp. 1B with left to diamonds, and with right to ovals, irrespective of stimulus orientation. Feature-related as well as response-related TBE would have predicted for diagnostic trials that participants respond to the horizontal diamond faster after the short FP, and to the horizontal oval faster after the long FP.

2.2. *Methods*

2.2.1. *Participants*

The participants were students of the University of Würzburg, or inhabitants of the city of Würzburg. All participants reported having normal or corrected to normal vision. They were rewarded by course credit or by a payment of 8 €. In Exp. 1A, 47 participants were tested (34 female, and 13 male). Their ages ranged from 17 to 44 ($M = 24.62$, SD = 4.94). In Exp. 1B, 48 participants were tested (33 female, and 15 male). Their ages ranged from 19 to 32 ($M = 22.73$, SD = 2.79).

2.2.2. *Apparatus and Stimuli*

Stimulus presentation and collection of responses were performed by an IBM-compatible computer with a 17-inch VGA-Display controlled by E-Prime (Schneider et al., 2002). Participants responded with the right hand on two adjacent buttons on a Serial Response Box (Psychology Software Tools), which was centrally aligned in front of the computer screen. Target stimuli were a black diamond or a black oval, presented vertically or horizontally (see Fig. 1), against a white background, at a viewing distance of 50 cm. The size of the stimuli was 2 cm × 1 cm. The fixation cross was the '+' symbol (typeface 'Arial', 1.3 × 1.3 cm). All stimuli were presented centrally on the screen.

2.2.3. *Procedure*

Each trial started with the presentation of a fixation cross. The duration of the fixation cross was either 600 ms or 1600 ms (the FP) and varied randomly from trial to trial. It was followed by the imperative stimulus. Participants were instructed to respond as fast and as accurately as possible to the imperative stimulus, according to a fixed mapping rule, which differed across subexperiments (see below). The target stimulus disappeared either when a response was detected or when 1000 ms had elapsed without a response. In the latter case, the words 'zu spät!' (German for 'too late') were displayed for 700 ms. When participants pressed the wrong key, the words 'falsche Taste!' (German for 'wrong key') were displayed for 700 ms. After trials with incorrect or late responses, the next trial started 500 ms after offset of the error message. After correct and timely responses, no explicit feedback was given and the next trial started 1200 ms after responding. The probability of the individual target stimuli as well as the probability of individual FP–target combinations was manipulated in a way that two of the stimuli appeared only after one FP, while the other two stimuli appeared equally often after both FPs.

In order to induce a potential TBE for stimulus features or for responses that would be comparable in strength with previous studies on TBE, we presented twice as many inductive as diagnostic trials. This had the effect that each response and each stimulus feature was coupled with its typical FP in 83.33% of its occurrences and with its atypical FP in 16.67% of its appearances. Previous studies on TBE have mostly used an 80%/20% distribution of events over FPs (Thomaschke & Dreisbach, 2013; Thomaschke et al., 2015; Wagener & Hoffmann, 2010a, 2010b). This distribution entails, however, that two of the stimuli appear twice as often as the others. Consequently we also expected a general FP-independent performance advantage for inductive trials relative to

Table 1.
Number of stimuli per block after the two FPs for both experiments. The table refers to the example in Fig. 3

Stimuli	Response in Exp. 1A	Response in Exp. 1B	Early	Late
Vertical diamond	left	left	100	0
Vertical oval	right	right	0	100
Horizontal diamond	right	left	25	25
Horizontal oval	left	right	25	25

diagnostic trials. The stimulus-response mapping varied between subexperiments 1A and 1B (see below, and Fig. 2).

Participants performed one practice block followed by three experimental blocks. Each block comprised 300 trials. Between the blocks, participants could take a short break of maximally 1 min. The experiment lasted approximately 1 h.

2.2.3.1. Experiment 1A

Participants had to respond via a feature-orthogonal rule. This means the horizontal oval and the vertical diamond were mapped to a different response than the vertical oval and the horizontal diamond. The design is illustrated in Fig. 2 (top panel). See also Table 1 for a distribution of stimuli across FPs in both experiments. The predictability of the feature dimensions was counterbalanced across participants (i.e., whether shape was temporally predictable or orientation). The role of non-predictable features in inductive and diagnostic trials was also counterbalanced across participants (i.e., whether diamonds or ovals were presented in inductive trials when orientation was predictable, and whether vertical or horizontal stimuli were presented in inductive trials when shape was predictable). The typical time for inductive stimuli was also counterbalanced across participants (i.e., which of the inductive stimuli was predicted by the short and which one by the long FP). The mapping between stimuli and the left and right response was also counterbalanced across participants.

2.2.3.2. Experiment 1B

The design is illustrated in the bottom panel of Fig. 2. Experiment 1B resembled Exp. 1A exactly with the only exception that the responses were mapped to the temporally predictable stimulus feature, instead of applying a feature-orthogonal response rule. This mapping has, however, implications for the impact of potential TBE in diagnostic trials. Now temporally predictable features coincide with temporally predictable responses (the cross-striped box in Fig. 2).

3. Results

Data from the practice block were excluded from the analysis. The first trial of each experimental block was also excluded. Response times from erroneous responses, as well as response times that where more than 2.5 SDs above each participant's condition mean, were not included in the RT analysis (Bush et al., 1993).

Data from two participants in Exp. 1A were excluded from analysis, because their error scores, 28.7%, and 29.9%, were more than 2.5 standard deviations, SD = 6.97, above the mean, $M = 10.66$. Data from one participant in Exp. 1B was also excluded from analysis, due to an error score, 92.8%, which was more than 2.5 standard deviations, SD = 13.27, above the mean, $M = 5.66$.

3.1. Response Times

Overall, participants responded faster in Exp. 1B (400 ms, SD = 40) than in Exp. 1A (521 ms, SD = 59, $t(90) = 11.710$, $p < 0.001$). This difference is probably due to different cognitive demands of the feature based stimulus-response mapping and the feature-orthogonal stimulus-response mapping (see also Thomaschke et al., 2011c). In Exp. 1A, responses in inductive trials (500 ms, SD = 55) were faster than response in diagnostic trials (576 ms, SD = 80, $t(44) = 10.186$, $p < 0.001$). In Exp. 1B, responses in inductive trials (393 ms, SD = 41) were also faster than responses in diagnostic trials (415 ms, SD = 39, $t(46) = 8.496$, $p < 0.001$). This general expectancy effect can be explained by the higher frequency of inductive trials (2/3 of all trials) than diagnostic trials (1/3 of all trials).

3.1.1. TBE in Diagnostic Trials

Only performance in diagnostic trials could potentially be informative on the cognitive locus of a potential TBE effect. Consequently we confined our analysis on these trials. We conducted a 2 × 2 × 2 × 3 mixed ANOVA with the between-subjects factor Experiment (1A, and 1B) and the within-subjects factors Combination-Frequency (frequent, and infrequent), FP (500 ms, and 1600 ms), and Block (1, 2, and 3). The factor Combination-Frequency refers to the overall frequency of the coupling of the current *response* with the current FP. Thus, TBE for stimulus features would, in Exp. 1A predict an advantage in 'infrequent' FP-response combinations, because these are 'frequent' FP-stimulus-feature combinations.

The only significant main effects were Experiment, $F(1, 90) = 154.663$, $p < 0.001$, $\eta^2_p = 0.632$, and Combination-Frequency, $F(1, 90) = 9.099$, $p = 0.003$, $\eta^2_p = 0.092$. Combination-Frequency interacted with Experiment, $F(1, 90) = 10.154$, $p = 0.002$, $\eta^2_p = 0.101$. The interactions between FP and Experiment, $F(1, 90) = 3.358$, $p = 0.07$, $\eta^2_p = 0.036$, and between Block, FP and Experiment, $F(2, 180) = 2.651$, $p = 0.073$, $\eta^2_p = 0.029$, reached only marginal significance. No other main effect or interaction was significant (all ps > 0.101). Due to the interaction between Combination-Frequency and Experiment, two separate repeated-measures 2 × 2 × 3 ANOVAs have been conducted for experiments 1A and 1B. The factors were, as above, Combination-Frequency (frequent, and infrequent), FP (500 ms, and 1600 ms), and Block (1, 2, and 3).

The ANOVA for Exp. 1A, revealed no significant main effect for Combination-Frequency, $F(1, 44) = 0.010$, $p = 0.919$, $\eta^2_p < 0.001$. No other main effect or interaction was significant (all ps > 0.196).

The ANOVA for Exp. 1B revealed, however, a significant main effect for Combination-Frequency, $F(1, 46) = 29.867$, $p < 0.001$, $\eta^2_p = 0.394$, and for Block,

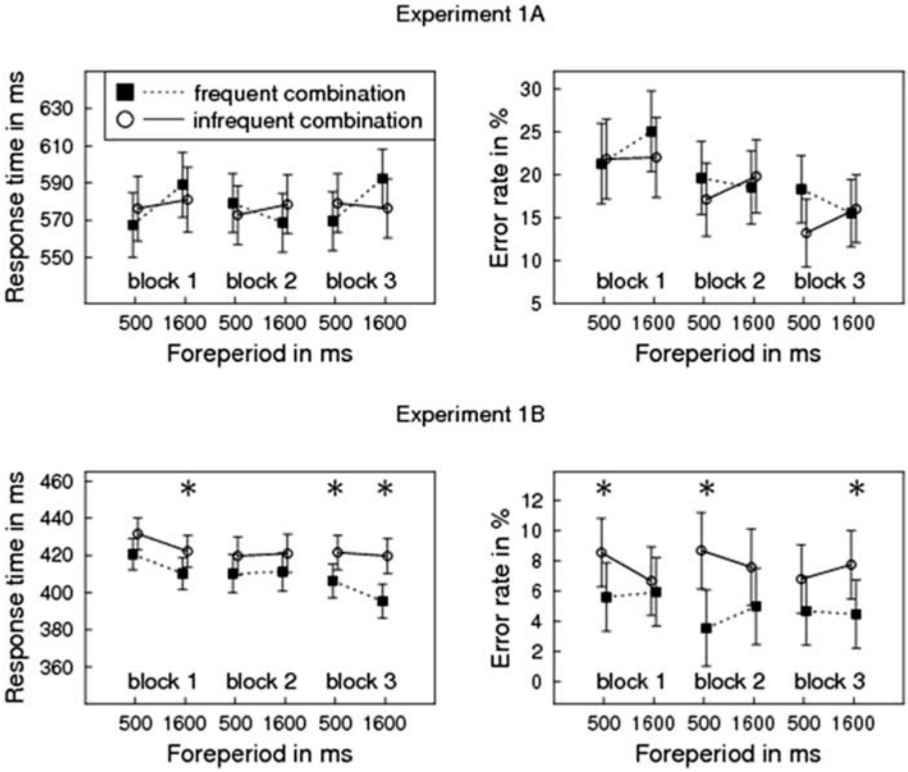

Figure 4. Mean response times and error rates in Exp. 1A and 1B. Asterisks denote significant differences between frequent FP-event combinations and infrequent FP-event combinations, evaluated separately at each FP in each block by directional two-tailed *t* tests (Leventhal & Huynh, 1996). α levels were set to 0.05. Error bars represent an average of the three error terms in a FP × Frequency ANOVA (Loftus & Masson, 1994; Masson & Loftus, 2003) for each individual block.

$F(1, 92) = 4.216$, $p = 0.018$, $\eta^2_p = 0.084$. The latter main effect was due to a linear trend towards faster responses in later blocks, $F(1, 46) = 8.821$, $p = 0.005$, $\eta^2_p = 0.161$. Block and Combination-Frequency did not interact, $F(2, 92) = 2.049$, $p = 0.135$, $\eta^2_p = 0.043$. Separate 2 × 2 ANOVAs for each block of Exp. 1B, with the factors FP and Combination-Frequency, additionally confirmed that the main effect for Combination-Frequency was present throughout the experiment (Block 1: $p = 0.005$, Block 2: $p = 0.032$, Block 3: $p < 0.001$, see Fig. 4).

3.2. Error Rates

Overall, participant responded with fewer errors in Exp. 1B (3.81%, SD = 3.4) than in Exp. 1A (9.87%, SD = 6.0, $t(90) = 6.016$, $p < 0.001$). In Exp. 1A, responses in inductive trials (5.30%, SD = 3.9) were less often erroneous than responses in diagnostic trials (19.00%, SD = 12.3, $t(44) = 8.707$, $p < 0.001$). In Exp. 1B, responses in inductive trials (2.61%, SD = 2.7) were also more often correct than responses in diagnostic trials (6.21%, SD = 5.58, $t(46) = 5.856$, ps < 0.001).

3.2.1. TBE in Diagnostic Trials

A 2 × 2 × 2 × 3 mixed ANOVA over diagnostic trials has been conducted. The between-subjects factor was Experiment (1A, and 1B). The within-subjects factors were Combination-Frequency (frequent, and infrequent), FP (500 ms, and 1600 ms), and Block (1, 2, and 3).

The main effects of Experiment, $F(1, 90) = 41.242$, $p < 0.001$, $\eta^2_p = 0.314$, of Combination-Frequency, $F(1, 90) = 10.132$, $p = 0.002$, $\eta^2_p = 0.101$, and of Block, $F(2, 180) = 11.146$, $p < 0.001$, $\eta^2_p = 0.110$, were significant. The interaction between Block and Experiment was also significant, $F(2, 180) = 7{,}048$, $p = 0.001$, $\eta^2_p = 0.073$. No other main effect or interaction was significant (all ps > 0.281). Although Frequency did not interact with Experiment, $F(1, 90) = 1.178$, $p = 0.281$, $\eta^2_p = 0.013$, two separate repeated-measures 2 × 2 × 3 ANOVAs have been conducted for Exps 1A and 1B, because in response times the result patterns differed considerably (see above). The factors were, as above, Combination-Frequency (frequent, and infrequent), FP (500 ms, and 1600 ms), and Block (1, 2, and 3).

The ANOVA for Exp. 1A, revealed only a significant main effect for Block, $F(2, 88) = 10.919$, $p < 0.001$, $\eta^2_p = 0.199$, due to a linear trend towards fewer errors in later blocks, $F(1, 44) = 20{,}212$, $p < 0.001$, $\eta^2_p = 0.315$. The main effect for Combination-Frequency was not significant, $F(1, 44) = 1{,}639$, $p = 0.207$, $\eta^2_p = 0.036$. No other main effect or interaction was significant (all $p > 0.207$).

In the ANOVA for Exp. 1B, the only significant effect was the main effect for Combination-Frequency, $F(1, 46) = 13.303$, $p = 0.001$, $\eta^2_p = 0.224$ (all other ps > 0.368). Separate 2 × 2 ANOVAs for each block of Exp. 1B, with the factors FP and Combination-Frequency, showed that the main effect for Combination-Frequency was present throughout the experiment, yet only marginally significant in Block 1 (Block 1: $p = 0.093$, Block 2: $p = 0.008$, Block 3: $p = 0.017$, see Fig. 4).

4. Discussion

We tested whether TBE facilitates features processing or response processing. In one subexperiment (Exp. 1A) TBE for feature and for response processing would have facilitated different types of diagnostic trials, while in another subexperiment (Exp. 1B) both types of TBE would have facilitated the same type of diagnostic trial.

Results were clear-cut. Errors and RTs consonantly showed no performance differences between different types of diagnostic trials in Exp. 1A, but a pronounced performance advantage for the temporally predicted trials in Exp. 1B. This pattern of results is obviously at odds with the hypothesis that one type of TBE (either for stimulus feature or response) is either exclusive or much stronger than the other type. This hypothesis would have predicted a significant difference between trial types in Exp. 1A. But the pattern of results clearly supports the hypothesis that TBE for stimulus features and TBE for responses of comparable strength were involved. In Exp. 1A, where both types of TBE impact on different trials, they cancel out each other's performance advantages. In Exp. 1B, where they consonantly impact on the same type of trial, they produce a strong TBE effect.

4.1. Conclusion

The data suggest that TBE can simultaneously be formed for stimulus features and for responses. Concerning the TBE for stimulus features, this study is, to our knowledge, the first demonstration of TBE for any kind of perceptual processing. Previous theorizing on TBE has mostly focused on response-related TBE (e.g., Thomaschke & Dreisbach, 2013; Thomaschke et al., 2011c). Yet, purely response-based TBE would not be consistent with the different patterns of results in both experimental groups. In both experiments, responses were highly correlated with FPs. Thus, response-related TBE should have been observable in diagnostic trials of *both* experiments.

However, previous research on TBE for stimulus features only applied stimulus features that were not task-relevant. The temporally predictable features in the present study were, on the contrary, task-relevant. Thus, we conclude that TBE can also be formed for stimulus features, as long as they are task-relevant. What does this mean for the football example from the introduction — the goalkeeper expecting a penalty shot? Our results suggest that he did not only prepare on a motor level to dive to a particular corner after a particular interval, but that his visual system was also tuned to process a shot at that corner after that interval faster.

4.2. TBE for Perceptual Processing

Our results suggest that TBE can affect perceptual processing. They do, however, not allow any conclusion about how temporal expectancy speeds up the perceptual process selectively for certain stimulus features. For TE, some authors have suggested that the expectancy accelerates the accumulation of visual information (Bausenhart et al., 2008; Correa et al., 2006b). Others have argued that temporal expectancy accelerates the detection of stimulus onset, so that the visual accumulation of response-relevant stimulus information starts earlier (the early onset hypothesis, Mo & George, 1977; Rolke & Hofmann, 2007). The early onset hypothesis for TE has recently been supported by several TE studies (Bausenhart et al., 2010; Seibold et al., 2011a, b).

However, in TBE, one can expect not only the point of target occurrence, but also the target itself. Thus, a further explanation of the visual impact of TBE would be, that visual processing is biased towards the stimulus feature that often appeared at the current FP, and hence, reaches the identification threshold earlier. From the present study, it cannot be concluded whether TBE speeds up the onset of visual information accumulation, or the accumulation process itself, or whether it is due to a temporally specific bias towards one of the targets. Further research into TBE would be required in order to distinguish between these possibilities.

4.3. Alternative Explanations

There are two potential alternative explanations of the result pattern, which we cannot reject based on the present data. They are however at odds with previous research.

4.3.1. A Response Mapping Account

One alternative account would ascribe the observed result pattern to mapping complexity. In Exp. 1A we employed a complex mapping: participants had to evaluate both feature dimensions to identify the response. In Exp. 1B, on the contrary, only one feature dimension had to be evaluated. One might argue that the general cognitive complexity of response choice might have overshadowed effects of TBE in Exp. 1A. According to this logic, the absence of a significant difference in diagnostic trials was not due to perceptual and motor TBE cancelling each other out, but instead to the absence of any form of TBE in this experiment at all. Indeed this explanation cannot be rejected based on the present data alone. Though we retain our initial explanation in terms of counteracting perceptual and motor TBEs, because in a previous study (Thomaschke et al., 2011c, Exp. 3) we employed exactly the same complex stimulus response mapping, and observed a reliable TBE effect. This finding is at odds with the claim that complex mappings overshadow TBE.

4.3.2. A Purely Perceptual Account

One might argue that our results are also compatible with a purely perceptual account of TBE. Such an account would have to propose that TBE is only possible for the response-*decisive* aspect of the stimulus, be it either a feature dimension, or the stimulus' identity. Such an account would assume the following: when response classes are distinguished by a stimulus feature dimension (e.g., shape or orientation), TBE can be formed along this feature dimension, in the sense that perceptually processing of one feature (e.g., horizontal) is expected after a short FP, and processing of the other features (e.g., vertical) is expected after the long FP. Consequently, TBE effects were observed whenever FPs correlated with response-decisive feature dimensions (Thomaschke et al., 2011a; Wagener & Hoffmann, 2010b), including Exp. 1B of the present study.

When stimuli are grouped into response classes via individual stimulus identities, as with feature-orthogonal stimulus-response mappings, TBE will, according to such an account, be formed for stimulus identities. That would mean that one would expect to perceptually process one stimulus after a short FP and another one after a long FP. Consequently TBE would be present whenever stimuli are correlated with FPs, and the stimulus-response mapping rule draws on stimulus identities (instead of stimulus features). This was the case in Thomaschke et al. (2011c, Exp. 3), and in inductive trials in Exp. 1A of the present study. As a potential TBE for stimulus identities cannot transfer to other stimulus identities, it was not observable in diagnostic trials of Exp. 1A. Consequently, we found TBE in diagnostic trials of Exp. 1B, but not in diagnostic trials of Exp. 1A.

Although such a purely perceptual account would fully explain the present results, we favor our explanation in terms of perceptual and motor expectancy, because TBE for motor processing has been shown in previous studies with very similar designs (e.g., Thomaschke & Dreisbach, 2013; Thomaschke et al., 2011c).

4.4. Limitations and Future Research

The present study provides evidence for TBE for stimulus features. However, this evidence is rather indirect, as we infer the existence of TBE from an inter-experiment comparison, where we assume a cancelling out between perceptual and motor TBE in one condition, but not in the other. Due to the indirect nature of our conclusion, the design also allows an alternative explanation without perceptual TBE. Thus, we recommend that future research on this topic aims at accessing perceptual TBE directly, for example by investigating TBE in a purely perceptual task without speeded motor responses.

4.5. General Conclusions

We have shown for the first time that TBE can be built for perceptual processing. One can form temporally specific expectancies for stimulus features, as long as these features are relevant for response choice. Further research has to determine whether TBE for stimulus features relies on a speeded detection of stimulus onset, or on a speeded accumulation of perceptual decision information.

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