Research Article

Temporal Cueing of Target-Identity and Target-Location

Annika Wagener and Joachim Hoffmann

Department of Psychology, Julius-Maximilians University of Würzburg, Germany

Abstract. In four experiments either a short or a long foreperiod preceded the presentation of one of two targets, presented either in the center of the screen (Experiment 1) or at one of two locations (Experiments 2–4). Participants were to identify the presented target by pressing a left or a right button as quickly as possible. In Experiment 1, each of the two targets and in Experiment 2, each of the two locations appeared frequently after one and infrequently after the other foreperiod. Experiments 3 and 4 explored the combined effects of disparate frequency distributions of targets and locations to the two foreperiods. Reaction times and error rates revealed faster processing and/or less errors for respectively those targets and locations which were frequent after the current foreperiod. The data suggest that besides location-specific target expectancies (Hoffmann & Kunde, 1999) also time-specific expectancies for those targets and target-locations are formed which are likely at the respective point in time.

Keywords: temporal cueing, foreperiods, covariation learning

Numerous experiments have shown that redundant distributions of stimuli in space affect stimulus processing. In particular, target stimuli are responded to more quickly if they are presented at locations where they frequently appear compared to locations where they rarely appear (e.g., Chun & Jiang, 1998, 2003; Hoffmann & Kunde, 1999; Hoffmann & Sebald, 2005a, 2005b; Meyers & Rhoades, 1978; Miller, 1988; Olson & Chun, 2002). The finding suggests that covariation between locations and targets leads to location-specific target expectancies (Hoffmann & Kunde, 1999). The present experiments were designed in order to explore whether these findings can be expanded to the dimension of time, that is, whether stimuli also are more quickly responded to if they are presented at points in time at which they frequently appear compared to points in time at which they rarely appear.

The study emanates from the "foreperiod paradigm" mainly. In a typical foreperiod experiment, a ready signal is initially presented. After a certain delay, the "foreperiod," another target signal is presented to which participants are to respond as quickly as possible. If the length of the foreperiod is fixed within blocks of trials, reaction times (RTs) increase with the duration of the foreperiod, what has been called the "fixed-foreperiod effect." However, if the foreperiod varies from trial to trial in an unpredictable manner, the reverse pattern is observed: RTs decrease as the foreperiod increases. This has been called the "variable-foreperiod effect" (cf. Niemi & Näätänen, 1981, for a comprehensive review).

The fixed-foreperiod effect has been ascribed to a decrease of the readiness to react and/or to a decrease in the accuracy of duration judgments the longer the foreperiod lasts. According to the former account, the readiness to react is high immediately after the ready signal and decays over time, causing an increase of RTs (e.g., Alegria, 1975; Gottsdanker, 1975; Vallesi & Shallice, 2007). According to the latter account, participants try to tailor response readiness to the point in time at which the target signal is to be expected. As long durations are less accurately estimated than shorter ones (the so-called "scalar property of variance," e.g., Allan & Gibbon, 1991; Gibbon, 1977; Gibbon, Church, & Meck, 1984; Wearden & Lejeune, 2008) the readiness to react more frequently misses target presentations after long than after short foreperiods so that RTs increase with the duration of the foreperiod.

The variable-foreperiod effect, on the other hand, is most probably due to an adaptation to the increasing conditional probabilities of target presentation, the so-called hazard function. Imagine, for example, an experiment in which four foreperiods are used with equal frequency. Initially, the probability for the presentation of a target after each of the four foreperiods is .25. After the first foreperiod has passed, three foreperiods remain after each of which the target is presented with a probability of .33. After the second foreperiod, the probability for each of the remaining two foreperiods increases to .5, and finally, after the third foreperiod, the target occurs after the longest foreperiod with a probability of 1.0. Participants most likely adjust to the increasing probability by continually enhancing their response readiness. In agreement with this account, the variable-foreperiod effect almost disappears if target presentations are made equally probable after each of the used foreperiods by inserting blank trials at which no target is presented (e.g., Bertelson & Tisseyre, 1968; Näätänen, 1970, 1971).

DOI: 10.1027/1618-3169/a000054

Altogether, the "foreperiod research" shows that target expectancies adapt to either fixed points in time of target presentation or to time-related conditional probabilities of target presentation. The present experiments go beyond these studies in two respects. First, instead of one definite target, two targets are presented which are *differently* distributed in time so that participants face not only one but two time-related target distributions at once. Second, not only the response relevant targets but also the response irrelevant target-locations were differently distributed in time. As mentioned above, covariation between *targets* and *locations* leads to adaptations of target-specific processing capacities to target-specific locations. To the best of our knowledge, the present study explores for the first time whether disparate distributions of targets and/or locations to certain points in time will also result in comparable adaptations of target-specific and location-specific processing capacities to the points in time at which these capacities are most likely required.

In the following experiments, participants mostly experience two target stimuli appearing at two locations after two foreperiods. Each stimulus, each location, and each foreperiod occurs equally often so that neither the stimulus, nor the location, nor the foreperiod is predictable on its own. A particular stimulus and/or a particular location is, however, more probable after a certain foreperiod than after the other one. Accordingly, the point in time when a stimulus appears carries information about the particular stimulus and/or the particular location that are typical or "valid" for this particular point in time. In this respect the present experiments resemble studies in which the point in time at which a definite target will most likely appear is explicitly cued in each trial (e.g., Coull, Frith, Büchel, & Nobre, 2000; Coull & Nobre, 1998). Unlike in these studies, however, there is neither an explicit nor an implicit cue for the forthcoming target or the forthcoming location in the present experiments. It is merely the moment in which something is happening that indicates which target and/or which target-location probably will appear.

Note that although both foreperiods are equally likely, they differ with respect to their predictability in the course of a trial: During the short foreperiod, the point in time at which one of the targets will appear is indeed unpredictable and so are targets and target-locations too. However, once the short foreperiod had passed, the target had to appear at the late point in time so that the target and/or the location, which often appear late, concurrently become predictable. Thus, we expect faster responses to late compared to early targets and/or target-locations (the "variable-foreperiod effect").

Experiment 1

Experiment 1 investigated the impact of a covariation between two foreperiods and two stimuli (targets) on performance in a choice RT task. Targets were presented in the center of the screen after a short or a long foreperiod. Participants were to respond as quickly as possible to the target-identity by pressing either a left or a right button. Targets and foreperiods were equally often presented in random order. After the short foreperiod one of the targets, however, was more likely whereas after the long foreperiod the other target was more likely. Accordingly, when a target appeared after a certain foreperiod, it could either be the target that typically appeared at this point in time or the target that appeared infrequently after this foreperiod. In this sense, the point in time at which a target appeared (the foreperiod) provided information about the likely identity of the current target as well as about the likely required response. If this temporally related information was used, responses to temporally probable or "valid" targets should be faster and/or less error prone than responses to temporally less probable or "invalid" targets.

Method

Participants

Twenty volunteers participated in exchange for pay. There were 9 males and 11 females with ages ranging from 20 to 28 years. All participants reported having normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Apparatus and Stimuli

A computer (Pentium IV, 2.6 GHz) with a 17 in. VGA Display was controlled by E-Prime (Schneider, Eschman, & Zuccolotto, 2002). Responses were executed with the index fingers of both hands and were collected with an external keyboard with three response keys (2.5 cm width and distance 3.6 cm). The middle response key served to start the session.

The imperative targets were a square and a circle with a size of approximately 2 × 2 cm, seen from a distance of about 50 cm. The targets were preceded by two foreperiods of either 600 or 1,400 ms in duration. During the foreperiod a 1 × 1 cm fixation cross was presented in the center of the screen. All characters were presented in white on dark-gray background, except for the feedback that was presented in red letters.

Procedure and Design

Each trial started with the presentation of a fixation cross either for 600 ms or for 1,400 ms (foreperiod). Then a target replaced the fixation cross for 100 ms followed by a blank interval of 900 ms. Participants were to respond as quickly as possible to the square and to the circle by pressing the left button with the left index finger or the right button with the right index finger. The mapping of responses to targets was counterbalanced between participants. After the blank interval had elapsed, response feedback was presented for

1,500 ms. An incorrect response was indicated by the German word for wrong (falsch). If no response was registered, the German words for "faster please" (bitte schneller) were presented.

The experiment was run in eight blocks with 100 trials each, presented in random order. In 40 trials, the circle was presented after a short foreperiod, and, in 40 other trials, the square was presented after the long foreperiod (or vice versa, resulting in 80 temporally valid trials). In 10 trials, the square was presented after the short foreperiod, and, in 10 further trials, the circle was presented after the long foreperiod (or vice versa, resulting in 20 temporally invalid trials).

Data Analysis

In this one and in all following experiments the first block was considered practice and excluded from analysis as well as the first trial of each block. For the analysis of mean RTs, trials with RTs deviating more than 2.5 standard deviations from the mean RT of each experimental condition and each participant were discarded as outliers (1.4%). Mean RTs for correct responses and mean percentages of error were separately computed for each participant and each combination of the factors temporal validity and foreperiod.

Results

The results of Experiment 1 are depicted in Table 1 (cf. also Figure 1). For the mean RTs, an analysis of variance (ANOVA) assessing the effects of temporal validity (temporally valid vs. temporally invalid) and foreperiod (short vs. long) revealed that participants responded faster to temporally valid trials (500 ms) than to temporally invalid trials (516 ms), $F(1, 19) = 36.6$, $p < .01$, $\eta_p^2 = .66$. In addition, participants were faster in trials with the long foreperiod (502 ms) than in trials with the short foreperiod (514 ms), $F(1, 19) = 23.3$, $p < .01$, $\eta_p^2 = .55$. There was no interaction between the two factors, $F(1, 19) = 0.6$, $p = .47$, $\eta_p^2 = .03$.

The same ANOVA on error rates showed that participants made less errors in temporally valid trials (3.9%) compared to temporally invalid trials (6.0%), $F(1, 19) = 9.3$, $p < .01$, $\eta_p^2 = .33$. There was no interaction between the two factors, $F(1, 19) = 1.3$, $p = .27$, $\eta_p^2 = .06$.

Table 1. RTs and error rates in Experiment 1

	RT in ms (*SE*)		Error rates in % (*SE*)	
Foreperiod in ms	Temporally valid	Temporally invalid	Temporally valid	Temporally invalid
600	508 (15)	520 (12)	4.3 (0.8)	5.5 (1.3)
1,400	492 (14)	512 (13)	3.6 (0.6)	6.4 (1.1)
Total	500 (14)	516 (12)	3.9 (0.6)	6.0 (1.1)

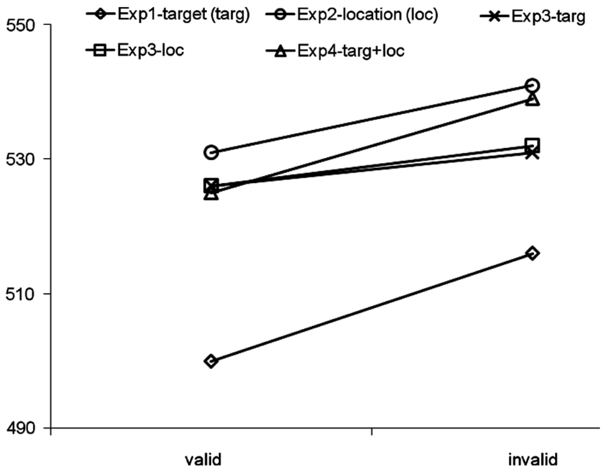

Figure 1. RTs (in ms) to time-related valid and invalid targets and/or to time-related valid and invalid locations in Experiments 1–4.

Discussion

In Experiment 1 participants responded with a left or a right button press to a circle and a square that appeared either 600 or 1,400 ms after the onset of a fixation cross. One of the two targets was more likely presented at the early point in time whereas the other target was more likely presented at the late point in time (temporally valid targets). The data show that the response to the temporally valid targets was faster and less error prone than to the temporally invalid targets at both possible points in time. This temporally related "validity effect" suggests that participants not only oriented unspecific attention to the points in time but rather assigned stimulus- and/or response-specific processing capacities to those points in time at which the corresponding stimulus-response couple were most likely to occur.

We already mentioned that the forthcoming presentation time and the forthcoming target remain unpredictable until the short foreperiod has elapsed. Thereafter, target presentation is certain at the late point in time and concurrently the respective late-valid target becomes most likely. Accordingly, participants responded faster and were less error prone to targets that were presented at the late point in time – the typical "variable-foreperiod effect."

Experiment 2

Experiment 2 investigated the impact of a covariation between two foreperiods and two locations on performance in a choice reaction task. As in Experiment 1, participants responded to a circle or a square after a short or a long foreperiod by pressing a left or a right button. In contrast to Experiment 1, the targets were not presented at the center of the screen but equally often on the right or the left of a central fixation cross in random order. Thus, foreperiods,

Table 2. RTs and error rates in Experiment 2

		RT in ms (*SE*)		Error rates in % (*SE*)	
Foreperiod in ms	Spatial S-R compatibility	Temporally valid	Temporally invalid	Temporally valid	Temporally invalid
600	Compatible	515 (13)	534 (18)	4.6 (1.3)	2.4 (0.8)
	Incompatible	556 (17)	560 (14)	6.7 (1.2)	7.2 (1.3)
1,400	Compatible	516 (17)	511 (15)	3.4 (0.7)	3.0 (1.1)
	Incompatible	535 (16)	561 (17)	5.2 (0.8)	6.9 (1.5)
Total		531 (15)	541 (15)	5.0 (0.8)	4.9 (0.8)

targets, and locations were equally likely. However, after each foreperiod, presentations at one location were more likely than presentations at the other location. Accordingly, the point in time at which a target appeared (the foreperiod) neither provided information about the probable target nor about the probably required response but it indicated the response irrelevant location at which the target would probably appear.[1]

Method

Participants

Twenty volunteers participated in exchange for pay (age range 18–48 years, 14 females). All participants reported having normal or corrected-to-normal vision and were not familiar with the purpose of the experiment.

Apparatus, Stimuli, Procedure, and Design

The apparatus, stimuli, procedure, and design were the same as in Experiment 1, except that targets were presented 5.5 cm left and right of the fixation cross and that instead of target-identity, target-location covaried with the foreperiod: After the short foreperiod one of the locations was more likely whereas after the long foreperiod the other location was more likely. Altogether, however, temporally likely and unlikely locations were of equal frequency.

Data Analyses and Results

Besides the first block and the first trial of each block, 1.1% outliers were excluded from the analysis of the mean RTs. The resulting data are depicted in Table 2 (cf. also Figure 1). For the mean RT, the ANOVA assessing the effects of temporal validity (temporally valid vs. temporally invalid), spatial compatibility (compatible vs. incompatible), and foreperiod (short vs. long) revealed significant main effects for all three factors: Participants responded faster to temporally valid trials (531 ms) than to temporally invalid ones (541 ms), $F(1, 19) = 26.1$, $p < .01$, $\eta_p^2 = .58$. Participants were faster in compatible trials (519 ms) than in incompatible trials (553 ms), $F(1, 19) = 70.2$, $p < .01$, $\eta_p^2 = .79$. Responding to trials with the long foreperiod was faster (531 ms) than responding to trials with the short foreperiod (541 ms), $F(1, 19) = 11.2$, $p < .01$, $\eta_p^2 = .37$. No other effect reached significance, all p's > .24.

The same ANOVA for the error rates showed that participants made less errors in compatible trials (3.3%) compared to incompatible trials (6.5%), $F(1, 19) = 14.2$, $p < .01$, $\eta_p^2 = .43$. Additionally, there was a significant interaction between temporal validity and response compatibility, $F(1, 19) = 7.4$, $p < .05$, $\eta_p^2 = .28$. No other effect reached significance, all p's > .24.

Discussion

In Experiment 2, participants responded to a circle and a square that appeared either left or right of a fixation cross after a foreperiod of 600 or 1,400 ms. At the early point in time targets were preferably presented at one of the two locations whereas the respective other location was most likely used at the late point in time (temporally valid locations). The data show that responses to targets at temporally valid locations are faster than responses to targets at temporally invalid locations. This temporally related "validity effect" suggests that spatial attention is somewhat faster oriented to the current target if it appears at a location at which targets in general frequently appear at the current point in time.

Participants again responded faster to targets that were presented at the late point in time reflecting the high predictability of late target presentations as soon as the short foreperiod has passed.

---

[1] Because the targets which were presented to the left and to the right of the fixation cross required responses with either the left or the right hand, RTs were influenced by spatial stimulus-response compatibilities. However, for the sake of clarity, compatibility effects are not further discussed in this and in the following experiments as they did not contribute to a further understanding of the temporal validity effects which are the main concern of the present paper. Yet, in order to make the effect sizes measures for temporal validity comparable across experiments, compatibility is, though, involved as an ANOVA factor.

Experiment 3

The two previous experiments found temporally related validity effects for targets and locations which were frequently presented at a certain point in time compared to targets and locations which were rarely presented at the respective points in time. Experiment 3 was conducted in order to test whether these findings can be replicated. Moreover, Experiment 3 aimed at a direct comparison of the temporal validity effects for target-identities and target-locations.

Recently, Doherty, Rao, Mesulam, and Nobre (2005) explored the impact of temporal and spatial predictions on performance (cf. also Lange, Krämer, & Röder, 2006). In their study participants watched a circle moving from left to right on a display. While moving, the circle disappeared behind an opaque square. When the circle reappeared, it could contain a black dot which was to be detected as quickly as possible. The circle moved either along a straight or along a randomly changing trajectory so that the location of its reappearance was either predictable or unpredictable. Additionally the circle moved either with a fixed velocity or with randomly changing velocities so that also the moment of its reappearance was either predictable or unpredictable. Doherty and colleagues found that spatial and temporal predictabilities independently improved detection performance. Accordingly, we also expect effects of the temporally related predictabilities of target-identities and target-locations as well.

Note that in the study of Doeherty et al. (2005) the move of the circle provided information about the forthcoming place and/or the forthcoming moment of its reappearance. In the present study, however, there are no cues at the outset of a trial, but the duration of the foreperiod provides information about the currently probable target as well as about its currently probable location. Consequently, there was a valid target as well as a valid location for each foreperiod. For example, after the short foreperiod, target's identity was likely a circle and target's location was likely left from the fixation cross (cf. Table 3). The frequencies were adjusted in such a way that both targets appeared equally often at both locations, that is, targets did not covary with locations. As a result, the ratio of valid trials to invalid trials per block (32:16) had to be reduced in comparison to the previous experiments (80:20, see Table 3).

The design does not allow an unbiased assessment of possible interactions between target-related and location-related temporal validities as the disparities in the frequency distributions are not balanced: For example, at temporally valid locations, the frequency relation of valid to invalid targets is 20:12 whereas at temporally invalid locations the relation is 12:4, an inevitable consequence of keeping the frequencies of both targets at both locations the same.

Table 3. Exemplary distribution of stimuli in one block of Experiment 3

	Circle		Square		
Foreperiod in ms	Left	Right	Left	Right	Total
600	20	12	12	4	48
1,400	4	12	12	20	48
Total	24	24	24	24	96

Method

Participants

Twenty-four volunteers (10 males and 14 females) participated either to satisfy course requirements or in exchange for pay. Their ages ranged from 18 to 37 years. All participants reported having normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli, and procedure were largely the same as in Experiment 2, except that the temporal distribution of targets and locations was adjusted according to the purposes of the experiment (see Table 3): In a block of 96 trials, each foreperiod was followed 32 times by a frequent target and a frequent location but only 16 times by a seldom target and a seldom location. For example, after a foreperiod of 600 ms, the circle appeared 32 times whereas the square appeared only 16 times. Likewise, targets appeared 32 times on the left and only 16 times on the right of the fixation cross. However, both targets were presented 24 times each at the left and the right location. Thus, the temporal validity of targets and locations was orthogonally varied, but targets and locations remained uncorrelated. The experiment was run in nine blocks.

Results

Besides the first block and the first trial of each block, 1.8% outliers were excluded from the analysis of the mean RTs. The results are depicted in Table 4 (cf. also Figure 1). The ANOVA for the RTs, assessing the effects of temporal target-validity (valid vs. invalid), of temporal location-validity (valid vs. invalid), and of foreperiod (short vs. long), revealed significant main effects of target-validity, $F(1, 23) = 15.9$, $p < .01$, $\eta_p^2 = .41$, location-validity, $F(1, 23) = 12.5$, $p < .01$, $\eta_p^2 = .35$, and foreperiod, $F(1, 23) = 12.3$, $p < .01$, $\eta_p^2 = .35$. Participants were faster (526 ms) in trials in which the target was temporally valid compared to those in which the target was invalid (531 ms). Furthermore, participants were faster in trials in which the location was temporally valid (526 ms) than in trials in which the location was invalid (532 ms). Further, participants were faster in trials with a long foreperiod (522 ms) than in trials with a short foreperiod (535 ms). No interaction reached significance, all p's > .24. The same ANOVA for error rates revealed no significant effects; all p's > .42.

Table 4. RTs and error rates in Experiment 3

	RT in ms (*SE*)				Error rates in % (*SE*)		
	Foreperiod in ms	Location-valid	Location-invalid	Total	Location-valid	Location-invalid	Total
Target-valid	600	537 (14)	537 (14)	526 (13)	5.1 (0.8)	5.0 (1.0)	4.9 (0.7)
	1,400	513 (16)	517 (14)		4.8 (1.5)	4.8 (1.0)	
Target-invalid	600	529 (14)	538 (15)	531 (13)	5.1 (0.9)	4.8 (1.4)	5.3 (0.9)
	1,400	524 (13)	535 (14)		5.5 (1.2)	5.9 (1.5)	
Total		526 (13)	532 (13)		5.1 (0.8)	5.1 (0.8)	

Discussion

In Experiment 3, participants again responded to a circle and a square that were presented after a foreperiod of 600 or 1,400 ms either left or right of a fixation cross. Each of the two targets appeared more often after one foreperiod than after the other. At the same time, each of the two locations was more frequent after one foreperiod than after the other. The data revealed corresponding temporally related frequency effects: If targets appeared at a point in time at which they most often appeared, participants responded more quickly in comparison to when targets appeared at a point in time at which they seldom appeared. At the same time, participants responded more quickly to targets appearing at a location that was more likely at the current point in time than to targets appearing at a location that was less likely at this point in time. Thus, Experiment 3 confirms the findings of Experiments 1 and 2 as the temporal validity effects concerning RTs were replicated, even with a reduction of the frequency disparities between valid and invalid trials from 80:20 in the previous experiments to 32:16 in the present experiment.

We already noted that the present design does not allow an unbiased assessment of possible interactions between the target-related and the location-related validity effects as the disparities between temporal valid and temporal invalid location- and target-frequencies are always greater when the respective other feature is invalid (12:4) compared to when it is valid (20:12). The numerical data reflect these unequal disparities: The average target-related validity effect increases from 1.5 ms for valid locations to 9.5 ms for invalid locations. The average location-related validity effect likewise increases from 2 ms for temporal valid targets to 10 ms for temporal invalid targets.

Participants responded more quickly to targets presented after the long foreperiod than to targets presented after the short foreperiod (the variable-foreperiod effect).

Taken together, the data confirm target-specific as well location-specific processing adaptations to the frequencies with which particular targets appear at particular locations at particular points in time. That is, time-specific target expectancies and time-specific location expectancies commonly affect performance.

Experiment 4

In Experiments 2 and 3, two targets were presented at two locations whereas both targets appeared equally likely at both locations. Such an equal distribution of stimuli in space is rather unlikely in natural settings. Stimuli or objects typically occur more often at particular locations than at other locations: Taps are typically above and not beside a basin, knives lie more often right than left to the plates, logos of television channels are typically presented in the right upper instead of in the left lower corner of the screen, etc. In the introduction, we already mentioned that human beings are very sensitive to such spatial redundancies. So far, the present experiments revealed comparable effects for redundant temporal distribution of target-identities and of target-locations if targets are equally distributed among the possible locations, that is, if time-related redundancies do not compete with space-related redundancies. In Experiment 4, we examine whether the found validity effects of time-related frequencies occur even beyond and in addition to the well-known validity effects of location-related frequencies.

For this purpose, targets often appeared at a particular location but the frequent target-location compounds additionally appeared more often at one certain point in time than at another one. For example, the circle appeared most often above the fixation cross and this happened mostly after the short and only seldom after the long foreperiod (see Table 5). In contrast, the rare target-location compounds were equally distributed over the two possible points in time. We expect faster processing of targets at their frequent locations, that is, the typical spatial validity effect. Additionally, we expect an effect of temporal validity, that is, participants are expected to respond quicker to the frequent target-location compound at that point in time at which the compound is frequently appearing compared to the point in time at which the compound seldom appears.

Additionally, we introduced so-called catch trials in order to reduce the variable-foreperiod effect. In catch trials, a cross was presented and participants were to withhold any response and to wait for the next imperative target. Accordingly, imperative targets were not always presented so that participants could no longer be sure that a late target would appear after the short foreperiod has passed. This, in turn, should reduce the tendency to expect a "late" imperative

Table 5. Exemplary distribution of stimuli in one block of Experiment 4

	Circle		Square		Cross		
Foreperiod in ms	Above	Below	Above	Below	Above	Below	Total
600	32	8	8	2	5	5	60
1,400	2	8	8	32	5	5	60
Total	34	16	16	34	10	10	120

target when no "early" target was presented (cf. Correa, Lupiáñez, & Tudela, 2006).

Method

Participants

Sixteen volunteers (8 males and 8 females) participated either to satisfy course requirements or in exchange for pay. Their ages ranged from 18 to 28 years. All participants reported having normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli, and procedure were largely the same as in Experiment 2, except that we inserted catch trials and that targets were presented 1.5 cm above and below instead of to the left and right of the fixation cross. Moreover, the distribution of targets and locations was adapted for the present purposes (cf. Table 5): From 120 trials in each block the circle and the square were presented 50 times each, thereof 34 times at one and only 16 times at the respectively other location. By this, a likely location was created for each target. For example, the circle appeared most likely above and the square appeared most likely below the fixation cross (see Table 5). Accordingly, there were 68 trials in each block in which targets appeared at their likely and 32 trials in which targets appeared at their unlikely location. Furthermore, the unlikely located targets were equally distributed among the two foreperiods (8 times after each foreperiod) whereas the likely located targets appeared most likely after one and seldom after the other foreperiod. For example, the circle above the fixation cross appeared 32 times after 600 ms but only 2 times after 1,400 ms. Accordingly, there were 64 trials in each block in which targets presented at their most likely position appeared at their valid point in time and 4 trials in which targets presented at their most likely position appeared at an invalid point in time. Finally, 10 crosses were presented after each foreperiod requiring no response (20 catch trials). The experiment was run in 9 blocks.

Data Analysis

Besides the first block, the first trial of each block, and the catch trials, 1.3% outliers were discarded from the analysis of the mean RTs. According to the purpose of the present experiment, the data were subject to two separate analyses. The first analyses aimed at assessing the impact of location-target covariation on stimulus processing. Therefore, we compared performance in all trials in which targets appeared at their likely location with performance in all trials in which targets appeared at their unlikely location. In the second analysis, all trials in which the frequent target-location compounds appeared at their valid point in time were compared with all trials in which these compounds appeared at their invalid point in time. This analysis will reveal the impact of temporally related target expectancies on performance over and beyond the impact of location-specific target expectancies.

Results

The results of Experiment 4 are depicted in Table 6 (cf. also Figure 1). The ANOVA for the RTs, assessing the effect of spatial redundancy (frequent vs. seldom target-location compounds) and foreperiod (short vs. long), revealed a significant main effect of spatial redundancy, $F(1, 15) = 71.8$, $p < .01$, $\eta_p^2 = .83$. Participants responded faster (532 ms) to targets appearing at their frequent location compared to targets appearing at their infrequent location (563 ms). No other effect reached significance, all p's > .20. The same ANOVA on error rates also revealed a significant main effect for spatial redundancy, $F(1, 15) = 14.7$, $p < .01$, $\eta_p^2 = .50$. Participants made less errors (3.2% vs. 7.5%) when responding to targets at their frequent location than when responding to targets at their infrequent location. No other effect was significant; all p's > .75.

The second ANOVA on mean RTs of only those trials in which the targets appeared at their frequent location, assessing the effect of temporal validity (temporally valid vs. temporally invalid) and foreperiod (short vs. long), revealed a significant main effect of temporal validity, $F(1, 15) = 11.94$, $p < .01$, $\eta_p^2 = .44$. Participants responded more quickly to temporally valid targets (525 ms) than to temporally invalid ones (539 ms). No other effect reached significance; all p's > .25. The same ANOVA for the error rates revealed no significant effects; all p's > .70.

Discussion

In Experiment 4, participants responded to a circle and a square that were presented after a foreperiod of 600 or

Table 6. RTs and error rates in Experiment 4

	RT in ms (*SE*)			Error rates in % (*SE*)		
	Frequency target-location combination			Frequency target-location combination		
Foreperiod in ms	Temporally valid	Temporally invalid	Seldom target-location combination	Temporally valid	Temporally invalid	Seldom target-location combination
600	523 (18)	547 (20)	563 (18)	3.0 (1.0)	3.5 (1.6)	7.5 (1.5)
1,400	528 (22)	531 (20)	563 (20)	3.1 (0.9)	3.2 (1.4)	7.6 (1.6)
Total	525 (19)	539 (19)		3.0 (0.9)	3.3 (1.3)	
	532 (19)		563 (19)	3.2 (1.0)		7.5 (4.2)

1,400 ms either above or below a fixation cross. Each of the two targets appeared more often at one than at the other location. Participants were clearly sensitive to this spatial redundancy in that they responded on average 31 ms faster and made 4% less errors in response to targets that appeared at their frequent compared to their infrequent location. In addition to this well-known spatial validity effect, and most important in the present context, the data also revealed a temporal validity effect: If targets appeared at their frequent location at a point in time at which they more often appeared, participants responded 14 ms faster, in comparison to targets that appeared at their frequent location but at a point in time at which they were unlikely to appear. Thus, the data again confirm that participants are sensitive for the point in time at which a particular target occurs beyond and additionally to their well-known sensitivity for the location at which the target most likely occurs.

There was no effect of foreperiod, that is, participants responded neither faster nor more accurately to targets presented after the long foreperiod than to targets presented after the short foreperiod. The absence of the variable-foreperiod effect is presumably due to the insertion of catch trials by which the probability for the appearance of a target in general and of a late target in particular has been reduced (cf. Correa et al., 2006).

General Discussion

Stimuli appear distributed in space and time. Redundant distributions of stimuli in space are known to have a strong impact on behavior: Stimuli at their typical locations are responded to more quickly and more accurately than the same stimuli appearing at untypical locations (e.g., Hoffmann & Kunde, 1999; Miller, 1988; Musen, 1996). The present experiments explore whether redundant distributions of stimuli in time result in comparable behavioral effects.

In four experiments either a short or a long time interval (foreperiod) preceded one of two targets presented either in the center of the screen (Experiment 1) or at one of two possible locations (Experiments 2–4). Participants were to identify the presented targets by pressing a left or a right button as quickly as possible. Crucially, there were covariations between the point in time, at which the targets were presented and the target-identity and/or the target-location. In Experiment 1, each of the two targets respectively followed often one foreperiod and seldom the other foreperiod. In Experiment 2, each of the two target-locations was frequently used after one foreperiod but infrequently used after the other one. In Experiment 3, both, target-identity as well as target-location, covaried with the two foreperiods. Finally, in Experiment 4, an unequal distribution of the two targets over the two locations was supplemented by a disparate distribution of the frequent target-location compounds over the two foreperiods.

All experiments provided evidence for a behavioral adaptation to the redundancies in the temporal distribution of targets and locations. After each of the foreperiods those targets, or targets at those locations, that were likely at this point in time were processed more quickly (and in Experiment 1 also more accurately) compared to targets and locations that were unlikely at this point in time.

Adaptations to target distributions in time are not a new phenomenon. Numerous foreperiod experiments already showed that the detection of a definite target is improved if it appears at points in time that were experienced as being likely for its presentation (e.g., Alegria & Bertelson, 1970; Drazin, 1961; Holender & Bertelson, 1975; Moss, 1969; Näätänen, 1970, 1971). Further, it has been shown that target detection is also facilitated at points in time that were either explicitly or implicitly cued as being currently likely (e.g., Albinet & Fezzani, 2003; Correa & Nobre, 2008; Coull et al., 2000; Coull & Nobre, 1998; Doherty et al., 2005; Griffin et al., 2002). The present results go beyond these findings as they reveal that not only general but rather target- and or location-specific processing resources are selectively assigned to those points in time at which the respective processing demands are frequently required.

The present findings contribute to the ongoing discussion regarding context-related processing tuning. Until now, the impact of spatial contexts has been preferably explored: As already mentioned, stimuli are faster processed if they appear at locations at which they are frequently experienced, that is, the spatial layout of a current situation seems to prime the processing of its constituents at their frequent locations (e.g., Chun & Jiang, 1998, 2003; Hoffmann & Kunde, 1999). Thereby it has been shown that a frequent local neighborhood suffices in order to create a corresponding priming context (Hoffmann & Sebald, 2005a, 2005b; Olson & Chun, 2002). Recently this research has been extended to preceding spatial cues (Risko, Blais, Stolz, & Besner, 2008): Targets which are often preceded by a stimulus at a certain location are faster processed in trials in which the stimulus was presented at the respective location compared to trials in which it appeared at another location, despite the stimulus itself as well as its location being completely irrelevant and uninformative for the task at hand. The authors argue that the frequently experienced stimulus-target events act as compound cues which facilitate the retrieval of the processing resources that has been frequently required in this situation thus being probably most appropriate at present. Finally, Crump, Gong, and Milliken (2006) have shown that a frequent spatial context may not only prime context-specific processing resources but also a context-related allocation of attention. In their experiments the spatial context indicated whether a Stroop item is probably congruent or incongruent. Accordingly the Stroop effect was found to be more pronounced in contexts with a high likelihood compared with contexts with a low likelihood of congruency, suggesting rapid context driven control over the amount of attention allocated to the color word of the current Stroop item (cf. also Crump & Milliken, 2009; Crump, Vaquero, & Milliken, 2008). Against this background the present findings suggest that not only the spatial but also the temporal aspects of a situation become part of a situational compound which then primes the retrieval of all its constituents including the targets and processes which are frequently required in this situation.

In the present experiments, at a certain point in time, not only a particular target but also the assigned response was more likely than the alternative target-response couple. Accordingly, any time-specific improvement of the performance could as well be due to the processing of the currently likely target as to the generation of the currently likely response. Even in Experiment 2, where the point in time provided information only about the likely location of the target, temporally related validity effects could have been due either to a faster encoding of targets at the likely location or to faster eye movements to the likely location. Thus, the present data do not allow a conclusion concerning whether the observed temporal validity effects are due to stimulus processing and/or response generation (cf. also Bausenhart, Rolke, Hackley, & Ulrich, 2006; Müller-Gethmann, Ulrich, & Rinkenauer, 2003).

Altogether, the present experiments expand the findings of the traditional foreperiod paradigm and of the temporal cueing research in showing that temporally related expectancies are not only formed for definite prespecified processing demands but adapt rather online to respectively those processes which are frequently required at the current point in time. Thus, the point in time at which something happens seems to create a context which primes the processes which are typically to perform at this point in time. The concrete mechanisms which mediate such flexible and rapid temporal cueing of certain processing demands remain to be elucidated by future experiments.

Acknowledgments

This research was funded through Deutsche Forschungsgemeinschaft Grant HO 1301-13-1 awarded to Joachim Hoffmann. We wish to thank Alexander Dietz for helping assessing the data, and Andrea Kiesel, Majorie Kinney, Juan Lupiáñez, Roland Thomaschke, and two anonymous reviewers for helpful comments on earlier versions of the manuscript.

References

Albinet, C., & Fezzani, K. (2003). Instruction in learning a temporal pattern on an anticipation-coincidence task. *Perceptual and Motor Skills, 97*, 71–79.

Alegria, J. (1975). Sequential effects of foreperiod duration: Some strategical factors in tasks involving time uncertainty. In P. M. A. Rabbit & S. Dornic (Eds.), *Attention and Performance*. (pp. 1–10). London: Academic Press.

Alegria, J., & Bertelson, P. (1970). Time uncertainty, number of alternatives and particular signal-response pair as determinants of choice reaction time. *Acta Psychologica, 33*, 36–44.

Allan, L. G., & Gibbon, J. (1991). Human bisection at the geometric mean. *Learning and Motivation, 22*, 39–58.

Bausenhart, K. M., Rolke, B., Hackley, S. A., & Ulrich, R. (2006). The locus of temporal preparation effects: Evidence from the psychological refractory period paradigm. *Psychonomic Bulletin & Review, 13*, 536–542.

Bertelson, P., & Tisseyre, F. (1968). The time-course of preparation with regular and irregular foreperiods. *Quarterly Journal of Experimental Psychology, 20*, 297–300.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36*, 28–71.

Chun, M. M., & Jiang, Y. (2003). Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 224–234.

Correa, Á., Lupiáñez., & Tudela, P. (2006). The attentional mechanism of temporal orienting: Determinants and attributes. *Experimental Brain Research, 169*, 58–68.

Correa, Á., & Nobre, A. C. (2008). Neural modulation by regularity and passage of time. *Journal of Neurophysiology, 100*, 1649–1655.

Coull, J. T., Frith, C. D., Büchel, C., & Nobre, A. C. (2000). Orienting attention in time: Behavioral and neuroanatomical distinction between exogenous and endogenous shifts. *Neuropsychologia, 38*, 808–819.

Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: The neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience, 18*, 7426–7435.

Crump, M. J. C., Gong, Z., & Milliken, B. (2006). The context-specific proportion congruent Stroop effect: Location as a contextual cue. *Psychonomic Bulletin & Review, 13*, 316–321.

Crump, M. J. C., & Milliken, B. (2009). The flexibility of context-specific control: Evidence for context-driven generalization of item-specific control settings. *Quarterly Journal of Experimental Psychology, 62*, 1523–1532.

Crump, M. J. C., Vaquero, J. M. R., & Milliken, B. M. (2008). Context-specific learning and control: The role of awareness, task set, and relative salience. *Consciousness and Cognition, 17*, 22–36.

Doherty, J. R., Rao, A., Mesulam, M. M., & Nobre, A. C. (2005). Synergistic effect of combined temporal and spatial expectations on visual attention. *The Journal of Neuroscience, 25*, 8259–8266.

Drazin, D. H. (1961). Effects of foreperiod, foreperiod variability, and probability of stimulus occurrence on simple reaction time. *Journal of Experimental Psychology, 62*, 43–50.

Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review, 84*, 279–325.

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. In J. Gibbon & L. G. Allan (Eds.), *Annals of the New York Academy of Sciences: Timing and time perception*. New York: New York Academy of Sciences (pp. 52–77).

Gottsdanker, R. (1975). The attaining and maintaining of preparation. (pp. 33–42). In P. M. A. Rabbit & S. Dornic (Eds.), *Attention and Performance*. London: Academic Press.

Griffin, I. C., Miniussi, C., & Nobre, A. C. (2002). Multiple mechanisms of selective attention: Differential modulation of stimulus processing by attention to space and time. *Neuropsychologia, 40*, 2325–2340.

Hoffmann, J., & Kunde, W. (1999). Location-specific target expectancies in visual search. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1127–1141.

Hoffmann, J., & Sebald, A. (2005a). Local contextual cuing in visual search. *Experimental Psychology, 52*, 31–38.

Hoffmann, J., & Sebald, A. (2005b). When obvious covariations are not even learned implicitly. *European Journal of Cognitive Psychology, 17*, 449–480.

Holender, D., & Bertelson, P. (1975). Selective preparation and time uncertainty. *Acta Psychologica, 39*, 193–203.

Lange, K., Krämer, U. M., & Röder, B. (2006). Attending points in time and space. *Experimental Brain Research, 173*, 130–140.

Meyers, L. S., & Rhoades, R. W. (1978). Visual search of common scenes. *Quarterly Journal of Experimental Psychology, 30*, 297–310.

Miller, J. (1988). Components of the location probability effect in visual search tasks. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 453–471.

Moss, S. M. (1969). Changes of preparatory set as a function of event and time uncertainty. *Journal of Experimental Psychology, 80*, 150–155.

Müller-Gethmann, H., Ulrich, R., & Rinkenauer, G. (2003). Locus of the effect of temporal preparation: Evidence from the lateral readiness potential. *Psychophysiology, 40*, 597–611.

Musen, G. (1996). Effects of task demands on implicit memory for object-location associations. *Canadian Journal of Experimental Psychology, 50*, 104–113.

Näätänen, R. (1970). The diminishing time-uncertainty with the lapse of time after the warning signal in reaction-time experiments with varying fore-periods. *Acta Psychologica, 34*, 399–419.

Näätänen, R. (1971). Non-aging fore-periods and simple reaction time. *Acta Psychologica, 35*, 316–327.

Niemi, P., & Näätänen, R. (1981). Foreperiod and simple reaction time. *Psychological Bulletin, 89*, 133–162.

Olson, I. R., & Chun, M. M. (2002). Perceptual constraints on implicit learning of spatial context. *Visual Cognition, 9*, 273–302.

Risko, E. F., Blais, C., Stolz, J. A., & Besner, D. (2008). Covert orienting: A compound-cue account of the proportion cued effect. *Psychonomic Bulletin & Review, 15*, 123–127.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-prime user's guide*. Pittsburgh: Psychology Software Tools.

Vallesi, A., & Shallice, T. (2007). Developmental dissociations of preparation over time: Deconstructing the variable foreperiod phenomena. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 1377–1388.

Wearden, J. H., & Lejeune, H. (2008). Scalar properties in human timing: Conformity and violations. *The Quarterly Journal of Experimental Psychology, 61*, 569–587.

Received July 11, 2008
Revision received July 28, 2009
Accepted August 13, 2009

Annika Wagener

Department of Psychology
Julius-Maximilians University of Würzburg
Institut für Psychologie III
97070 Würzburg
Germany
Tel. +49 (0) 931 312191
E-mail wagener@psychologie.uni-wuerzburg.de