Temporal Preparation Decreases Perceptual Latency

Evidence from the Clock Paradigm

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Tanja Seifried
aus Pforzheim

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1. Berichterstatter:	Prof. Dr. Rolf Ulrich
2. Berichterstatter:	Prof. Dr. Jeffrey Miller, PhD

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I. Introduction

How does time shape human perception and behavior? This and related questions have engaged researchers as well as laymen for a long time (for an overview on the concept of time in philosophy and psychology see Roeckelein, 2001). Already Augustinus (2009 version) noted: “Quid est ergo tempus? Si nemo ex me quaerat, scio; si quaerenti explicare velim, nescio” (What, then, is time? When no one asks me, I know it; when I want to explain it to the one who asks, however, I do not know it., author’s translation, p. 586). This quote captures quite nicely the ever present fascination but also the difficulty that is inherent in the research on time. Nevertheless, research accepts this challenge since time is an important constituent of everyday’s life. On a large temporal scale, circadian rhythms organize our daily routines and influence our cognitive performance (e.g., Bratzke, Rolke, Steinborn, & Ulrich, 2009). On a small temporal scale, motor behavior (e.g., Shafir & Brown, 2010), speech (e.g., Kello, 2003), and music (e.g., Repp, 1992), for example, depend heavily on the correct timing of their constituting elements.

A good everyday example for the importance of the timing of behavior is the crossing of a street. One stands at the kerb, observes the traffic, and tries to find a gap between the cars during which it will be safe to cross the street. One has to estimate the time until a car will arrive at the crossing point as well as the time it will take to cross the street. Then, a complex integration of all these temporal estimations is necessary to correctly anticipate the moment for a safe transition of the street. Poor anticipation could lead to a too early or too late crossing of the street which might have fatal consequences. Such timing of behavior requires the estimation of temporal intervals (‘How long does it take until the car arrives at my position?’) as well as the orientation of attention to certain points in time (‘When do I have to start crossing the street?’). These mental operations eventually mean that one prepares for the moment in time when the crossing of the street will start. This *temporal preparation* or *temporal attention* is at the core of this thesis.

Even though this example demonstrates the importance of temporal information for human behavior, terms like ‘orientation of attention’ or ‘preparation’ have classically been more strongly associated with the other important dimension of human behavior besides time, that is, space. Since the seminal paper of Posner, Snyder, and Davidson (1980) it is well documented that orienting attention to a certain location in the visual field enhances processing of stimuli at this location. Posner et al. introduced a spatial cuing paradigm in which a cue indicates with a certain validity at which position (e.g., to the left or to the right of fixation) the succeeding target stimulus will be presented. As a result, responses to such stimuli are much faster (e.g., Posner, 1980) and discrimination accuracy is improved (e.g., Yeshurun & Carrasco, 1999). This finding is commonly attributed to covert attention (i.e., attention without eye movements) being attracted to the stimulus location by the preceding cue and hence facilitating the processing of stimuli presented inside this so-called “spotlight of attention” (cf. Posner et al., 1980, p. 172, cf. left panel of Figure 1).

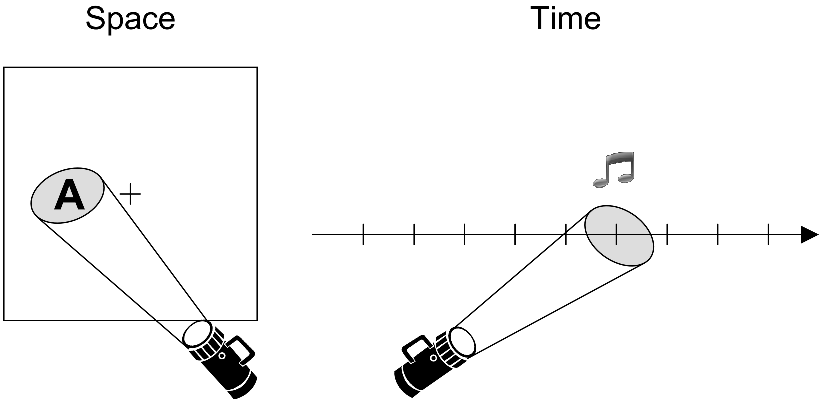

Figure 1. Schematic illustration of the orientation of attention in space and time.

The attentional spotlight is assumed to be highly adaptive (cf. Posner & Cohen, 1984, p. 550) since we constantly move through space and have to be prepared for suddenly occurring interesting or even dangerous events.

But we also move through time, and so must our attention, that is, we also need to orient ourselves in time. Already Wundt (1862) noted that we cannot 'contract' our attention equally at all times ("[...], dass wir unsere Aufmerksamkeit keineswegs immer gleichmäßig anzuspannen im Stande sind.", Wundt, 1862, p. 264). Hence, just like spatial attention cannot be allocated to all locations at the same time, temporal attention, too, is restricted. Therefore, it is also useful to have some kind of 'temporal spotlight' (cf. right panel of Figure 1) which allows us to allocate attention to those points in time at which some important event is likely to happen.

As the foregoing example about the street crossing has illustrated, such temporal orienting and preparation is quite useful and beneficial. This has also been established inside the laboratory. Researchers have found reduced reaction times (RT) and improved discrimination performance in conditions with good temporal preparation, that is, in conditions in which participants knew *when* to expect the target stimulus (e.g., Correa, Lupiáñez, & Tudela, 2005; Niemi & Näätänen, 1981; Rolke & Hofmann, 2007).

A vital research question arising from these findings concerns the locus of this temporal preparation effect in the chain of information processing. Traditionally it has been suggested that motor processes benefit from temporal preparation (e.g., A. F. Sanders, 1980a), but recently a growing number of results indicate a rather perceptual locus (e.g., Correa, Sanabria, Spence, Tudela, & Lupiáñez, 2006). Specifically, it has been suggested that temporal preparation shortens the duration of perceptual processes (Correa, Sanabria, et al., 2006; Rolke & Hofmann, 2007). This thesis provides evidence for this idea by reporting four experiments in which temporal preparation decreases the perceptual latency of auditory stimuli. For the measurement of perceptual latency the experiments employ a *clock paradigm* (e.g., Haggard, Clark, & Kalogeras, 2002; A. J. Sanford, 1974; Wundt, 1911), in which participants indicate with the help of a clock hand when they perceived the onset of a stimulus.

The ground for these experiments will be set in three main parts that constitute the Introduction of this thesis. The focus in the first part lies on temporal preparation, including concepts, theoretical accounts, and findings. The second part traces the development of the clock paradigm from its very beginnings in astronomy to its recent applications in cognitive psychology and its critical reception. Finally, in the third part, the research question and the experimental approach are presented in detail.

1. Temporal preparation

Humans can use advance information about upcoming events to attune to these events. That is, they can *prepare* themselves and thereby gain a performance benefit (e.g., Osman, Moore, & Ulrich, 1995; Rolke & Hofmann, 2007). Requin, Brener, Ring, Jennings, and Coles (1991) defined *preparation* as "the processes by which organisms are readied for perceiving future events and reacting to them" (p. 361). Requin et al. distinguished two types of preparation: *event preparation* and *temporal* or *time preparation*. In the first case, one has advance information about the features of the upcoming stimulus or the associated response and hence, the response alternatives are reduced. In short, one knows *what* stimulus will be delivered and *which* response is required. In the second case, one has advance information about the temporal moment of the upcoming stimulus, that is, one knows *when* the stimulus will be delivered.

For an example of event preparation, assume a driver steering a car on a curvy road in the mountains. Various traffic signs will announce whether the next curve is a leftward or a rightward curve. The driver can use this information to prepare the necessary steering movements, even though he might not yet be able to see the next curve. In the laboratory, event preparation is usually studied with choice RT-tasks in which at least two different stimuli require each a specific response movement (e.g., Osman et al., 1995; Rosenbaum, 1980). Rosenbaum (1980) developed the so-called pre-cuing procedure in which a pre-cue provides participants with advance information about the response movement that has to be executed. He observed that advance knowledge about one or more parameters of the required response movement (e.g., side, direction, or distance) decreased RT. Similarly, Osman et al. (1995) found that pre-cues reducing a four-alternative to a two-alternative choice task decreased RT and more specifically, the motor part of RT. To sum up, when participants know in advance what kind of response will be required by the target stimulus, they can prepare motor aspects of the response in advance and hence, respond faster.

Everyday examples for temporal preparation can be found in various situations like, for example, in traffic and in sport. Assume a driver standing at a red traffic light. Before the light turns green and he can actually accelerate, the yellow light will appear. Or, assume a runner performing a 100-m-sprint and listening to the shouting of ‘Ready—steady—go!’. In both examples, the start signals, that is, the green light or the shouting of ’go!’, are announced by a warning signal, that is, the yellow light or the shouting of ‘steady’. The driver and the runner can use these warning signals to anticipate, and thus prepare for, the occurrence of the start signals and hence initiate an earlier acceleration or start, respectively. Just like event preparation reduces the number of response alternatives, temporal preparation reduces the potential time points of stimulus presentation and thus decreases RT.

In the first section of this introductory part, I will present concepts, terminology, and paradigms that are relevant in the temporal preparation research. Second, I will introduce theoretical accounts on how temporal preparation leads to a performance benefit. Finally, I will give an overview over findings concerning the locus of the temporal preparation effect in the chain of information processing from stimulus to response.

1.1. Concepts, paradigms, and terminology

The realm of temporal preparation research knows different paradigms and tasks as well as different concepts and terms, for example temporal uncertainty and expectancy. In addition, a new research branch has arisen recently that also deals with the question how knowledge about the time point of stimulus occurrence influences performance. Temporal attention and temporal orienting are the key words in this area that also brought forward different types of paradigms. In the following I will picture these two conceptual frameworks including the appendant paradigms.

1.1.1. Temporal preparation and the foreperiod paradigms

Temporal preparation (also *readiness* or *set*, cf. Teichner, 1954, p. 136) may be regarded as the reduction of uncertainty (Requin et al., 1991, p. 361). Requin et al. (1991) argue that the timing of upcoming events is always more or less uncertain, that is, we do not know *when* something will happen. Consequently, these authors regard temporal preparation as a "behavioral mechanism for dealing with [temporal] uncertainty" (p. 361). Reduction of uncertainty, and thus successful preparation, involves the anticipation of the upcoming events. As already noted above, temporal preparation comprises therefore all processes that enable an optimal internal state for perceiving and responding to future events (Requin et al., 1991; see also Rolke & Ulrich, 2010).

These basic cognitive abilities—preparation and anticipation—have been in the focus of psychological research for a long time. At the beginning of experimental psychology, Wundt (1880, p. 238) measured RT to the noise made by a ball after it was dropped by a "Fallapparat" (cf. "drop apparatus" in James, 1890/1950, p. 428). This sound was either the only stimulus or it was preceded by a warning signal, namely the noise the apparatus made when it let go of the ball. Wundt reports that the RTs were greatly reduced in the condition with a warning signal (cf. also James, 1890/1950, p. 428). This is the basic finding in temporal preparation research: A warning signal announces an upcoming target stimulus, thereby allows participants to prepare for the onset of the target stimulus, and consequently RT gets reduced. Following his early experiment on the influence of a warning signal, Wundt attributed his finding to the "vorbereitende Spannung der Aufmerksamkeit" (preparing tension of attention, author's translation, p. 239).

This early observed decreasing effect of a warning signal on RT, and thus the effect of temporal preparation can nowadays be considered a fairly robust finding (e.g., Klemmer, 1956; Müller-Gethmann, Ulrich, & Rinkenauer, 2003; Teichner, 1954; Woodrow, 1914). It has been generalized for various modalities and different RT tasks. Temporal preparation reduces RT to visual (e.g., Rolke & Hofmann, 2007), auditory (e.g., Niemi, 1979), and even tactile target stimuli (e.g., Miles, Poliakoff, & Brown, 2008). Analogously, this RT reduction can be caused by visual (e.g., Alegria & Bertelson, 1970), auditory (e.g., Bertelson & Tisseyre, 1968), and tactile warning signals (e.g., Mattes & Ulrich, 1997). Finally, it has also been found for different types of RT tasks, that is, for simple RT tasks (e.g., Klemmer, 1956), for choice RT tasks (e.g., Müller-Gethmann et al., 2003), and for Go/NoGo tasks (e.g., Seibold, Bausenhart, Rolke, & Ulrich, in press). The latter two RT tasks are theoretically especially important: When stimulus discrimination is required (choice RT task) or sometimes a response has to be initiated and sometimes to be held back (Go/NoGo task), the response is not defined before the target stimulus is actually delivered. Hence, these latter findings show that participants can temporally prepare even when event uncertainty is high (cf. Müller-Gethmann et al., 2003, p. 597–598).

The first systematic investigation of temporal preparation was carried out by Woodrow in his seminal work 'The measurement of attention' published in 1914. In his experiments, Woodrow thoroughly analyzed the influence of the *preparatory interval* (also cf. Niemi & Näätänen, 1981). This preparatory interval is defined as "the interval elapsing between a warning signal of some sort, i.e., a signal to get ready, and the stimulus to which the subjects reacts [sic]" (p. 16). The preparatory interval has also been called *foreperiod* (FP, e.g., Teichner, 1954, p. 136), a term which has stuck until today. Corresponding paradigms are therefore called *foreperiod paradigms.* In these paradigms, temporal preparation or temporal uncertainty is manipulated by varying the FP, that is, the interval between the onset of the warning signal and the onset of the target stimulus.[1] In some studies on temporal preparation the experimenter also refrains from employing a warning signal and just presents a series of target stimuli. Here, the inter-stimulus-interval (ISI) acts in the same manner as the FP, that is, every target stimulus acts as a warning signal for the following one (e.g., Näätänen, 1971; see also Nickerson & Burnham, 1969).

Woodrow (1914) realized experiments in which he used the same FP in several consecutive trials and others in which the FP changed from trial to trial. These two approaches constitute the two basic subtypes of foreperiod paradigms. The former of Woodrow's approaches is known as the *constant foreperiod paradigm*, the latter one as the *variable foreperiod paradigm* (cf. Niemi & Näätänen, 1981). Since the typical results of these approaches as well as the corresponding theoretical frameworks differ, I will introduce them separately.

The constant foreperiod paradigm

In the constant foreperiod paradigm, a warning signal announces the upcoming target stimulus in a regular manner. For example, a tone is presented before a letter to which the participant has to make a speeded response. The FP between tone and letter is kept constant within a block of trials, but it is varied between blocks of trials. Hence, in a given block of trials participants can expect the letter to occur always at the same time point after the tone. The typical result pattern of such an experiment is an increase of RT with increasing FP length (e.g., Müller-Gethmann et al., 2003; Woodrow, 1914). This result pattern is commonly explained by less temporal uncertainty and thus better temporal preparation at shorter FPs.

Niemi and Näätänen (1981) assume that the warning signal—through its initiation of the FP—provides a temporal frame of reference during which participants prepare for the occurrence of the target stimulus. RT will be

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[1] Note that in some studies the FP is defined as the offset-onset interval between warning signal and target stimulus (e.g., Alegria & Bertelson, 1970; Posner, Klein, Summers, & Buggie, 1973).

lowest when their state of preparation is optimal at the time point of target stimulus delivery. Critically, such an optimal state of preparation can only be upheld for a short time period (Alegria, 1974). Thus, it is assumed that in a constant foreperiod paradigm participants anticipate the occurrence of the target stimulus and try to synchronize their period of optimal preparation with its occurrence (Näätänen, Muranen, & Merisalo, 1974; Niemi & Näätänen, 1981). Näätänen et al. (1974) referred to this state of optimal preparation as a state of high expectancy and defined it in terms of the subjective probability of immediate delivery of the target stimulus (cf. also Näätänen, 1970, 1971). According to Näätänen et al., "the degree of the former [expectancy] would to a great extent determine the degree to which the organism is prepared to respond to S2 [the target stimulus]" (p. 461).

The relation between RT decrease and anticipation of the moment of target delivery was investigated by Näätänen et al. (1974). These authors compared the RT in a constant foreperiod paradigm with participant's accuracy in anticipating the moment of target delivery. Specifically, in one part of the experiment participants performed in a regular simple RT task whereas in another part they synchronized a key press with the target stimulus onset rather than responding to it. As a result, the anticipation times mirrored the RTs quite closely. Thus, faster RT is due to better anticipation of the target stimulus.

Anticipation of the correct time point and therefore optimal preparation adjustment, however, become worse as FP increases because participants have greater difficulty in estimating long than in estimating short temporal intervals (Klemmer, 1957; Näätänen et al., 1974). Various studies on time perception report such a decline in estimation accuracy with interval length (e.g., Treisman, 1963). Hence, longer FPs comprise more temporal uncertainty and thus induce a lower level of temporal preparation than shorter FPs.

However, this relation is not true for very short FPs. Instead, one observes a sharp reduction of RT (Bertelson & Tisseyre, 1969b; Müller-Gethmann et al., 2003) up to around 200 to 400 ms. Based on this U-shape of the FP effect on RT, it has been assumed that it takes some time until a sufficient amount of temporal preparation has been built up (cf. Bausenhart, Rolke, & Ulrich, 2008). The fact that RTs at very short FPs are nonetheless faster than RTs to stimuli that are not preceded by a warning signal (e.g., Müller-Gethmann et al., 2003) might rather be due to arousal induced by the warning signal than to temporal preparation (e.g., Ulrich & Mattes, 1996).

Interestingly, the ability to estimate the passage of time during the FP can be improved by additional cues interspersed in the FP. Simon and Slaviero (1975), for example, let their participants perform in a visual choice RT task. The target stimulus was preceded by a visual warning signal and an FP of 2 sec. In one block of trials, the FP was empty and in a second block of trials—the so-called countdown trials—the progress of the FP was indicated by presenting six visual countdown lights. The countdown lights progressed from the left side of the computer screen to the right side and were presented every 0.28 sec. Simon and Slaviero found that in such countdown trials, RT was much faster than in trials with an empty FP. As put by Niemi and Näätänen (1981), this can be explained by the fact that the effective FP in the countdown trials was the interval between the last countdown light and the target stimulus. Hence, the FP was shorter in the countdown trials, thus, temporal preparation was better, and RT faster than in empty trials.

Taken together, the warning signal in a constant foreperiod paradigm initiates the participants' temporal preparation for the upcoming target stimulus. Since the FP is constant over a block of trials, participants can learn to estimate the duration of the FP. Furthermore they learn to adjust their optimal state of preparation to the end of the FP, at which time point their expectancy of the target stimulus is highest. Since time estimation is worse for longer FPs, temporal preparation decreases and temporal uncertainty as well as RT increase.

The variable foreperiod paradigm

The type of uncertainty that one encounters in the constant foreperiod paradigm is related to participants' ability to estimate the FP and hence varies with the duration of the constant FPs (Klemmer, 1956). According to Klemmer (1956) a second source of temporal uncertainty is the clock-time variability of the target stimulus which is related to the FP variability. This means that it is uncertain at which time point in the trial the target stimulus will occur what plays an important role in the variable foreperiod paradigm. Here, the FP is varied randomly from trial to trial. Therefore, it is hard for participants to synchronize their response with the target stimulus, since the FP duration is not known at the beginning of a trial. Thus, the level of temporal uncertainty in this paradigm is generally higher, and RTs are usually longer than those obtained with constant FPs (e.g., Bevan, Hardesty, & Avant, 1965; Mattes & Ulrich, 1997). As far as the different FP durations are concerned, the common result pattern in the variable foreperiod paradigm is quite the opposite of the constant foreperiod paradigm. Specifically, in a given range of employed FPs, RT usually *decreases* with FP. That is, participants respond fastest when the target stimulus occurs after the longest FP in an experiment (Klemmer, 1956; Mattes & Ulrich, 1997; Steinborn, Rolke, Bratzke, & Ulrich, 2008).[2]

This pattern of results is most probably due to a change in conditional probability of target occurrence over the time course of a single trial. As I begin to elaborate this explanation in more detail, remember that in a constant foreperiod paradigm the target stimulus occurs at a certain time point with a probability of 100% in a given block of trials. In contrast, the time point of the target stimulus in the variable foreperiod paradigm is uncertain in a block of trials. Nevertheless, the elapsing of the FP itself provides the participant with some information about target occurrence (Elithorn & Lawrence, 1955; Niemi & Näätänen, 1981). It is assumed that the participant's expectancy or preparation increases with the *aging* of the FP, that is, its elapsing during one experimental trial (Näätänen, 1971; Niemi & Näätänen, 1981). Usually, a rectangular FP distribution is used in experiments with the variable forepe-

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[2] Note, however, that the size of the FP effect also depends on the ratio between FP range and mean FP. When the range of employed FPs is kept constant, but the mean FP increases, the effect of FP on RT gets smaller (see Niemi & Näätänen, 1981).

riod paradigm. That is, the occurrence of every FP duration is equally likely for one block of trials. For example, assume a variable foreperiod paradigm with n different FPs. In this situation, the target stimulus can appear at one of n possible time points t_i from $i = 1$ to $i = n$. The a-priori-probability for the target stimulus to appear at any of these time points is thus $1/n$. Further assume that in the time course of a trial, t_1 elapses without presentation of the target stimulus: The probability for the remaining time points rises to $1/(n-1)$. More generally, at a given time point t_i the probability for target occurrence is $p_i = 1/(n-i+1)$. Accordingly, the *conditional probability* for the occurrence of the target stimulus increases with every possible time point t_i that passes without target occurrence. Finally, when t_{n-1} has passed, the probability for t_n is $p_n = 1/(n-n+1) = 1$.

During an experimental session, participants are assumed to learn this change in probability and to adjust their expectancy and thus their preparation for the target stimulus accordingly. This learning process can be regarded as a result of the fact that a level of high preparation is rather merited by immediate delivery of the target stimulus, when the FP has already farther proceeded (Niemi & Näätänen, 1981). The idea of an increase in preparation throughout the course of the FP is also in line with the notion that a high state of preparation can only be upheld for a short time (Alegria, 1974). Participants should only induce this strenuous state, when target stimulus probability is high (Los, 2010).

If the variable FP effect is indeed due to the increase in conditional probability over time, it should vanish when this increase is avoided. This issue has been examined with the help of so-called *non-aging* FPs. Since in rectangular FP distributions the conditional probability of target occurrence changes over a single trial, such a distribution has been called “aging” (Näätänen, 1971, p. 316). In contrast to that, an FP distribution in which the probability of target occurrence is independent from its age has been called “non-aging” (Nickerson & Burnham, 1969, p. 453; cf. also Feller, 1964). Nickerson and Burnham (1969) borrowed this term from probability theory, in which it describes “a process, the probability of whose immediate termination remains constant over time" (p. 453). Different approaches haven been chosen in order to create such non-aging FPs. One approach is to use a right-skewed distribution in which the shortest FP has the highest relative frequency (Baumeister & Joubert, 1969; Näätänen, 1970). Another approach is the incorporation of a Bernoulli process for the probability of each FP (Näätänen, 1971; Nickerson & Burnham, 1969). Under such circumstances the usual variable FP effect vanishes. In other words, the destruction of increasing conditional probability with the elapsing FP also destroys the FP effect. This is evidence for the notion that participants use conditional probabilities to adjust their preparation.

A further characteristic of the variable foreperiod paradigm is the *sequential effect*. This describes the finding that the RT in a variable foreperiod paradigm is not only affected by the actual FP in a trial i, but also by the FP in the preceding trial $i - 1$. If FP_{i-1} was long, the RT in the trial i is typically longer than if FP_{i-1} was shorter or equally long (Baumeister & Joubert, 1969; for a recent overview see Steinborn et al., 2008). This sequential effect has thus also been called the *previous preparatory interval effect* (cf. Baumeister & Joubert, 1969, p. 393). The sequential effect is asymmetrical, that is, it is pronounced for the shortest FP, becomes less with increasing FP, and vanishes for the longest FP in a given experimental setup (e.g., Steinborn et al., 2008).

Several explanations have been proposed to account for the sequential effect (Niemi & Näätänen, 1981), for example the re-preparation or multiple preparation hypothesis (Baumeister & Joubert, 1969; Niemi & Näätänen, 1981). Accordingly, participants try to be highly prepared at various time points at which the target stimulus can occur. Initially, they select the preceding FP as the first time point for high preparation. When the target stimulus is not presented, they can re-prepare for the next possible delivery moment. At this time point, RT is consequently short, whereas it is long when the target stimulus occurs at a FP that terminates before the first preparation peak, that is, when FP_i is shorter than FP_{i-1}. In contrast to this rather strategic view, in which participants prepare more or less intentionally for certain time points, a more recent account explains the sequential effect and the overall variable FP effect on the basis of trace-conditioning (Los, Knol, & Boers, 2001; Los & Van Den Heuvel, 2001; Steinborn et al., 2008). In short, the warning signal is viewed as the conditioned stimulus, the target stimulus as the unconditioned stimulus, and the learning rules of reinforcement, extinction and persistence are suggested to contribute to the variable FP effect (Los et al., 2001). Since, however, variable FPs are not at the core of this thesis, I will not go deeper into this account.

In conclusion, constant as well as variable foreperiod paradigms offer a participant information about when to be highly prepared and high preparation decreases RT. However, participants are never explicitly instructed when to expect the target stimulus. Temporal preparation within these paradigms is therefore inherent in the temporal structure of a single trial and considered to be rather implicit in nature (cf. Nobre & Coull, 2010).

1.1.2. Temporal attention and the orienting paradigms

In contrast to this implicit temporal preparation in the foreperiod paradigms, a rather recent research approach employs a more explicit form of temporal preparation for target occurrence at certain time points in a trial. This approach can be subsumed under the term of *temporal orienting* or *temporal attention*. The appendant temporal orienting paradigms create temporal preparation by instructing participants to expect the target stimulus after a specific interval, that is, at a specific time point. Thus, temporal preparation is directed voluntarily to a time point in the trial structure and is hence rather explicit (cf. Nobre & Coull, 2010).

According to Los (2010), the distinction between temporal preparation and temporal attention is a "schism in the literature" (p. 289) which might be invalid. The term temporal preparation is conventionally used in studies that employed foreperiod paradigms, whereas the term temporal attention has rather been used in temporal orienting studies. Even though the relationship between these two concepts has not yet been fully described or understood, many recent studies put them into a common frame (e.g., Bausenhart et al., 2008; Nobre, Correa, & Coull, 2007). Hence, I will follow these authors and also Los and introduce the relevant paradigms and results alongside the foreperiod paradigms.

In one of the first studies on temporal orienting by Coull and Nobre (1998), temporal orienting was described as the question "whether and how information about time intervals can be used to direct attention to a point in time when a relevant event is expected, to optimize behavior" (p. 7426). Two types of paradigms that utilize this concept are currently in use, the *temporal Posner paradigm* first used by Coull and Nobre and a *temporal Hillyard paradigm* first used by Lange, Rösler, and Röder (2003, cf. also Lange & Röder, 2010). As the names already reveal, these paradigms emerged from different backgrounds of attention research in the visual and the auditory domain. In the following I will outline the origin, the experimental setup and research logic of these paradigms.

The temporal Posner paradigm

In 1998, Coull and Nobre developed a temporal variant of the Posner paradigm (Posner, 1980; Posner et al., 1980; Posner, Nissen, & Ogden, 1978) which is widely used to investigate visual spatial attention. The Posner paradigm reveals that covert spatial attention enhances information processing such that responding to attended stimuli is facilitated compared to unattended ones. The typical results show that participants respond faster to validly cued target stimuli than to invalidly cued ones (Posner, 1980; Posner et al. 1980, 1978; cf. also the very beginning of this Introduction).

Analogous to this research logic, Coull and Nobre (1998) aimed to observe whether stimuli after validly cued time intervals were detected more efficiently than those after invalidly cued intervals. In their first experiment they investigated temporal as well as spatial attention. To this end, they employed an experimental display which consisted of two squared position frames, one to the left and one to the right of fixation and a cuing stimulus at fixation. The cuing stimulus consisted of a small circle inside of a diamond, both surrounded by a greater circle. This cue could either be neutral (all parts of the cuing stimulus were highlighted), it could predict the left or right position frame (highlighting of the left or right side of the diamond: spatial cuing), or it could predict whether the target stimulus would occur after a short or after a long cue-target-interval (CTI, highlighting of the inner or outer circle, respectively: temporal cuing). After being announced by the cue, the target stimulus ('x' or '+') appeared either in the left or in the right position frame and either after a short or after a long CTI with a validity of 80%. The participants' task was to detect the target stimulus as quickly as possible.

For the spatial condition the well-known spatial attention effect emerged, that is, attended (i.e., validly cued) stimuli were detected faster. Crucially, such a validity effect was also observed for the temporal cuing condition—at least for the short interval. In the long interval, the RT increase for invalidly cued target stimuli was not as large as in the short interval. More precisely, the disadvantage arising when participants expected the target stimulus after the short CTI but it occurred after the long one, was negligible. This result can be attributed to re-preparation: When the target stimulus did not occur after the short CTI, participants knew that it would certainly occur after the long one and could thus re-prepare for the long CTI (Coull & Nobre, 1998). In line with this explanation, a recent study by Correa, Lupiáñez, and Tudela (2006) revealed the temporal validity effect also for long intervals under the condition of catch trials. According to Correa, Lupiáñez, and Tudela, catch trials induce temporal uncertainty which in turn leads to a dispreparation that prevents reorienting to the long intervals (RTs were generally longer at long intervals with catch trials). Consequently, validly cued target stimuli did now also have a preparation advantage also at long intervals.

To sum up, in the temporal Posner paradigm a symbolic cue directs temporal attention to a specific time point in the trial. Target stimuli that appear at these attended time points gain a processing benefit. Up to now this paradigm has been employed in a range of studies on temporal orienting (e.g., Correa et al., 2005; Griffin, Miniussi, & Nobre, 2002; Miniussi, Wilding, Coull, & Nobre, 1999) which have expanded and advanced the research on temporal preparation.

The temporal Hillyard paradigm

The second type of temporal orienting paradigms has its roots in the electrophysiological research on selective auditory attention. Hillyard, Hink, Schwent, and Picton (1973) aimed to assess the event-related potential (ERP) for selectively attended auditory stimuli. The ERP is derived from electroencephalographic (EEG) measurements by averaging many EEG episodes time-locked to a specific internal or external event. Conceptually, certain ERP components can be attributed to specific psychological processes (cf. Fabiani, Gratton, & Federmeier, 2007). In Hillyard et al.'s experiment, auditory beeps were presented either to the left or to the right ear of a participant. Each ear was presented with a standard frequency (e.g., 800 Hz right ear, 1,500 Hz left ear). The stream of standards on each ear was interspersed with deviating beeps that differed slightly in frequency (840 Hz and 1,560 Hz). Participants were required to attend only to one of the two ears and to count the deviants. Hillyard et al. then compared the ERP for the standard at the attended versus the unattended ear. As a result, an ERP component that indicates early perceptual processes (i.e., the N1, see also Subsection 1.3.2.) was enhanced for attended stimuli compared to unattended ones.

Hillyard et al. (1973) made clear that three features of their study were essential for the detection of early ERP modulation: Relevant and irrelevant stimuli were easy to distinguish (differed in spatial location as well as in frequency), stimuli were presented at such a high rate that it was impossible to focus on anything else but the to-be-attended channel, and the discrimination task for the attended stimuli was difficult (i.e., a small frequency difference between standards and deviants). Lange et al. (2003) incorporated these features when they designed a temporal variant of the Hillyard paradigm in order to investigate whether temporal orienting could affect early processing stages.

In detail, their experimental setup was as follows. Two white noise bursts marked empty temporal intervals of either 600 or 1,200 ms. For standard temporal intervals the onset and offset noises had the same intensity, whereas for deviating intervals, the intensity of the offset noise was increased. The to-be-attended channel was defined as one of the two durations, that is, participants either had to focus on the short interval (attend-short) or on the long one (attend-long). Since the intervals were terminated by the offset noise, participants had to attend to a specific moment in time with respect to the onset noise. The to-be-attended interval duration was alternated run-wise, and the participants' task was to respond as fast as possible to intensity deviants at the end of this interval. Just as in the spatial Hillyard paradigm, Lange et al. (2003) then compared ERPs to standards at attended and unattended points in time. As a result, these authors found an enhanced N1 amplitude for stimuli that occurred at attended moments in time. Thus, with their temporal variant of a Hillyard paradigm, Lange et al. could show that temporal attention influences early perceptual processing.

Recently it could also be shown that target detection gets improved in such a paradigm. L. D. Sanders and Astheimer (2008) presented auditory stimuli (a standard or a deviant tone) after a short, medium, or long interval measured from fixation onset. Participants detected the deviants much more frequently when they were attending to the relevant time point. In addition, they replicated Lange et al. (2003) such that they, too, found an enhanced N1 amplitude for standards at temporally attended time points. Since this study employed more than only two intervals, it thus suggests even more vividly that participants can flexibly direct their attention in time.

To sum up, in the temporal Hillyard paradigm participants are instructed to attend to the end of a certain time interval, and processing of stimuli at these time points is enhanced. Hence, the temporal Posner as well as the temporal Hillyard paradigm are suited to explicitly direct participants' attention in time and thereby elicit a processing advantage.

I have now introduced two different types of paradigms (i.e., foreperiod paradigms and temporal orienting paradigms) each with its subtypes. Both have produced a number of findings on what is influenced by temporal preparation and how and where in the information processing chain from stimulus to response this influence takes place. Before I elaborate on these findings in Section 1.3., Section 1.2. will address theoretical accounts on the mechanism of temporal preparation.

1.2. Theoretical accounts on temporal preparation

In this section I will present two theoretical accounts that try to explain the mechanisms behind the effects of temporal preparation. The *motor readiness model* by Näätänen (1971) is an account based on motor variables, whereas the *early onset hypothesis* by Rolke and Hofmann (2007) proceeds from the perceptual stages of information processing.

1.2.1. The motor readiness model

According to the motor readiness model (Näätänen, 1971), a motor response is elicited when *motor readiness* exceeds a certain criterion, that is, the *motor action limit*. Näätänen (1971) conceptualized motor readiness as a difference measure, that is, motor excitation minus motor inhibition (cf. also Näätänen & Merisalo, 1977). Motor readiness is suggested to fluctuate continuously due to cortical control processes that try to keep excitation and inhibition forces in balance. An optimal state during an RT task would, on the one hand, involve a motor readiness level that is quite close to the motor action limit, so that, when the target stimulus finally occurs, little additional activation is needed to elicit a response. On the other hand, motor readiness should still be far enough from the motor action limit to prevent premature reactions without or before presentation of the target stimulus. Premature reactions could be triggered by the random fluctuations of motor readiness. Such a balanced motor readiness allows for fast responses, since RT is the shorter the smaller the distance of motor readiness to the motor action limit.

Crucially for temporal preparation research, it is suggested that motor readiness can be adjusted by preparation (Näätänen, 1971; Näätänen &

Merisalo, 1977). Specifically, when a participant can expect a stimulus to occur at a certain time point, motor readiness can be increased beforehand. This advance increase can be timed most accurately when temporal preparation is high. Consequently, the difference between motor action limit and motor readiness is small under high temporal preparation, and thus, little additional excitation is sufficient for the release of the response and RT is short.

The motor readiness model has gained further support through experiments showing an increase of response force (Jáskowski & Verleger, 1993; Mattes & Ulrich, 1997) and a decrease of false alarms (Mattes & Ulrich, 1997; Steinborn et al., 2008) with decreasing temporal preparation. Participants in the study by Mattes and Ulrich (1997), for example, performed in a simple RT task under high or low temporal preparation. Besides RT, the authors also measured response force. For variable as well as for constant FPs these authors observed not only the typical increase of RT for low temporal preparation but also an analogous increase in response force. Mattes and Ulrich suggest that a less accurate adjustment of motor readiness under low temporal preparation can account for this finding. Accordingly, under low temporal preparation, the motor readiness is far from the motor action limit, and thus a vast amount of excitation will be needed in order to assure a fast response. This may lead to an overshoot of excitation which should then be reflected in increased response force. Under high temporal preparation, however, less final excitation suffices to cross the motor action limit, and hence the response is not only fast but its force is also optimally adjusted. In a similar way, the authors accounted for the observed increase in anticipatory responses under high temporal preparation. Since motor readiness is close to the motor action limit, a small random excitation can already lead to a premature response without presentation of the target stimulus. Steinborn et al. (2008) made analogous observations when they employed catch trials within a variable foreperiod paradigm. They found that the percentage of false alarms increased with increasing temporal preparation.

Taken together, temporal preparation is suggested to adjust motor readiness so that it is quite close to the motor action limit at target occurrence (Näätänen, 1971; Näätänen & Merisalo, 1977). Thus, RT and response force decrease under high temporal preparation whereas false alarm rate increases (Mattes & Ulrich, 1997; Steinborn et al., 2008).

1.2.2. The early onset hypothesis

The early onset hypothesis is a specific idea about how temporal preparation might influence perceptual stages of the S–R chain. It was brought forward by Rolke and Hofmann (2007, see also Rolke, 2008) and basically suggests that under high temporal preparation perceptual processing of a stimulus may begin earlier (for a similar suggestion see Grosjean, Rosenbaum, & Elsinger, 2001). This account was developed by Rolke and Hofmann based on the results of a masked spatial discrimination task. Specifically, in a constant foreperiod paradigm a visual warning signal prepared participants for the presentation of a Landolt square (i.e., a square with a spatial gap). The participants' task was to judge whether the gap was on the left or on the right side, and the Landolt square was presented for one of three possible target durations after whose elapsing a random noise mask was displayed. Results revealed the common FP effect, that is, RT increased with FP duration. Crucially, however, an FP effect was also observed for perceptual discrimination, that is, d' decreased with FP duration. Hence, participants expressed better discrimination performance when temporal preparation was high.

According to Rolke and Hofmann (2007) these results can be understood by putting them into a perspective based on theories of backward masking (for an overview on visual masking see Breitmeyer & Öğmen, 2006) and criterion models (Grice, 1968; Luce, 1986). First, the interruption theory of masking (e.g., Kahneman, 1968) suggests that a mask, like the one employed in this experiment, disrupts the perceptual processing of the masked stimulus and overwrites its visual memory trace. Hence, perceptual processing of the target stimulus can only occur prior to mask presentation. Second, criterion models (e.g., Grice, 1968; Luce, 1986) proceed from the idea that each stimulus has an internal representation in the nervous system. This representation is generated by transduction of the physical stimulation into an internal activation (cf., Luce, 1986, p. 82) which can be regarded as a series of impulses that are accumulated over time. When this accumulated impulse count reaches a certain criterion the stimulus is detected and responded to. A schematic illustration of such a model is depicted in the upper panel of Figure 2.

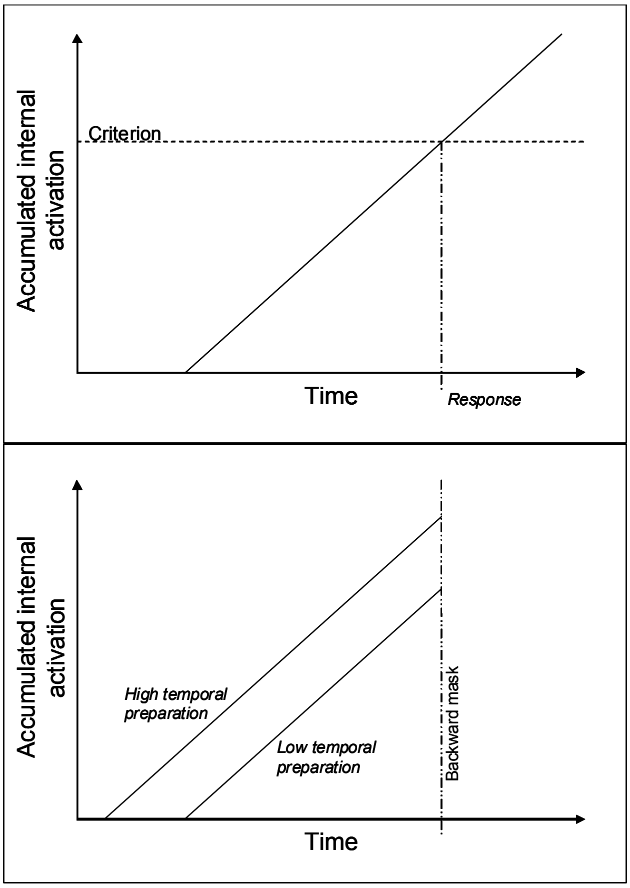

Figure 2. Upper panel: Schematic illustration of a basic criterion model (cf. Grice, 1968). Lower panel: Information accumulation under high and low temporal preparation with backward masking (cf. Rolke & Hofmann, 2007).

Based on these two approaches Rolke and Hofmann (2007) assume that high temporal preparation leads to an earlier beginning of perceptual processing of a stimulus. Consequently, the accumulated internal activation can increase to a higher level before the mask interrupts perceptual processing (cf. Figure 2, lower panel). Thus, any discrimination decision—here a gap discrimination—can be based on a larger amount of accumulated information, which will lead to better discrimination performance as observed by Rolke and Hofmann. Furthermore, Rolke and Hofmann suggested that the early onset hypothesis can also account for the decreased RT under high temporal preparation. When information accumulation starts earlier, the response criterion will also be reached earlier and RTs are faster under high than under low temporal preparation.

To sum up, the early onset hypothesis suggests that temporal preparation prepones perceptual processing and thus leads to faster RT as well as to better discrimination performance (Rolke & Hofmann, 2007).

1.3. The locus of the temporal preparation effect

An important question in the investigation of temporal preparation concerns which part in the chain of information processing from stimulus to response benefits from it. Knowing these parts helps to shed light on the mechanisms that underlie the temporal preparation effect. For example, if temporal preparation operated primarily on motor processes, a motor-specific account of temporal preparation would have to be advanced (e.g., the motor readiness model; Näätänen, 1971), whereas a perceptual account (e.g., the early onset hypothesis; Rolke & Hofmann, 2007) would be needed if it operated primarily on perceptual processes. Thus, knowing the locus of the temporal preparation effect within the stimulus-response (S-R) chain is a prerequisite for further theoretical development on this topic.

The S-R chain comprises the processes between the onset of a target stimulus and the occurrence of the instructed response (e.g., a key press, a vocal response). The processes that occur from stimulus onset to the response are usually divided in perceptual, central, and motor processes (see Figure 3). In a finer resolution one may also distinguish more processes (cf. A. F. Sanders, 1980b): signal pre-processing, feature extraction, signal identification (perceptual), response selection (central), response programming, and motor adjustment (motor). The temporal interval between the onset of the target stimulus and the onset of the response is defined as the reaction time.

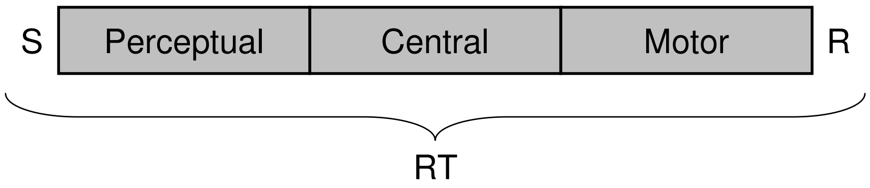

Figure 3. A basic Stimulus-Response (S-R) information processing chain.

For a long time, the general consensus on the locus of temporal preparation was that the effects of temporal preparation are limited to late processes in the S-R chain, that is, that temporal preparation rather influences motor processes (e.g., Teichner, 1954; Sanders, 1980a; for overviews see Müller-Gethmann et al., 2003; Hackley & Valle-Inćlan, 2003). Recently, however, more and more findings emerged that suggest an influence on pre-motor processes. In this section, I will present an overview on studies that allow conclusions about the locus of temporal preparation effects. First, I will present studies that gathered evidence for a motor locus of temporal preparation. The second subsection will then cover evidence for a pre-motor, and more specifically, a perceptual locus of temporal preparation.

1.3.1. Evidence for a motor locus

Most evidence for a motor locus of temporal preparation stems from RT studies and is therefore presented first in this subsection. Second, experiments on response force and muscular activity are introduced as supporting evidence. Third, studies on reflexes and motor-evoked potentials are presented, and finally the influence of temporal preparation on ERP components is discussed.

Reaction time

Unfortunately, a regular RT experiment can only measure the "complete" RT. Hence, when one finds a decrease in RT—due to high temporal preparation—one cannot know which process' duration was actually diminished by temporal preparation. However, the *Additive Factor Method* (AFM, Sternberg, 1969, 1998) offers an experimental way to infer the locus of an RT effect in the S-R chain. The AFM relies on the RT data of a factorial experiment (e.g., factors A and B) and infers from the observed result pattern which processes were influenced by A and B. Crucially, when A and B influence different processes of the S-R chain, they can only produce additive effects on RT. Consequently, when an interaction between A and B is observed, this suggests that both factors affected at least one process together (cf. Sternberg, 1998, p. 747). The AFM was applied several times in the search of the locus of temporal preparation. The general picture of results suggests that temporal preparation shows additive effects with factors typically influencing pre-motor processes (e.g., Alegria & Bertelson, 1970; Frowein & Sanders, 1978; Posner et al., 1973; Spijkers & Walter, 1985) and interactive effects with factors typically influencing motor processes (e.g., Meulenbroek & Van Galen, 1988; A. F. Sanders, 1980a; Spijkers, 1990).

Frowein and Sanders (1978), for example, employed a constant foreperiod paradigm and assessed the influence of FP, stimulus degradation, and S-R compatibility, whereby the latter two factors are known to influence perceptual and central processes, respectively. Specifically, participants were presented with a visual warning signal which they should use to prepare for the occurrence of the visual target stimulus. The FP was either short or long, and the target stimulus consisted of a diagonal and a horizontal line that joined each other at one of the four corners of the visual display. Participants had to indicate this corner by pressing a key as fast and as accurate as possible. In the compatible S-R condition, the correct button was adjacent to the target corner, whereas in the incompatible condition, the correct button was the one shifted in counter-clockwise direction. Furthermore, the target stimulus was either intact or degraded by a superimposed visual noise pattern. FP, S–R compatibility as well as stimulus degradation were varied blockwise. As one would expect, all factors influenced RT; RT was shorter for intact stimuli, the compatible S-R assignment and for the shorter FP. However, there was no sign of an interaction between FP and the other factors. This is at variance with an influence of temporal preparation on perceptual or central processes and rather suggests an influence on motor processes.

Further evidence for a motor locus of temporal preparation comes from AFM studies that found interactive effects of temporal preparation and factors that influence motor processing (Meulenbroek & Van Galen, 1988; A. F. Sanders, 1980a; Spijkers, 1990). A. F. Sanders (1980a), for example, presented warning signal and target stimulus both in the visual modality. The target stimulus and the task were actually identical to the ones in the study by Frowein and Sanders (1978). FP was varied blockwise, and in addition instructed muscle tension was manipulated. In the low tension condition, participants should relax their muscles completely, whereas in the high tension condition they were told to tense their muscles such that they felt in a state that would lead to a highly effective performance in the upcoming task. The RT result pattern showed decreased RT for the shorter FP and for the high muscle tension condition. Importantly, these two experimental factors also interacted, that is, the effect of muscle tension was more pronounced in the short FP condition. This result pattern suggests a stronger motor preparation at the short FP and thus also supports a motor locus of temporal preparation.

However, for a further factor, namely stimulus intensity, the result pattern is not that clear-cut. On the one hand, several studies have shown that stimulus intensity, at least for visual targets, produces additive effects with temporal preparation (e.g., Bernstein, Chu, & Briggs, 1973; Niemi, 1979). On the other hand, Niemi and Lehtonen (1982) found interactive effects for visual target stimulus intensity and variable FP duration, that is, the FP effect was more pronounced when the target stimuli were dim. For auditory stimuli, most studies also found interactions between intensity and temporal preparation (Bernstein et al., 1973; Kellas, Baumeister, & Wilcox, 1969; Niemi, 1979; Niemi & Lehtonen, 1982). Since stimulus intensity is supposed to affect perceptual processes (Jáskowski, Kurczewska, Nowik, Van Der Lubbe, & Verleger, 2007; Miller, Ulrich, & Rinkenauer, 1999), these results contradict an exclusive influence of temporal preparation on motor processes and rather suggest an influence on pre-motor, even perceptual, processes.

This conclusion, however, is not necessarily warranted, since several studies could show that stimulus intensity also influences the motor-specific variable response force for auditory (Miller, Franz, & Ulrich, 1999) as well as visual stimuli (Angel, 1973). Specifically, Miller, Franz, and Ulrich (1999) could show that RT decreased and response force increased with auditory target stimulus intensity in simple RT, choice RT as well as Go/NoGo tasks. This result was also observed for auditory accessory stimuli when the target stimulus was a visual one. An explanation for this effect is provided by arousal models (Miller, Franz, & Ulrich, 1999). Accordingly, intensity influences RT not only via the perceptual stage of the S–R chain but also via an external route that controls arousal. Intense stimuli are highly arousing and energize the response which is evident in increased response force as well as in decreased RT. Consequently, it is not completely clear whether an interactive effect of stimulus intensity and temporal preparation on RT actually indicates a perceptual locus of temporal preparation.

Taken together, RT studies based on the AFM suggest that FP duration, and thus temporal preparation, operates on motor stages of the S-R chain (e.g., Alegria & Bertelson, 1970; A. F. Sanders, 1980a). However, interactive effects between FP duration and target stimulus intensity question this account (e.g., Niemi, 1979), although an exclusive perceptual locus of stimulus intensity has been doubted (e.g., Miller, Franz, & Ulrich, 1999). Furthermore, as Müller-Gethmann et al. (2003) emphasized, evidence based on the AFM has to be interpreted cautiously since this logic depends necessarily on the correctness of discrete stage models (but see Miller, Van Der Ham, & Sanders, 1995).

Response force and muscular activity

In addition to RT, also other indices of motor processing were found to be sensitive for temporal preparation, for example response force (Mattes & Ulrich, 1997) and muscular activity (Tandonnet, Burle, Vidal, & Hasbroucq, 2005). Specifically, Mattes and Ulrich (1997) presented a visual warning signal that was followed by a visual target stimulus. Participants responded to the onset of the target stimulus with a flexion of their right index finger, and the response force of this flexion was sampled for an interval that began shortly before the onset of the target stimulus and continued for 2 sec. RT was assessed at the time point at which the measured response force reached a certain criterion and the FP was varied blockwise (constant foreperiod paradigm) as well as trialwise (variable foreperiod paradigm). As expected, RT increased with FP in the constant FP condition and decreased with FP in the variable FP condition. The same result pattern was found for response force, hence, temporal preparation was shown to diminish response force. A further experiment replicated this result and showed that it is also valid for auditory target stimuli and also for different intensities of visual as well as auditory targets.

As already noted in Section 1.2., Mattes and Ulrich (1997) explained their results within the framework of the motor readiness model by Näätänen (1971). Accordingly, in a trial in which the participant is poorly prepared, motor readiness is far from the motor action limit (i.e., the criterion at whose transgression the response is triggered) and a large excitation increment is needed for the triggering of the response. This overshoot in excitation then leads to increased response force, whereas a well-adjusted motor readiness level under high temporal preparation leads to a fast and less forceful, that is, force-adjusted, response.

Similar evidence for a motor locus of temporal preparation comes from a study by Tandonnet et al. (2005) who have shown that temporal preparation directly influences the activity of the involved muscles. These authors realized a constant FP experiment and concurrently measured the electromyographic (EMG) activity of a specific hand muscle. Specifically, at the beginning of each trial, participants had to set up a tonic contraction in the response-relevant muscle agonists, that is, the muscles of the index fingers, and the corresponding response force was measured. This basic contraction was needed to make observable the EMG changes in the further trial course. When the force of this contraction reached a certain level, an auditory warning signal was presented and after a short or long FP the visual target stimulus required a choice reaction. Participants had to abduct one index finger when a red target was presented and the other index finger when a green target was presented. RT was defined as the interval between target stimulus onset and the time at which the force exceeded a certain criterion. Furthermore, EMG of the first dorsal interosseus of both index fingers was recorded for 1,500 ms, that is, from 500 ms before the response to 1,000 ms after the response. The EMG was then averaged time-locked to the response and pooled together for the agonist of the required response hand and the agonist of the non-required response hand.

Besides an increase of RT with FP, there was also an influence of FP on the EMG. First, Tandonnet et al. (2005) observed that the EMG activity of the required response agonist increased before the response, compared to the baseline that was defined over the time window from -600 to -160 ms before the response. The maximal amplitude of this activity was lower in the short FP than in the long one. Second, compared to the baseline, the EMG activity of the non-required response agonist decreased before the response. The slope of this decrease was smaller for the long FP than for the short one. Thus, the deactivation of the non-required agonist is more pronounced when temporal preparation is high. These findings, too, fit in with the motor readiness model by Näätänen (1971). Accordingly, under low temporal preparation the motor readiness is far from the motor action limit and a large excitation is needed to trigger the response. The corresponding excitation overshoot is present here as a larger EMG amplitude of the required response agonist in the long FP.

Furthermore, under high temporal preparation the motor readiness is close to the motor action limit what holds a higher risk for a wrong response. Hence, the more pronounced deactivation of the non-required response agonist may therefore help to beware of such errors.

To sum up, motor indices like response force (e.g., Mattes & Ulrich, 1997) and muscular activity (Tandonnet et al., 2005) are influenced by temporal preparation such that response force, for example, decreases with temporal preparation. However, a caveat to this evidence for a motor locus of temporal preparation has to be noted (see Müller-Gethmann et al., 2003). A correlation between RT and response force is often lacking (e.g., Mattes, Ulrich, & Miller, 1997) and therefore, it is questionable whether a decrease in response force actually contributes to the decrease in RT.

Reflexes and motor-evoked potentials

A further finding that points to a motor locus of temporal preparation concerns the occurrence of reflexes which index the excitability of the spinal motor structures. Several studies have shown that temporal preparation varies this excitability (e.g., Hasbroucq, Kaneko, Akamatsu, and Possamaï, 1999; Semjen, Bonnet, & Requin, 1973; for a review see Requin et al., 1991). Basically, in a FP experiment, when monosynaptic reflexes (i.e., Hoffmann-reflex and Tendinous-reflex) are triggered, their amplitude decreases during the FP. Whereas most of the evidence has been gathered from a lower limb muscle, it has also been generalized to upper limb muscles.

Hasbroucq et al. (1999), for example, required their participants to press two buttons with both thumbs in order to maintain a background muscle tension which is necessary to elicit an Hoffmann-reflex in the hand muscles. Then, a visual warning signal was presented that was followed by the likewise visual target stimulus after a constant FP of 500 ms. Participants had to perform in a choice RT task on this target stimulus, that is, to perform a flexion of that thumb on whose side the target stimulus was shown. A Hoffmann-reflex in the involved muscles was electrically elicited at warning signal onset, at target stimulus onset, and at two time points during the FP.

To this end, electric stimulation was applied over a nerve at the right wrist, and the evoked response, that is, the Hoffmann-reflex, was measured via the EMG for a thumb muscle. The reflex at warning signal onset was used as a reference for each participant, and the evoked response was observed in certain time windows that had been defined in adjustment trials before the actual experiment. As a result, the standardized amplitude of the Hoffmann-reflex was found to diminish during the FP and thus, the excitability of the corresponding motor structures was lowered before the delivery of the target stimulus.

In a similar vein, Hasbroucq, Kaneko, Akamatsu, and Possamaï (1997) have evoked motor potentials by applying transcranial magnetic stimulation (TMS) to the motor cortex areas corresponding to a hand muscle. TMS is a magnetic stimulation applied non-invasively over the motor cortex. It elicits motor potentials contralateral to the application locus. Hasbroucq et al. employed this technique in combination with a constant foreperiod paradigm and a visual choice RT task. Participants were presented with a visual warning signal, and after a short or a long FP the warning signal was replaced by a likewise visual target stimulus. Participants had to judge whether the target was on the left or on the right side and had to press a corresponding button. In one half of the trials, TMS was applied either at warning signal onset or at target onset, and motor evoked responses were measured via the EMG activity of the relevant finger muscle. For the no-stimulation trials the usual FP effect on RT emerged, that is, participants responded faster when the FP was short and temporal preparation was high. Furthermore, the peak amplitude of the evoked potentials were compared for the two time points of TMS application. Crucially, for the short FP, the amplitude was smaller at target onset than at warning signal onset. For the long FP, however, this difference could not be observed. Consequently, the cortico-spinal excitability is suggested to decrease over the FP in the condition in which participants are highly prepared.

In conclusion, this decrease of spinal excitability, evidenced through reflex research as well as TMS research has been interpreted as an increase of inhibition at the presynaptic level of the motoneuron afferents (Hasbroucq et al., 1999; Requin et al., 1991). This can be seen as an adaptive mechanism that increases the sensitivity of the cortico-spinal structures for the upcoming response to the target stimulus (Hasbroucq et al., 1997, 1999). For example, task-unrelated afferents could be inhibited so that wrong or premature responses can be avoided. Just as for response force and muscular activity, however, it is not clear whether this relationship between temporal preparation and cortico-spinal excitability can directly account for the decreasing effect of temporal preparation on RT (Müller-Gethmann et al., 2003).

Event-related potentials

Among the components of the event-related potential the contingent negative variation (CNV, Walter, Cooper, Aldridge, McCallum, & Winter, 1964) has been proposed to indicate motor preparation. The CNV is a slow potential that develops between a warning signal and the target stimulus, that is, during the FP. It is a slow negativity and is made up of two waves (Rohrbaugh & Gaillard, 1983), an earlier, fronto-centrally dominant wave (also called O-wave [orientation], see Loveless & Sanford, 1974) and a later, centro-parietally dominant wave (also called E-wave [expectancy], see Loveless & Sanford, 1974). As the names O-wave and E-wave suggest, the earlier one has been proposed to indicate the orienting reaction that is induced by the warning signal. The later one is thought to index expectancy and anticipation of the target stimulus, but also motor preparation (cf. for an overview Verleger, Wauschkuhn, Van Der Lubbe, Jáskowski, & Trillenberg, 2000).

It is this motor-related CNV which numerous studies have shown to vary with temporal preparation (e.g., Loveless, 1973; McAdam, Knott, & Rebert, 1969; Van Der Lubbe, Los, Jáskowski, & Verleger, 2004). For example, McAdam et al. (1969) presented participants with two successive clicks of which the first one was instructed as the warning signal and the second as the target stimulus. Participants had to respond as fast as possible to the target stimulus and were informed that the FP was constant for one block of trials. As one would expect, RT increased with FP, and in addition, the amplitude of the CNV was found to decrease with FP. Loveless (1973) found analogous results for a variable foreperiod paradigm. Here, RT decreased with FP whereas CNV amplitude increased. Thus, decreasing temporal preparation leads to a decrease of the motor-related CNV and therefore indicates a motor locus of temporal preparation.

The database on variable FPs was further extended by Van Der Lubbe et al. (2004) who investigated the question whether and how the sequential effect is mirrored in the CNV. The participants in the study of Van Der Lubbe et al. were presented with an auditory warning signal that was followed by the letter L or R after a variable FP. The participants used the middle and index finger of either their left or right hand (varied blockwise) to indicate which letter had been shown. Remember that in a variable foreperiod paradigm the RT is not only influenced by the current FP, but also by the FP of the previous trial. More specifically, when the previous FP was longer than the current FP, RT typically lengthens (e.g., Steinborn et al., 2008). Van Der Lubbe et al. found this result pattern not only for RT, but also for the CNV such that at the shortest FP the CNV amplitude was largest when the previous FP had also been short.

In addition to the CNV, Van Der Lubbe et al. (2004) also assessed the lateralized readiness potential (LRP). The LRP is a difference measure of the EEG measured above the primary motor areas contra- and ipsi-lateral to the response hand. It very specifically indexes motor activation since the subtraction deletes all activity that is not related to the response side. Thus, in contrast to the CNV, the LRP has the advantage of providing a measure of motor activation that is free of confounding influences, as for example, effects of the presentation of the warning signal per se (cf. Van Der Lubbe et al., 2004, p. 249). Since in the study of Van Der Lubbe et al. the response hand was fixed for a block of trials (i.e., in one block of trials participants always responded with the left hand and in another block of trials always with the right hand), the LRP developed during the FP and was measured from 90 ms before the warning signal until 1,000 ms after the warning signal. The analyzes were restricted to 40 ms around the first possible target presentation at the shortest FP. As a result, for the shortest FP an effect of the previous FP on the LRP amplitude could be observed. Specifically, the LRP amplitude was larger when the previous FP had been short than when it had been longer.

Summing up, motor-related ERP components like the CNV and the LRP vary with temporal preparation what indicates a motor locus of temporal preparation (e.g., McAdam et al., 1969; Van Der Lubbe et al., 2004). However, here too, doubts arise about whether these variations are actually causing the RT decrease due to temporal preparation. First, the causal relationship is not completely clear. For example, McAdam et al. (1969) note that approximately 80% of the variance in RT and CNV cannot be explained by variations in the respective other measure (p. 356). Furthermore, Van Der Lubbe et al. (2004) tried to find a relation between the LRP and the RT at the shortest FP. To this end, they calculated for LRPs and RT respectively the differences between the short and long previous FP and compared these differences. No significant relation between those two measures could be found. Second, the interpretation of the CNV as an motor index is not completely clear cut. It has predominantly been suggested as an index of motor preparation, but also non-motor types of anticipation have been suggested (e.g., memory, time estimation; Macar & Besson, 1985; Ruchkin, Canoune, Johnson, & Ritter, 1995, see also Van der Lubbe et al., 2004).

Concluding this subsection, various findings based on the AFM (e.g., Alegria & Bertelson, 1970), response force (e.g., Mattes & Ulrich, 1997), reflexes (e.g., Hasbroucq et al., 1999), and ERP components (e.g., Van Der Lubbe et al., 2004) suggest a motor locus of the temporal preparation effect. There are, however, also many critical points that make it questionable whether temporal preparation actually influences the duration of motor processes and whether this influence accounts for the reduction in RT (cf. Müller-Gethmann et al., 2003).

1.3.2. Evidence for a perceptual locus

As I have shown in the previous subsection, it is still not completely clear whether the RT decrease by temporal preparation can actually be attributed to a shortening of the duration of motor processes. In fact, recent findings support the idea that temporal preparation may rather affect pre-motor processes. Some studies have even suggested that temporal preparation influences perceptual stimulus processing. Whereas the first part of the present subsection focuses on studies providing evidence for a pre-motor locus of temporal preparation, the second part introduces behavioral studies showing that even pure perceptual measures can be influenced by temporal preparation. The final part, then, comments on studies that found temporal preparation effects on perceptual ERP components.

Temporal preparation affects pre-motor processes

The locus of a certain experimental manipulation in the information processing chain has been searched for with the help of the psychological refractory paradigm (PRP paradigm, also overlapping tasks paradigm; for a review see Pashler & Johnston, 1989) as well as with the help of the LRP (e.g., Osman et al., 1995). Recently these means have also been employed for revealing the temporal preparation effect.

The PRP paradigm has originally been developed to investigate the temporal course of information processing in a dual-task situation (e.g., Welford, 1952); in a typical trial, the participant has to complete two tasks (Task 1 and Task 2). Specifically, two stimuli (S1 and S2) are presented shortly after another and the participant has to respond to both of them (R1 and R2) as fast as possible. In the experiment by Bausenhart, Rolke, Hackley, and Ulrich (2006) for example, Task 1 was a color discrimination task, and participants had to respond to a green or red rectangle by pressing one of two designated keys with the middle and index finger of their left hand. Task 2 was a pitch discrimination task, and participants had to decide whether S2 was a low-, medium-, or high-pitched sine wave by pressing one of three keys with the index, middle, or ring finger of their right hand. The typical RT pattern of such an experiment is such that RT2 (i.e., the reaction time to S2) increases with decreasing stimulus onset asynchrony (SOA) between S1 and S2, whereas RT1 is uninfluenced by the SOA.

This so-called *PRP effect* has been proposed to emerge from a bottleneck in the information processing chain (Pashler, 1994). This bottleneck is supposed to be located at the central stage of information processing, that is, at response selection. According to this bottleneck logic, response selection can only take place for one stimulus at a time, whereas the pre-bottleneck (perceptual) and post-bottleneck (motor) processes, however, can occur concurrently for S1 and S2. Consequently, when S2 is presented shortly after S1 (short SOA), S2 response selection has to wait until the response for S1 has been selected and thus, RT2 lengthens. When the SOA is longer, S1 has already completed the response selection stage when S2 arrives and hence, no waiting time prolongs RT2.

In their search for the locus of temporal preparation, Bausenhart et al. (2006) utilized the so-called *effect propagation property* of the PRP paradigm (see Miller & Reynolds, 2003; Pashler, 1994). Remember that S2 may enter the perceptual stage immediately but cannot enter the central stage until the response for S1 has been selected. Consequently, when the SOA is short, any prolongation of the perceptual or central stages of S1 will prolong the waiting time for S2 and thus *propagate* to Task 2. At long SOAs, however, the central processing of S1 will already be over when S2 occurs so that S2 can directly transit from perceptual to central processing. Hence, any experimental factor that affects the pre-motor stages of S1 will affect RT1 as well as RT2 at short SOAs, whereas at longer SOAs RT2 will be unaffected. In contrast, an experimental factor that affects the motor (postcentral) stages of S1 processing will not affect the waiting time for S2 and thus its effect should only be observed for RT1, but not for RT2.

Bausenhart et al. (2006) confronted their participants with a dual-task-situation (color and pitch discrimination) as described above and presented a warning signal before S1. Temporal preparation was manipulated via a constant foreperiod paradigm. As expected, the RT data showed the typical PRP effect, that is, RT2 increased with decreasing SOA, whereas RT1 was uninfluenced by SOA. Furthermore, RT1 decreased with FP duration, that is, when the FP was longer, participants were less prepared for the occurrence of S1 and thus responded slower. Crucially, this effect was also found for RT2 but only at shorter SOAs. More specifically, at short SOAs the temporal preparation effect on Task 1 propagated to Task 2. Based on this effect propagation, Bausenhart et al. concluded that temporal preparation does not alter the duration of motor processes but rather shortens perceptual or central processes.

Besides the PRP paradigm, the LRP onset has been used to localize the effects of certain experimental manipulations on RT (Osman et al., 1995). As already outlined in Subsection 1.3.1., the LRP is a difference measure and occurs as a negativity prior to a response, contralateral to the responding hand. When the response hand is not pre-specified at the beginning of a trial, but can only be selected after the target stimulus has been presented and identified (as, for example, in a typical 2 alternative forced choice task, 2AFC task), the onset of this negativity can be used to bisect RT in an early pre-motor phase and a late motoric phase. More specifically, when participants have to respond to the target with either the left or the right hand, one will observe an asymmetrical readiness potential which is more negative over the hemisphere contralateral to the response hand.

The onset of this asymmetry is regarded as the onset of the LRP and is supposed to indicate the beginning of response-specific processes (Osman et al., 1995). The LRP onset can either be measured with reference to the onset of the target stimulus (stimulus-locked) or to the onset of the response (response-locked). The duration from target onset to stimulus-locked LRP (S-LRP interval) denotes RT processes prior to hand-specific response activation (pre-motor), and the duration from response-locked LRP to response (LRP-R interval) denotes RT processes after response activation (motor processes). Thus, by investigating whether an experimental manipulation affects the S-LRP interval or the LRP-R interval, one can determine if the manipulation affects the duration of early or late stages of processing, respectively. Research has employed the LRP to investigate the effects of warning signals and have found that temporal preparation influences the S-LRP interval rather than the LRP-R interval (Hackley, Schankin, Wohlschlaeger, and Wascher, 2007; Müller-Gethmann et al., 2003; for reviews see Hackley, 2009; Hackley and Valle-Inćlan, 2003).

Müller-Gethmann et al. (2003), for example, employed a constant foreperiod paradigm with eight different FP durations between 50 and 6,400 ms. A visual warning signal was presented and the following auditory target stimulus required a pitch discrimination (low vs. high) by a key press. RT and LRP were measured as the main dependent variables and for RT, the typical U-shaped function was observed. From 50 ms to 200 ms the RT sharply decreased with FP, then, RT increased with FP. Crucially, the S-LRP interval pattern resembled the RT results closely, that is, it increased with increasing FP except for very short FPs. In contrast to that, the LRP-R interval pattern did also vary with FP but rather unsystematically—its pattern was far from being similar to the RT data. Additionally, the S-LRP interval highly correlated with RT—that is, the shorter the S-LRP interval the shorter the RT—whereas the correlation between RT and R-LRP interval was only moderate. In a second experiment, Müller-Gethmann et al. could replicate these results for a visual target stimulus and an auditory warning signal. Again S-LRP interval varied systematically with FP whereas R-LRP interval was now uninfluenced by FP. Thus, the data suggest that temporal preparation diminishes the duration of early processes prior to LRP onset.

To sum up, studies based on the PRP logic (Bausenhart et al., 2006) as well as the LRP (e.g., Müller-Gethmann et al., 2003; Hackley et al., 2007) contradict the traditional consensus that temporal preparation exclusively affects motor processes. Rather, these studies suggest that the duration of pre-motor processes is diminished, what in turn might also lead to a decrease in RT.

Temporal preparation affects perceptual indexes

The studies discussed above show that the early part of information processing is influenced by temporal preparation. Nevertheless, based on the PRP (Bausenhart et al., 2006) and LRP results (e.g., Müller-Gethmann et al., 2003) reported above it cannot be decided unequivocally whether central or rather perceptual processes are affected. However, several studies could show that temporal preparation affects purely perceptual measures which clearly supports a perceptual locus. As a matter of fact, temporal preparation has been shown to improve visual discrimination performance (Correa et al., 2005; R. Klein & Kerr, 1974; Lowe, 1967; Rolke, 2008; Rolke & Hofmann, 2007), auditory discrimination and detection performance (Bausenhart, Rolke, & Ulrich, 2007; Howarth & Treisman, 1958; Loveless, 1975; Treisman & Howarth, 1959) as well as temporal resolution (Bausenhart et al., 2008; Correa, Sanabria, et al., 2006).

Temporal preparation for a visual target stimulus facilitates visual discrimination performance; this finding is meanwhile well documented. Two early studies on this topic have been realized by Lowe (1967) and R. Klein and Kerr (1974). On the one hand, R. Klein and Kerr asked their participants to detect a weak visual target stimulus that was followed by a mask. An auditory warning signal preceded the target stimulus and thus allowed for temporal preparation in a variable foreperiod paradigm. Mirroring the traditional RT effect, the discriminability of the target stimulus increased with FP. That is, better temporal preparation improved perceptual processing of the target stimulus.

On the other hand, Lowe (1967) manipulated temporal preparation in a rather unusual paradigm. Specifically, each trial started with an auditory warning signal and after a constant interval the so-called observation interval started. During this observation interval the target stimulus, a light flash, was presented. The length of the observation interval determined the possible occurrence times for the target stimulus and was varied over blocks of trials. The longer the observation interval, the more possible occurrence times and hence, the lower the possible temporal preparation. Participants performed in a detection task and it was found that detection performance got worse with increasing observation interval length, that is, with decreasing temporal preparation. Lowe suggested that this is due to a more likely confusion of signals with noise when temporal preparation is low.

More recent studies on visual discrimination have been performed by Rolke (2008, Rolke & Hofmann, 2007) and Correa et al. (2005). As described in Subsection 1.2.2. about the early onset hypothesis (Rolke, 2008; Rolke & Hofmann, 2007), Rolke and Hofmann could show that temporal preparation improves the spatial resolution. Specifically, d' in a Landolt square discrimination task increased significantly when participants could prepare for the onset of the Landolt square. Later, Rolke (2008) even extended this finding to higher-level perceptual processing, namely to the identification of letters. Rolke's participants had to discriminate ten letters whereby a warning signal with a constant FP announced the occurrence of the letters. Just as in the experiment by Rolke and Hofmann, a visual noise pattern masked the letters after a variable letter duration. Any speed related strategies were prevented by requiring participants to withhold their responses until a response signal was presented after the mask. Besides the usual RT effect, that is, increasing RT with increasing FP, percent correct decreased with FP. This effect of FP on percent correct was, however, modulated by the duration of the letter presentation. Actually, a significant effect of temporal preparation on percent correct could only be detected for the shortest duration, that is, for the most difficult condition.

A similar finding was obtained in a further experiment. Here, the difficulty of the task was not manipulated via the target duration but via the contrast of the target stimuli. Again, the FP effect on percent correct interacted with difficulty, namely stimulus contrast. The FP effect was more pronounced for low-contrast stimuli and vanished for high-contrast stimuli. Interestingly, such an interaction did not emerge for the RT results. RT increased with FP, independently of task difficulty. This findings suggest that for the observation of temporal preparation effects on perceptual processing, a perceptually highly demanding task is necessary (e.g., short target duration, low contrast); a prerequisite that has also been suggested by Correa, Lupiáñez, Madrid, and Tudela (2006).

The research group of Correa and colleagues, who employ a temporal orienting paradigm, also provided evidence that temporal preparation influences visual perceptual processing. Correa et al. (2005), for example, used a rapid serial visual presentation task in which a fast series of letters was presented to the participants. Participants had to respond when the target letter, an X, occurred in the letter series. At the beginning of each trial, a symbolic cue announced whether the target would appear soon or late in the stimulus series. This cue should enable participants to orient their attention to the specified point in time, and, consequently, a valid cue should facilitate the discrimination of the target. As one would expect, Correa et al. found an increased d' in validly compared to invalidly cued trials. Crucially, the results for beta, that is, the response criterion, did not differ with cue validity. Therefore, the observed discrimination advantage of valid trials can actually be interpreted as higher perceptual sensitivity when participants know in advance when to expect the target stimulus.

In a later study, Correa, Cappucci, Nobre, and Lupiáñez (2010) extended the beneficial effect of temporal orienting on perceptual processing to an even more complex situation. Specifically, they assessed whether temporal orienting is able to improve executive control. To this end, Correa et al. employed a Simon-Stroop task in combination with a temporal orienting paradigm. In detail, participants were presented with four placeholders: one to the left, one to the right, one above, and one below fixation. A symbolic cue indicated when to expect the target display (short vs. long, 75% validity), which consisted of double-head arrows (pointing up and down) in three of the placeholders and a one-head arrow (pointing either up or down) in the remaining one. The participants' task was to indicate whether the one-head arrow pointed up or down by pressing a key with a finger of either the left or the right hand. Due to the specific layout of the display, a Simon effect as well as a Stroop effect could emerge. When the one-head arrow appeared in the horizontal axis (i.e., to the left or to the right of fixation), a Simon effect arose, that is, faster responses when the stimulus was on the same side as the response hand (congruent). When the one-head arrow appeared in the vertical axis (i.e., above or below fixation), a spatial Stroop effect arose, that is, faster responses when the direction of the arrow and its spatial location coincided (congruent). Most crucially, these two effects were modulated by the validity of the temporal cue, that is, temporal orienting. For the Simon task, which involves a conflict at the response level, the conflict was aggravated by temporal orienting. For the Stroop task, which involves a conflict at the perceptual level, however, the conflict was attenuated by temporal orienting. Hence, temporal orienting does not only facilitate simple perceptual processing but also complex situations in which executive control over perceptual processing is required.

Taken together, a beneficial effect of temporal preparation on visual perceptual processing has been shown for a wide range of tasks and measures. Detection (Lowe, 1967) as well as discrimination performance (e.g., Rolke & Hofmann, 2007), measured as percent correct or d', improves when participants know in advance when to expect the target stimulus. Furthermore, this effect is primarily found for perceptually demanding tasks and is even present in higher-level processing, that is, letter processing (Rolke, 2008) and the dissolution of perceptual conflicts (Correa et al., 2010).

Early evidence for an influence of temporal preparation on the perceptual processing of auditory stimuli was provided by Howarth and Treisman (1958; see also Treisman & Howarth, 1959). These authors employed a constant foreperiod paradigm in which they presented a visual warning signal and an auditory target stimulus. For the target stimulus, the detection threshold was determined via the descending method of limits. That is, the intensity of the stimulus was decreased stepwise until the participant did not detect it anymore. This was carried out four times for each FP and the mean of the four measurements was taken as the final threshold for each FP. Howarth and Treisman observed a decrease in the auditory threshold with decreasing FP. In other words, high temporal preparation led to a better performance in detecting an auditory stimulus which clearly indicates a perceptual influence of temporal preparation.

Quite similar evidence was provided by Loveless (1975) who let his participants perform in an auditory signal detection task. The target stimulus, consisting of white noise, was announced by a sine wave and the FP between them was varied constantly. Importantly, d' was found to decrease with FP, that is, perceptual sensitivity benefitted from high temporal preparation. Furthermore, the measure of the criterion, beta, did not change significantly with FP. Thus, one can conclude that the increase in sensitivity was truly perceptual and not due to a change in decisional processes.

More recently, Bausenhart et al. (2007) extended the evidence for an influence of temporal preparation on auditory perception to an auditory discrimination task. In a constant foreperiod paradigm with two FPs these authors investigated pitch discrimination. To this end, a white noise acted as a warning signal for a pure tone which could be either high pitched or low pitched. Refraining from a speeded response, participants had to wait for a response prompt upon which they indicated which of the two target stimuli had been presented. Crucially, the duration of the target stimuli changed according to an adaptive rule. Thus, Bausenhart et al. could estimate for each participant which target duration was necessary in order to reach 75% correct responses, that is, the discrimination threshold. As a result, this threshold was much lower for the short FP. Hence, better temporal preparation improved pitch discrimination and thus, this study supports the perceptual locus account of temporal preparation. Summing up, for auditory processing, too, there is are a number of studies showing that detection (e.g., Loveless, 1975) as well as discrimination performance (Bausenhart et al., 2007) improves when participants can temporally prepare for stimulus occurrence.

Apart from the perceptual sensitivity in the visual and auditory modality, higher precision in temporal resolution is also an indicator for fast and improved perceptual processing. In fact, two studies, one with a constant foreperiod paradigm (Bausenhart et al., 2008) and one with a temporal orienting paradigm (Correa, Sanabria, et al., 2006), show that temporal preparation can improve the temporal resolution of visual perception. Both studies employed a temporal order judgment task (TOJ task), in which participants have to report which of two target stimuli (e.g., left and right) appeared first. In a TOJ task, one varies the SOA between these two stimuli according to the psychophysical method of constant stimuli or to an adaptive method.

From the response pattern of a participant, one can estimate a corresponding psychometric function. In such a function, the probability for the response 'right stimulus first' is depicted as a function of SOA. The Difference Limen (DL, also called the just noticeable difference, JND) indexes the smallest SOA at which a participant can still correctly report which of the two stimuli occurred first and is thus a direct index of the accuracy of temporal processing. Hence, the smaller the DL, the better the temporal resolution.

Specifically, Bausenhart et al. (2008) presented a white frame in each trial which acted as the warning signal. After a short or a long FP (varied constantly), one of two target stimuli, a white dot, appeared either on the left or on the right side of fixation and after the variable SOA the second target stimulus was added. A visual noise pattern masked the targets and then a question mark prompted participants to indicate their response, namely, whether the left or the right target stimulus had occurred first. As a result, the percentage of correct responses in the short FP condition was higher and the DL was smaller than in the long FP condition.[3]

In Experiment 3 of their study, Bausenhart et al. (2008) employed a wider range of FPs (6 different durations from 150 up to 4,800 ms) in order to identify the temporal course of temporal preparation influence on temporal resolution. Notably, the result pattern of the DL showed the typical U-shape that has also been reported for RT (Bertelson & Tisseyre, 1969b; Müller-Gethmann et al., 2003) and for the S-LRP interval (Müller-Gethmann et al., 2003). From a FP of 300 ms up to 4,800 ms the DL increased with FP, but

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[3] Bausenhart et al. (2008) also measured the point of subjective simultaneity (PSS), that is, the SOA at which participants perceived both target stimuli as simultaneous. The PSS could point to a bias in temporal processing but note that Bausenhart et al. did not observe an influence of temporal preparation on PSS in any of their experiments.

for the shortest FP of 150 ms, DL was at a similarly high level as at for the longest FP. This U-shape has been suggested as evidence that it takes some time until temporal preparation is established (Bausenhart et al., 2008).

To explain the influence of temporal preparation on temporal resolution Bausenhart et al. (2008) as well as Correa, Sanabria, et al. (2006) suggested that under high temporal preparation the accumulation rate of perceptual information sampling might increase. Such a higher accumulation rate under high temporal preparation could not only explain the higher temporal resolution but also the increased perceptual accuracy in general. For an example, in a masked stimulus presentation (e.g., Rolke & Hofmann, 2007) more information could be accumulated before stimulus processing is interrupted and thus, accuracy would be better. Note that a higher information accumulation rate under high temporal preparation is actually an alternative explanation to the early onset hypothesis (Rolke, 2008; Rolke & Hofmann, 2007). Both accounts predict, however, a decrease of the duration of perceptual processes.

Summing up, Bausenhart et al. (2008) and Correa, Sanabria, et al. (2006) show that temporal preparation influences the DL in a TOJ task—a performance measure that mainly depends on perceptual processing—and thus strengthen the notion of a perceptual locus of temporal preparation. Furthermore, the similar effect patterns of temporal preparation on temporal resolution and RT suggest that a common mechanism underlies both RT decrease and improvement of perceptual processing.

In conclusion, studies with foreperiod paradigms (e.g., Howarth & Treisman, 1958; Loveless, 1975; Rolke & Hofmann, 2007) as well as studies with temporal orienting paradigms (e.g., Correa et al., 2005) have observed a beneficial influence of temporal preparation on perceptual measures like detection and discrimination accuracy. Such evidence was provided for visual (e.g., R. Klein & Kerr, 1974), auditory (e.g., Bausenhart et al., 2007), and also for temporal processing (Bausenhart et al., 2008; Correa, Sanabria, et al., 2006).

Temporal preparation affects perceptual ERP components

Various studies also provide electrophysiological evidence for a perceptual locus of temporal preparation. It has been shown for auditory as well as visual stimuli that early components of the ERP, for example the N1, are influenced by temporal preparation (Correa, Lupiáñez, Madrid, & Tudela, 2006; Lange et al., 2003; Lange, Krämer, & Röder, 2006; Lange & Röder, 2006; L. D. Sanders & Astheimer, 2008). The N1 component is classed among the exogenous or sensory components which are “thought to represent the activity of the sensory pathways that transmit the signal generated at peripheral receptors to central processing systems” (Fabiani et al., 2007, p. 98). The N1 amplitude is known to be sensitive to auditory selective attention (cf. Hillyard, Teder-Sälejärvi, & Münte, 1998), that is, its amplitude is enhanced for attended stimuli. It occurs very early, around 100 to 150 ms after stimulus onset and is therefore thought to index perceptual processing.

For the auditory modality, I have already described the study by Lange et al. (2003) in Subsection 1.1.2. Repeated in short, employing a temporal Hillyard paradigm these authors could show that stimuli at attended points in time elicit an enhanced N1 component compared to stimuli at unattended points in time. This modulation of a very early ERP component suggests that perceptual processes are influenced by temporal preparation. In a further study, Lange et al. (2006) could replicate this finding, and L. D. Sanders and Astheimer (2008) could generalize it to an experimental design with three intervals (also see Subsection 1.1.2.)

The robustness and generality of this finding was further extended by a cross-modal study by Lange and Röder (2006). Just as in the previous studies, Lange and Röder employed a temporal Hillyard paradigm, in which the trial structure was as follows. An interval always started with a tactile stimulus at the index finger of both hands. After either a short or a long duration the end of the interval was marked with an auditory or a tactile stimulus. This standard offset marker was a single stimulus and the deviant was a double stimulus (i.e., two stimuli shortly after each other). The participant’s task was to attend either to the short or to the long interval and either to the tactile or auditory modality and report for this condition any deviant they detected. For each modality separately, the N1 for stimuli at attended time points was enhanced. Crucially, when the tactile modality had to be attended N1 amplitude for auditory stimuli at attended time points was also enhanced. This shows that temporal preparation not only enhances perceptual processing within a modality but even across modalities.

For visual stimuli, the first evidence for a modulation of perceptual ERP components by temporal attention was provided by Correa, Lupiáñez, Madrid, and Tudela (2006). To this end, they chose a perceptually highly demanding task, namely, a letter discrimination task. Temporal attention was manipulated blockwise with a symbolic cue that told participants to expect the letter either after a short or a long interval. As one would expect, an RT benefit was observed for validly cued target letters. As far as the ERP results are concerned, the amplitude of the P1 component was increased for validly cued stimuli compared to invalidly cued ones. Since the P1, as an early positivity, is linked to visual processing (cf. Gonzalez, Clark, Fan, & Luck, 1994), this study extends the finding of improved perceptual processing through temporal attention to the visual modality.

Taken together, recent studies show that for visual as well as for auditory stimuli temporal attention affects early ERP components (e.g., Correa, Lupiáñez, Madrid, & Tudela, 2006; Lange et al., 2003). That is, when a symbolic cue directs attention to the time point of occurrence, the early perceptual ERP components in response to the respective target stimuli are enhanced. This finding extends the behavioral results from RT studies (e.g., Bausenhart et al., 2006) and studies on perceptual indexes (e.g., Howarth & Treisman, 1958) to the electrophysiological level and suggests yet more markedly a perceptual locus of the temporal preparation effect.

Temporal preparation decreases perceptual latency?

As the present subsection has shown so far, there is meanwhile vast evidence that temporal preparation can influence perceptual processing. Perceptual measures like discrimination accuracy (e.g., Rolke & Hofmann, 2007) as well as early ERP components (e.g., Lange et al., 2003) have been shown to be affected by temporal preparation. More specifically, when participants know in advance *when* a certain stimulus will occur, they do not only respond faster to this stimulus but also more accurately and they express higher spatial and temporal resolution. Some of the studies described above suggest that the RT decrease as well as the beneficial influence on perceptual processing might be due to diminishing duration of the perceptual stage of information processing (e.g., Bausenhart et al., 2006; Correa, Sanabria, et al., 2006; Müller-Gethmann et al., 2003; Rolke, 2008; Rolke & Hofmann, 2007). More specifically, Rolke and Hofmann (2007) suggested that perceptual processing might begin earlier under high temporal preparation, whereas an alternative account assumes a higher information accumulation rate under high temporal preparation (Bausenhart et al., 2008; Correa, Sanabria, et al., 2006). Since both accounts assume a shortened perceptual stage, one can postulate the general hypothesis that temporal preparation—over and above any effects it might have on motor stages—diminishes the duration of perceptual processing, that is, the time taken up in the system before a stimulus is detected.

This *perceptual latency* (e.g., Breitmeyer & Öğmen, 2006; Cattell, 1886) has also been termed *perceptual lag* (A. J. Sanford, 1974) or *Empfindungszeit* (sensation time, author's translation, Fröhlich, 1923, 1929). Fröhlich (1923) defined Empfindungszeit as "jene Zeit (...), welche zwischen der Einwirkung des Lichtreizes und dem Auftreten der mit ihm verknüpften Lichtempfindung vergeht" (that time, which elapses between the impact of a luminous stimulus and the occurrence of the corresponding luminous sensation, author's translation, p. 58). In the framework of the already mentioned accumulation models (e.g., Grice, 1968; Luce, 1986; Miller & Schwarz, 2006), perceptual latency is equal to the interval from stimulus onset to the point in time when the criterion is reached.

The present study was designed to evaluate the general hypothesis that temporal preparation diminishes the duration of perceptual processing directly for stimulus detection. That is, it was examined whether perceptual latency to detect a target stimulus decreases when a participant can temporally prepare for the occurrence of this stimulus. To measure perceptual latency, a clock paradigm was employed—sometimes also called the rotating spot method (e.g., Haggard et al., 2002; Haggard & Cole, 2007; Pockett & Miller, 2007; A. J. Sanford, 1974; Wundt, 1862). The clock paradigm allows an experimenter to measure the time point when a participant perceives a target stimulus. Since the onset of the target stimulus is known to the experimenter, the difference between these two time points indexes the perceptual latency. Thus, the following chapter introduces this traditional psychological paradigm and traces its development and employment in experimental psychology.

2. The clock paradigm

The beginnings of the clock paradigm are closely linked to the beginnings of experimental psychology itself. The paradigm as well as the discipline are rooted in astronomy and, more precisely, in the timing of the transit of stars and planets. Starting from one astronomer's dismissal because of presumably false measurements, this second part of the Introduction traces the clock paradigm's evolvement from astronomy (e.g., Mollon & Perkins, 1996) to its current reception and use in experimental psychology (e.g., Carlson, Hogendoorn, & Verstraten, 2006; Libet, Gleason, Wrigth, & Pearl, 1983; Haggard et al., 2002; Joordens, Spalek, Razmy, & Van Duijn, 2004; Miller, Vieweg, Kruize, & McLea, 2010).

2.1. The passage instrument: "From astronomy to psychology"

The first section of this introductory part covers the clock paradigm's very beginnings in astronomy and the development of psychology as a scientific discipline.[4] The section is mainly based on historical articles by Ben-David and Collins (1966), Brooks and Brooks (1979), Kirsch (1976), and Mollon and Perkins (1996) which in turn elaborate on original sources as the 'Astronomical observations made at the royal observatory at Greenwich' for example (cf. Mollon & Perkins, 1996).

It all started with the necessity of the timing of star transits. A star transit is the crossing point of an imaginary star trajectory with, for example, the Meridian (cf. Schödlbauer, 2000, p. 202–203). The timing of such and alike transits was very important because it was needed for calibrating other astronomical observations and also for the calibration of clocks and ship chronometers (Brooks & Brooks, 1979; Kirsch, 1976). The most used instrument for these timings was the *passage instrument* (cf. Schödlbauer, 2000, p. 463), and the method employed was the *eye-and-ear method* (cf. E. C. Sanford, 1888, p. 5; see Figure 4 for a schematic illustration of this method).

The passage instrument was basically a telescope that was aligned with the Meridian. Several parallel wires—of which the middle one corresponded to the Meridian—divided the field of the telescope (cf. Kirsch, 1976; Schödlbauer, 2000, p. 464). When a star was about to cross the field of the telescope, the observer noted the time of the transit on a clock and started to count the second-beats of the clock's pendulum. Most crucial were the beats right before and right after the crossing of the Meridian. The observer had to mentally preserve the star's position and hence its distance from the wire at these two beats. He would then divide this distance in ten parts, whereby one part corresponds to one tenth of a second. Thus, he could convert the spatial distance into a temporal one and thereby estimate the time of the star's transit to a tenth of a second (cf. Brooks & Brooks, 1979; Kirsch, 1976; Mollon & Perkins, 1996; E. C. Sanford, 1888).

For a long time the accuracy of the eye-and-ear method was assumed to be around two tenth of a second (cf. Kirsch, 1976). However, in 1795 an in-

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[4] The notion "From astronomy to psychology" in the title of this Section was already used by Kirsch (1976, p. 121)

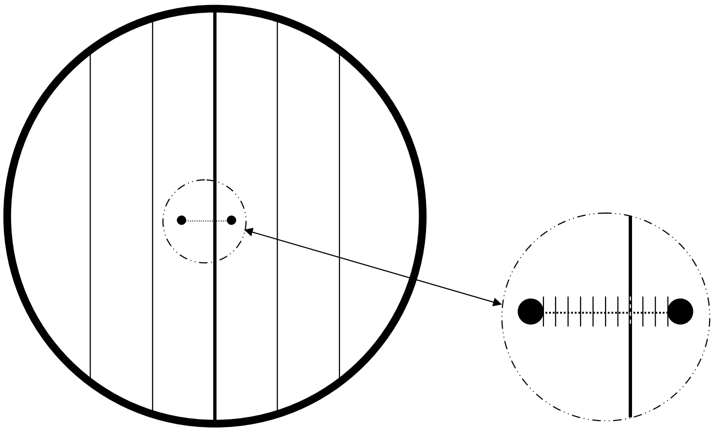

Figure 4. Schematic illustration of the eye-and-ear method. The left picture shows what an observer would see through the passage instrument when a star crosses the field of the telescope from the right to the left. The right dot marks the star's position at the clock beat right before it crosses the middle wire. The left dot marks the star's position at the clock beat right after it crosses the middle wire. The right picture shows an enlargement of the relevant part of the left picture. The vertical dashes indicate how the observer would divide the distance between the two star positions in ten parts. As a consequence he could calculate that the star crossed the middle wire 0.3 s after the first clock beat.

cident took place that should not only question this assumption and occupy astronomers for years, but it should also eventually trigger the development of psychology as a scientific discipline (Brooks & Brooks, 1979). Back then, Nevil Maskelyne was the Astronomer Royal at the Royal Observatory Greenwich. He and his assistant David Kinnebrook were engaged in the timing of stellar transits when Maskelyne noted one day that Kinnebrook's measurements differed from his own by 800 ms (Mollon & Perkins, 1996). Maskelyne was convinced that Kinnebrook did not adhere to the eye-and-ear method as he was supposed to and consequently released him from his duty. It has been assumed, however, that there was also a more 'private' cause for Kinnebrook's dismissal, that is, his refusal to marry a female protegée of Maskelyne (Mollon & Perkins, 1996, p. 102). Nevertheless, about 20 years later, the 'Maskelyne incident' came to the attention of Friedrich Wilhelm

Bessel, a German astronomer and mathematician.

Bessel became eager to find out *why* Kinnebrook's and Maskelyne's measurements differed by so much (cf. Brooks & Brooks, 1979). He was specifically interested in whether such a difference was unique to the Maskelyne-Kinnebrook comparison, or whether it could be found between other observers as well. To this end he compared his own observations with fellow astronomers and also the observations of these colleagues with each other. The result of his research was the description of the so-called *personal equation* (cf. E. C. Sanford, 1888). The *absolute* personal equation would be one observer's deviation from the true crossing time of the star, whereas the *relative* personal equation would be the difference between two observers A and B (see E. C. Sanford, 1888). As long as one observer, say A, is accepted as an experienced and rather 'unbiased' oberserver, the resulting difference might be used to calibrate observer B and correct for his systematic bias. To Bessel's disappointment he had to learn that there was a large variability of the personal equations. Finally, he had to accept that there were inter-individual differences in perception and that even these differences were not stable (cf. Brooks & Brooks, 1979).

Searching for the cause of the variability of the personal equation, some thought that it was due to physiological differences between the observers. Bessel, however, "favoured a psychological explanation" (Brooks & Brooks, 1979, p. 14). Since the eye-and-ear method required the simultaneous attending to two different modalities (i.e., visual: the star; auditory: the clock beat), he supposed that differences in the information accumulation rate could be responsible for the personal equation. In the following, the eye-and-ear method was advanced to a motoric method, in which the observer no longer perceptually registered the transit of the star, but simply pulled a trigger when the star crossed the wire. Consequently, the personal equation, that is, the individual bias of an observer, could now be measured more easily. The development of the first reaction time measuring devices, for example the Hipp chronoscope (cf. Wundt, 1911, p. 365–374), has to be seen in close relation to these motoric methods in astronomy (see E. C. Sanford, 1888,

p. 32). Simultaneously to the reaction time measurements in astronomy, other disciplines, as physiology and then psychology, began to experiment with reaction times as well: Hermann von Helmholtz with his research on the speed of conduction in the motor nerves of first frogs, then humans, and Franciscus Cornelis Donders with his *subtractive method* were the pioneers in this new field of *mental chronometry* (cf. Hergenhahn, 2001, p. 206–211 and p. 236–237).

Among those who were eager to measure psychological variables was also the physiologist Wilhelm Wundt. Wilhelm Wundt, who is nowadays regarded as one of the founders of scientific psychology (Ben-David & Collins, 1966) started his career as a physiologist in 1857. Back then, university chairs for physiology were fought for pretty hard and Wundt did not succeed in gaining a chair for 17 years. He finally changed disciplines and accepted a chair for philosophy, first in Zürich, then in Leipzig. Eventually, in 1879, he was to found the first laboratory for experimental psychology at the University of Leipzig (Ben-David & Collins, 1966). Among other things, Wundt replicated much of Donders' work and—what is of greater interest for this thesis—engaged himself in studies that were based almost directly on the eye-and-ear method involving the first application of a clock paradigm in psychological research.[5] Back then, the experimental apparatus were the *complication apparatus* and the *complication clock*, and the corresponding experiments were called *complication experiments.* Wundt described these investigations as the measurement of "die Zeit des schnellen Gedankens" (the time of fast thought, author's translation, 1862, p. 264). The next section describes these studies in more detail.

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[5] Note that similar observations were carried out in parallel by astronomers (E. C. Sanford, 1888, p. 25–30), who even partially reached similar conclusions as Wundt, for example, regarding the role of attention.

2.2. The Wundt clock: Wilhelm Wundt and the complication experiments

The term *complication* can be traced back to a very early textbook on psychology written by Johann Friedrich Herbart (Herbart, 1834/1965). According to Herbart (1834/1965), complications are the combinations of "nicht entgegengesetzte Vorstellungen" (perceptions that are not opposed to each other, author's translation, p. 17), for example a tone and a color. In the lingua of modern psychology, a complication is therefore a combination of stimuli from different modalities. Wundt (1911) states that such complications arise, for example, when a continuous series of visual stimuli is disrupted by disparate stimuli at constant intervals. Consequently, Wundt calls experiments of this kind complication experiments and the apparatus employed in such experiments are thus complication apparatus. Wundt explicitly refers back to the passage instrument as the first genuine complication apparatus and notes that the star that crossed the field of the telescope constituted the continuous series of visual stimuli and the clock complicated this series with its beats (p. 58).

In contrast to the passage instrument, Wundt's (1911) apparatus for his psychological experiments—that is, the *pendulum apparatus for complication experiments* as well as the *complication clock*—allowed to compare the objective time point of stimulus' occurrence with the apparent one. In its simplest form a pendulum apparatus consisted of a pendulum clock, a metal bar, and a bell made of glass or brass (for the first description of Wundt's "Gedankenmesser" see Wundt, 1862, p. 264). The end of the pendulum operated as a clock hand, and with each swinging this clock hand crossed a scale, that is, a clock face. In the center of the pendulum was a horizontal metal bar and this bar could nudge a laterally attached bell. The participant's task was to observe the clock face and to report the position of the clock hand when he heard the bell ring. By moving the bell up and down the experimenter could change the time point of the bell ringing and the participant did never know this point in advance. A further version of the pendulum apparatus (cf. Von Tchisch, 1885; Wundt, 1911) contained a sound hammer as well as a device with which one could apply electrical stimulation to the skin. Thus, auditory as well as tactile stimuli (or complications) could be examined. Furthermore, the speed of the pendulum could be adjusted, thus allowing for the investigation of the clock speed's influence on the participants' judgments.

The complication clock differs from the pendulum apparatus as the clock hand movement is not set up by the swinging of a pendulum but it is a clock hand moving itself. This leads to a major difference as far as the speed or acceleration is concerned. When a clock is employed, the clock hand has a steady speed (e.g., Angell & Pierce, 1892; Geiger, 1903). The pendulum, however, which operates as the clock hand for the pendulum apparatus (e.g., Pflaum, 1900; Von Tchisch, 1885), sometimes accelerates and sometimes decelerates, that is, its speed changes.

In a common complication experiment, the participant had to judge where the clock hand was when a disparate stimulus, usually a tone, was presented. Usually the disparate stimulus was presented at the same position for several trials, since the participants needed more than one trial to give a sound judgment of the clock hand's position at tone onset. The participant's response (e.g., 5) could then be compared with the actual position of the clock hand when the bell rang (e.g., 6). The difference between these two measures (e.g., $5-6=-1$) denotes a "negative Zeitverschiebung" (Wundt, 1911, p. 59; cf. "negative time-displacement", James, 1890/1950, p. 412), that is, the perceived position of the clock hand at tone presentation lies before the actual position at tone presentation. Accordingly, in the case of a "positive Zeitverschiebung" ("positive time-displacement") the perceived position of the clock hand at tone presentation lies after the actual position at tone presentation.

Following the first description of the complication apparatus (Wundt, 1862), many complication studies were published, especially by students of Wundt (e.g., Angell & Pierce, 1892; Dunlap, 1910; Geiger, 1903; Leatherman, 1940; Pflaum, 1900; Stevens, 1904; Von Tchisch, 1885). A main result that is evident in all these studies is a prevailing negative time-displacement, independent of the modality of the disparate stimulus (i.e., auditory, tactile, and electrical stimulation, cf. Von Tchisch, 1885). This is not surprising when one takes into account that visual signals have a longer latency than auditory (e.g., Jáskowski, Jaroszyk, & Hojan-Jezierska, 1990; Zampini, Guest, Shore, & Spence, 2005) or tactile ones (e.g., Spence, Shore, & Klein, 2001, see also the third part of the Introduction). However, Pflaum (1900) notes that positive time-displacements also occur quite often so that both, negative as well as positive time-displacements, have to be regarded as normal. Pflaum also provides the reader with another back-reference to the eye-and-ear method (p. 147–148). He reports that the individual differences in his and other complication experiments are by far smaller than in the astronomers' personal equations. He attributes these smaller variations to the more favorable experimental setup and the fact that participant's were allowed various observations of the pendulum before they had to report their judgment.

According to Wundt (1911) and other studies, the following main factors, amongst others, can be identified as having an influence on the extent and the direction of the time-displacement: the speed of the clock hand, its direction and the number of disparate stimuli. When the speed of the clock hand increased, the negative time-displacement first decreased and finally was inverted to a positive displacement (Wundt, 1911). When Von Tchisch (1885) comments on this finding, which he also observed, we encounter again a reference to the astronomers. Specifically, he notes that already Bessel discovered that the negative time-displacements in the eye-and-ear method decreased when he used a clock that indicated half seconds instead of seconds (p. 620–621, cf. also E. C. Sanford, 1888, p. 13). The direction of the clock hand's rotation affected the judgments in the following way: When the clock hand performed an ascending movement, the time-displacements were rather negative, whereas they were rather positive when the clock hand performed a descending movement (Geiger, 1903). According to Geiger (1903) and Wundt (1911) this is due to the fact that an ascending movement is harder to follow, that is, the gaze lags behind the clock hand movement. A descending movement, however, is easier to follow and the gaze can fixate the clock hand more immediately.

In order to investigate the influence of the number of stimuli on the time-displacement, Von Tchisch (1885) increased the number of disparate stimuli from one to five and also varied whether they were of the same modality or of different modalities. In general, he observed that the addition of stimuli from different modalities led to a decrease in the time-displacement and that eventually (for three different stimuli) the time-displacement changed from negative to positive. Furthermore, when stimuli of the same modality were added, it mattered whether they could be integrated into a compound stimulus or not. For example, two tactile stimuli applied at adjacent skin positions were integrated and the time-displacement was not different from a single stimulus, that is, it was negative. Two tactile stimuli, of which one was applied at the hand and one at the foot, however, led to the same results as stimuli from different modalities, that is, a decrease in time-displacement.

The greatest interpretative problem of the complication experiments was of course the prevailing negative time-displacement and hence, a reported time of stimulus detection that lay before the actual time of presentation. As already noted above, the different perceptual latencies of auditory and visual stimuli are a main factor for this—at first sight unexpected—finding. In addition, attention was proposed as a crucial factor. First, in terms of a general attentional preference for the auditory stimuli in a complication experiment and second, in terms of an influence of temporal preparation.

First, Wundt (1911) concluded that auditory stimuli do not only have a shorter latency, but also that in a complication experiment more attention is devoted to them than to the clock face. Hence, he anticipated the phenomenon of *prior entry* (Titchener, 1908) when he stated that "the stimulus for which we are predisposed requires less time than a like stimulus, for which we are unprepared, to produce its full conscious effect" (p. 251). This idea of a prior entry of the attended modality was investigated by Stevens (1904), who observed a negative time-displacement when he attended to the bell and a positive one when he attended to the clock hand. Hence, the attended stimulus was perceived earlier than the unattended one.

Second, and important to the present work, Wundt (1911) observed some kind of temporal preparation in his experiments. Specifically, in most of the complication studies, there was more than one trial in which the tone always was presented at the same clock hand position. Therefore, after a few trials, participants could expect the tone to occur at a certain time point. One might describe this as a temporal preparation experiment, in which the FP, that is, the interval from the beginning of the clock hand rotation to tone occurrence, is kept constant over a number of trials. Wundt states that because of the expectation of the tone, attentional adjustment to the tone is accomplished earlier and hence it is perceived earlier, which is evident in the negative time-displacement.

The influence of this expectation was investigated by Geiger (1903). Specifically, he examined how the time-displacement changes when the speed of the clock hand is kept constant, but an auditory stimulus is only delivered every second trial. He found that compared to a condition in which the tone occurs in every trial, the mean time-displacement increased, that is, the tone was perceived later. According to Geiger this was due to a lack of preparation because the rhythm was now too slow. From a current perspective, this slower rhythm might be seen as a longer FP in comparison to a faster rhythm in which the FP is shorter. Consequently, the perception of the tone is faster in the short FP condition, that is, with better temporal preparation. This result actually points to an influence of temporal preparation on perceptual processing such that the perceptual processes have a shorter duration.

Hence, with regard to the different perceptual latencies and to the twofold attentional preference of the complicating stimuli, that is, more attention on auditory stimuli and temporal preparation, Wundt (1911) was not surprised that negative displacements prevailed. He also notes (e.g., p. 59) that this, of course, does not have to be understood as a perception of the stimulus before it is even presented—as Von Tchisch (1885) did (p. 621). Rather, the disparate stimulus is associated with one point of the clock face and the more attention is allocated to the stimulus, the earlier is this association. Hence, when the attentional “Spannung” (tension, author’s translation) as Wundt (p. 67) puts it, increases, the time-displacement is negative. This tension is suggested to be less pronounced for a faster speed of the clock hand and for the presentation of more than one disparate stimulus. In the former case, the adjustment of attention is not fully developed when the tone arrives, since faster clock hand speed means also faster succession of tones (cf. also Geiger, 1903). In the latter case the attentional allocation is more difficult, and a positive displacement arises.

Eventually, it is important to state that the time-displacements in a complication experiment can only have a relative meaning, but not an absolute one (cf. Geiger, 1903, p. 399). Thus, the sheer existence of a negative time-displacement of a stimulus A does not necessarily bear much information. But, when a stimulus B results in a less negative time-displacement than stimulus A, one can conclude that B was perceived earlier than A. Or to put it in other words: Stimulus B has a shorter perceptual latency than stimulus A. This comparative application of the clock paradigm will be elaborated more thoroughly in the third part of the Introduction.

Taken together, the early complication studies revealed that several factors can influence the nature of the time-displacement. Amongst these are features of the clock (speed, direction) as well as features of the complications (modality, number). The most important conclusion one can draw from these early studies is what was pointed out by Geiger (1903): The observed time-displacements should not be interpreted in an absolute but only in a relative manner. With such a relative interpretation, the clock paradigm offers various and valuable application possibilities. For example, one can vary physical features of the stimuli (e.g., intensity, temporal preparation) and observe how these features influence the perceptual latency of the stimuli. Despite these application possibilities, the use of the clock paradigm experienced a decline until the end of the 20th century. An overview on the clock paradigm’s second emergence will be given in the next section.

2.3. The Libet clock: Clock results on the topic of free will

A genuine revival was given to the clock paradigm by Benjamin Libet and his colleagues (Libet et al., 1983). Their application of the clock paradigm revealed exceptional findings about free voluntary movements and whether they can be initiated unconsciously, that is, before one is aware of one's decision to move. These findings with their implications for the topic of *free will* had a wide reception since free will is of interest for a range of disciplines (e.g., psychology, philosophy, humanities, law studies). Actually, the clock paradigm became much more closely linked to Benjamin Libet than to Wilhelm Wundt. This is evident, for example, in the fact that recent studies rather cite Libet than Wundt when they refer to the clock paradigm (e.g., Haggard et al., 2002; Joordens et al., 2004).

Libet and his colleagues (1983) established a modern version of the complication clock. Specifically, participants watched a cathode ray oscilloscope (CRO) whose beam circulated in a clockwise revolution. Through this motion the sweep of a clock hand was simulated that completed one revolution in 2.56 s. At the external edge of the CRO screen was a clocklike scale with marks from 5 to 60 in conventional intervals of 5 (5, 10, 15, etc.). In addition, a plastic grille showed illuminated radial lines between the intervals of 5. Participants fixated the center of the CRO throughout the experiment; the small radius of 1.8° visual angle prevented a loss of visual acuity.

Via this clock participants had to judge the onset of three different events. The judgments were required blockwise, that is, only one of the events was involved in the trials of one block. In the first type of trials, participants had to initiate a voluntary movement (i.e., a quick flexion of the fingers of the right hand) whenever they wanted. Then, they had to judge the time of their conscious *awareness of 'wanting' to perform* (W) this movement. This event was also explained to them as an 'intention' or 'decision' to move or an 'urge'. In the second type of trials, participants also had to make a voluntary movement, but afterwards they should judge when they became aware that they *actually moved* (M). Finally, in the third type of trials, participants had to judge the time of their *awareness of the sensation* (S) that was elicited by an external stimulus which was a near-threshold pulse applied to the back of their hand. This stimulus was applied at random time points that were not communicated to the participant. Taken together, the authors collected latency measures for awareness of intention, awareness of movement, and a measure for perceptual latency. This measure of perceptual latency is of course most similar to the early complication experiments by Wundt (1911) and others: Participants watch a rotating clock and are suddenly presented with a complicating stimulus.

For the three latency measures two different 'mode of recalls' (Libet et al., 1983) were employed. The so-called *absolute mode* was identical to the method already used in the early complication experiments: At the end of a trial the clock hand stopped, and participants had to report the position (in the units of the mounted scale) of the respective awareness. The *order mode* was similar to a time order judgment: At the end of a trial the clock hand jumped randomly to several positions and stopped at a certain position. Subsequently, participants had to indicate whether this position lay before awareness ('clock hand first'), after it ('awareness first'), or whether they fell together ('together').

For the perceptual latency S, the results were similar to the early complication studies by Wundt and his students (e.g., Von Tchisch, 1885; Wundt, 1911). There was a constant negative time-displacement for almost all participants, that is, the clock position of reported awareness was before the clock position at which the stimulus was actually applied to the participants' hand. The time-displacements for M and W were determined relative to the EMG that indicated the muscle activation for the voluntary movement. For these measures, too, the mean time-displacement was negative. Far more relevant were, however, W's relation to the electrophysiological data that were also collected. Libet et al. (1983) measured the readiness-potential (RP), an ERP component that precedes a voluntary motor act and indicates its preparation. The relation between the RP and the participants' awareness of 'wanting to move' (W) was the main and most spectacular result of this study. W lay reliably *after* the "neuronal processes that precede a self-initiated voluntary action" (Libet et al., 1983, p. 635), that is, the RP. This was also the case, when the W times were corrected for S, that is, the perceptual latency of each participant. More specifically, RP occurred at least 500 ms before the reported wanting to move. According to Libet (1999) this means that "the initiation of [a] freely voluntary act appears to begin in the brain unconsciously, well before the person consciously knows he wants to act" (p. 51). Consequently, Libet (1999) argued for a new concept of free will, in which the voluntary act is initiated unconsciously, but can be vetoed consciously.

The results' absolute interpretation poses a major problem of this study since this, as I elaborated in the previous section, holds the danger of misinterpretation. More specifically, the deviation of the W measure from the RP was only interpreted absolutely and not in comparison with another condition. The observed succession of the RP and the W measure must not be seen as unequivocal evidence for a true succession of first RP, then awareness of the decision to move. Because of this and because of their provocative nature, the Libet results (cf. also Haggard & Eimer, 1999; Haggard & Libet, 2001) entailed a broad discussion—also with respect to philosophical and legal aspects—about whether the concept of free will can be upheld (e.g., Kawohl & Habermeyer, 2007). Nevertheless, Libet et al. (1983) revived the complication clock and gave it a modern appearance. Consequently, the 'Libet clock' became a widely known dictum.

2.4. Critical reception of the clock paradigm

Besides theoretical and philosophical discussions about the experiments by Libet et al. (1983), a lot of criticism was also put forward based on methodological grounds (e.g., Gomes, 2002; S. Klein, 2002; Pockett, 2002; see also the commentaries to Libet, 1985). Whereas some studies focused on the reinvestigation of the results on the RP (e.g., Keller & Heckhausen, 1990; Trevena & Miller, 2002), others were preoccupied with various aspects of the clock paradigm (Danquah, Farrell, & O'Boyle, 2008; Joordens, Van Duijn, & Spalek, 2002; Joordens et al., 2004; Miller et al., 2010; Pockett & Miller, 2007) that may influence the judgments in such an experiment. An integral feature of the clock paradigm is that participants have to observe and judge the position of a moving stimulus, that is, the clock hand. Regarding a moving stimulus, several types of localization biases can be observed, for example, the Fröhlich effect (e.g., Fröhlich, 1923; Müsseler, Stork, & Kerzel, 2002), the representational momentum (e.g., Freyd & Finke, 1984; Hubbard & Bharucha, 1988; Müsseler et al., 2002), and the flash lag effect (e.g., Nijhawan, 1994, 2002; Müsseler et al., 2002). The Fröhlich effect and the representational momentum occur when participants are required to localize the initial or the final location of a moving stimulus, respectively. In either case, the moving stimulus is perceived ahead of its actual position. The flash lag effect occurs when a second stimulus is 'flashed' while participants observe a moving stimulus. Here the flash is reported to 'lag' behind the moving stimulus.

Such biases could of course play a role in the clock paradigm in which the timing of internal and external stimuli requires the localization of a moving clock hand. Joordens et al. (2002), for example, applied the representational momentum logic to the Libet experiments. When the timing of an internal or external event were influenced by representational momentum, a later clock hand position than the actual one would be assigned to these events. Thus, in the experiment by Libet et al. (1983), the decision to act could actually have occurred much earlier, that is, maybe even before the RP. In order to assess whether the representational momentum affects timing within the clock paradigm, Joordens et al. presented participants with a clock hand and let them report when the clock perimeter changed its color. As a result, the color change was reported approximately 70 ms later than it had actually happened. That is, Joordens et al. found a positive time-displacement of the stimulus to be judged, which could question the validity of the results by Libet et al. When the awareness to move in the studies by Libet et al. was maybe also reported later than it actually occurred, the true time point may lie well before the RP, and therefore in the expected order.[6]

The author group around Joordens also introduced another factor in the discussion on the clock paradigm that might somehow bias the judgments, that is, a compensation process (Joordens et al., 2004). In 2002, Joordens et al. had employed a judgment task in which participants were presented with a reference dot on the clock perimeter and needed only to report whether the clock hand was before or after this reference dot when they encountered the color change of the perimeter. In 2004, they used a different procedure, in which participants judged the absolute clock hand position by clicking with a mouse on the corresponding clock hand position. Interestingly, with such a procedure the positive time-displacement disappeared. Joordens et al. explained this with a compensation process. Specifically, based on anecdotal narrations by their participants they propose that participants might be worried that their reports could be biased due to the continuing clock hand movement after the color change. Hence, they might try to compensate for this suspected bias and choose an earlier clock hand position than they might otherwise have. In other words, an automatic representational momentum effect might be compensated for in a controlled manner by the participants. The idea of the compensation process as a rather controlled mechanism is strengthened by the finding that compensation is less evident when a concurrent task detracts cognitive resources (Joordens et al., 2004). To sum up, based on these two different biases that they propose for the clock paradigm, Joordens et al. (2004) critically note that “the reliability of the clock-watching task as an accurate timing measure is questionable at best” (p. 48). They advise to always include an external event when the clock paradigm is used, so that any potential bias can be assessed.

Further evidence for the variability of the clock paradigm was also given by Danquah et al. (2008), who could show that the time-displacement for an external stimulus differed with the modality of the stimulus and also with the speed of the clock hand, that is, a decrease in negative time-displacements

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[6] Note, however, that the S judgment in the study by Libet et al. (1983) resulted in a negative time-displacement.

with increasing clock speed was observed. Such a result had already been observed in the early complication experiments (Von Tchisch, 1885). Danquah et al. also discussed the influence of representational momentum for this finding and finally came to a similar conclusion as Joordens et al. (2004), namely that "the method is associated with fundamental biases, the nature of which merit further investigation" (p. 625).

Such a—quite extensive—investigation was accomplished by Pockett and Miller (2007). Since the modern clocks often do not utilize a clock hand but rather a rotating spot these authors also refer to it as the *rotating spot method*. They remark that the clock paradigm "presently remains essentially the only widely used method of timing subjective events" (p. 241). In order to gain insight into the accuracy of this method, their participants had to make a voluntary movement (a key press) and judge afterwards where the clock hand had been when they made this movement (i.e., they measured the M time of Libet et al., 1983). This time point has the advantage that in comparison to the point of awareness of intention, awareness of movement has an objective measurable counterpart, that is, the actual time of the key press. The dependent measure was therefore the difference between the objective and the subjective time point of the key press. Altogether seven factors were investigated, three of which concerned the instructions for the participants and four of which concerned physical characteristics of the clock. Instructions varied in whether the participants should act spontaneously or preplan their key press, whether they should report when they started moving their finger or when they had completed the key press, and finally, whether they should fixate the center of the clock or follow the clock hand with their eyes. The clock itself varied with respect to the color of the spot (dark vs. light), the radius of the clock (small vs. big), the diameter of the rotating spot (small vs. big), and lastly the speed of the rotation (slow vs. fast).

The data showed that the judgments for the start and the end of the movement differed significantly, that is, the start was reported earlier than the end of the movement. According to Pockett and Miller (2007) this is evidence for the general accuracy of the clock paradigm: Two events that were objectively successive have also been reported in this succession. Besides that, however, none of the other manipulated factors influenced the judgments. This led Pockett and Miller to conclude that the clock paradigm is a rather robust method, for which small physical or instructional changes do not affect the judgments—at least for the timing of a movement. In addition to these results, the authors offer some advices for future experiments with the clock paradigm. Based on a combination of conditions for which they observed quite low within-subject variability, they recommend the following: Naïve subjects, short recording sessions, a small diameter of the clock and a fast rotating spot, precise instructions to the participants (e.g., whether the start or the end of an event should be timed), analysis of trimmed means instead of simple means, and finally a large sample (they assessed 20 participants).[7]

To conclude, the modern clock paradigm offers a similar plethora of differing results as did the original complication experiments. Not only the timing of internal events, like decision times, but also that of external stimuli has resulted in varying time-displacements. Some studies reported positive displacements (Haggard et al., 2002; Joordens et al., 2002), others reported negative ones (Danquah et al., 2008; Joordens et al., 2004; Miller et al., 2010). First, this can be due to differences in the physical characteristics of the clock (e.g., speed), second to differences of the external stimulus (e.g., modality). Finally, several biases for moving stimuli have been discussed (e.g., Fröhlich effect, representational momentum, flash lag effect) which, too, may vary with contextual factors and may influence the time-displacements. It is again clear from all these investigations that the absolute value of the time-displacements gathered from a clock paradigm might not bear much validity. In addition, the comparison of results from different contexts is difficult. If one refrains, however, from the aspiration of using the clock as an absolute measure, it is nevertheless a useful tool. Within a standardized experimental setup, it is possible to use the clock paradigm to measure relative differences in time-displacements by comparing several experimental

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[7] Note that besides the use of trimmed means the present experiments adhere to all of these recommendations.

conditions. Some studies that used the clock paradigm in such a comparative manner will be introduced in the following section.

2.5. Recent applications of the clock paradigm

As already noted in the previous sections, the clock paradigm can be applied in a sound way when at least two experimental conditions are introduced and the observed latencies are compared with each other and/or with a control condition. Several recent studies employed the clock paradigm in such a way (Banks & Isham, 2009; Carlson et al., 2006; Fendrich & Corballis, 2001; Haggard et al., 2002; A. J. Sanford, 1974) to measure the timing of perceptual and attentional as well as intentional processes.

A. J. Sanford (1971, 1974) employed a clock paradigm to measure the perceptual latency (cf. "perceptual lag", A. J. Sanford, 1974, p. 443) of auditory stimuli. In 1974, A. J. Sanford's participants watched a revolving clock hand while listening to auditory stimuli of varying intensity. More specifically, there was a constant background noise of 60 db SPL during the whole trial. About 1,000 to 2,000 ms after the start of the clock rotation, the background noise rose to 62, 63, 67, or 78 dB SPL. This intensity change constituted the target tone and was terminated not before the end of the trial. The intensity of the target tones was randomized in one block of trials and in addition about 45% catch trials were included, that is, trials without target presentation. Participants had two tasks: First, they had to respond as fast as possible to the target tone. Second, they had to report the position of the clock hand at the onset of the target tone. The observed time-displacement was then used to infer the perceptual latency of the target tone.

A. J. Sanford (1974) found RT as well as time-displacements to decrease with target tone intensity. This effect is consistent with the idea that perceptual latency decreases with stimulus intensity—a hypothesis also confirmed by other converging operations (e.g., Jáskowski et al., 2007; Miller, Ulrich, & Rinkenauer, 1999; Sugg & Polich, 1995)—and supports the notion that the clock paradigm is a useful tool to assess the duration of perceptual processing. Importantly, the overall time-displacement was not of interest in this study. Rather, the covariation of the time-displacement with the manipulated variable (i.e., intensity) was interpreted. This is exactly the kind of comparative application that makes the clock paradigm a sound paradigm for experimental research.

For another instance, Carlson et al. (2006), used a modified version of the clock paradigm to measure the speed of visual spatial attention. Usually, spatial attention is measured through performance measures, that is, attention is assumed to have been at a certain location when the performance for this location reaches a specific criterion (e.g., above chance level). With the use of the clock paradigm, however, Carlson et al. intended to measure the speed of attention directly. In their clock version, participants were presented with a circular array of 10 clock faces. Participants fixated the middle of the clock array and at a random time point (T), one of the clocks was indicated and participants had to report the position of the respective clock hand. Three conditions were compared; in the baseline condition participants already knew before the start of each trial which clock would become relevant and T was indicated by a color change of the clock perimeter from black to red. Hence, attention could be allocated to the relevant clock throughout the trial. In the peripheral cuing condition, however, the relevant clock was unknown until the color change at T. Finally, in the central cuing condition, the relevant clock was also unknown until a line from fixation to a clock indicated at T which clock hand position should be reported.

Whereas the time-displacement in the baseline condition was near to zero, it was positive in the two cuing conditions. This indicates that attention in the cuing conditions first had to be shifted to the relevant clock, before a judgement about clock hand position could be made, and that this shifting of attention is a time-consuming process. Also, the positive time-displacement was more pronounced in the central cuing condition than in the peripheral cuing condition (240 ms compared to 140 ms). This confirms the finding from other studies (e.g., Nakayama & Mackeben, 1989) that an endogenous shift of attention induced by central cues, is slower than an exogenous shift of attention induced by peripheral cues. Crucially, this study also illustrates the comparative application of the clock paradigm and the importance of a relative interpretation of time-displacements. Only the comparison with the baseline condition and with each other provides the time-displacements of the cuing conditions with meaning.

A last example for a comparative application of the clock paradigm stems from Haggard et al. (2002). These authors recently used the clock paradigm to illustrate a new phenomenon called *intentional binding*. Participants in this study watched a rotating clock hand and had to report the perceived onset times of four events: a tone, a voluntary key press, a muscle twitch induced by TMS over the motor cortex, and an audible click induced by sham-TMS over the parietal cortex (i.e., an audible click was heard by the participants but no motor activation resulted). In the baseline conditions, these events were presented and had to be judged separately, that is, one event per trial. In the operant conditions, however, the tone was presented 250 ms after the voluntary key press, the TMS, or the sham-TMS and the participants either judged the onset of the first event or the tone. The time-displacements of the baseline conditions were subtracted from the time-displacements in the operant condition to correct them.

As a result, when a voluntary movement preceded the tone, the tone was reported much earlier than its actual onset, and the key press was reported later than it actually occurred. Thus, the tone was shifted backward in time, whereas the voluntary movement was shifted forward in time. Or in other words: The voluntary action and the tone were attracted to each other. Such an attraction was neither observed for a click induced by sham-TMS and a tone nor for an involuntary movement induced by TMS and a tone; for the latter one the effect actually reversed. Haggard et al. (2002) thus suggested that the binding phenomenon only emerges when subjects perceive the tone as a consequence of their own voluntary action or intention, and thus termed it intentional binding. This study, too, illustrates the comparative application of the clock paradigm.

The results of A. J. Sanford (1974), Carlson et al. (2006), as well as

Haggard et al. (2002) receive their meaning from a comparison of the time-displacements of various conditions and not from their absolute values. All these studies show how the clock paradigm can be applied in a comparative manner in order to reveal useful information about the timing and duration of perceptual, attentional, and intentional processes, or, more specifically, the relative effects of physical and psychological manipulations on these processes. Therefore, the clock paradigm seems highly appropriate to investigate the research question that was raised in the first part of the present Introduction, which basically is concerned with the effects of an attentional manipulation on the latency of perceptual processing. More precisely, for the present experiments, the clock paradigm will be combined with a constant foreperiod paradigm to investigate the influence of temporal preparation on perceptual latency. The characteristics of the present clock paradigm and its application will be described in more detail in the following part of the Introduction.

3. Research question and experimental design

As I have elaborated in the first part of this Introduction, traditional consensus has it that temporal preparation decreases RT by influencing motor processes (e.g., Alegria & Bertelson, 1970; Mattes & Ulrich, 1997). However, I have also shown that various recent findings rather suggest that temporal preparation may decrease the duration of perceptual processes (e.g., Correa et al., 2005; Rolke & Hofmann, 2007). This decrease has been suggested to be due to an earlier beginning of perceptual processing (early onset hypothesis, Rolke, 2008; Rolke & Hofmann, 2007) or to an increased rate of perceptual processing (Correa, Sanabria, et al., 2006) under high temporal preparation. Since both accounts predict a decrease of perceptual latency for high temporal preparation, the present experiments were designed to assess whether this general hypothesis holds.

To this end, a clock paradigm was employed, that allows to measure perceptual latency directly. As outlined in Section 2.5., the clock paradigm is a sound assessment tool, when one resorts to a comparative application. The present clock paradigm was designed on the basis of A. J. Sanford's experiments (1971, 1974), in which he demonstrated an influence of a physical stimulus property (tone amplitude) on perceptual latency. In analogy to these studies, the participants in the present experiments had to judge the occurrence of a target tone while watching a revolving clock hand.

In order to assess whether temporal preparation decreases perceptual latency, the clock paradigm was combined with a constant foreperiod paradigm. Specifically, a warning signal preceded the target tone, and the interval between those two stimuli (i.e., the FP) was kept constant within blocks but varied from block to block of trials. Remember that in such a constant foreperiod paradigm, participants anticipate the occurrence of the target tone and thereby temporally prepare for its occurrence (cf. Niemi & Näätänen, 1981). This anticipation, however, becomes worse as FP increases because participants have greater difficulty to estimate long compared to short temporal intervals (Klemmer, 1956; Näätänen et al., 1974). Hence, shorter FPs induce a higher level of temporal preparation than longer ones. Consequently, if temporal preparation diminishes the duration of perceptual processing, the clock paradigm should reveal shorter perceptual latencies for short than for long FPs.

The index for the perceptual latency of the target tone in the clock paradigm (i.e., the time-displacement) requires some elaboration, because one can easily be misguided in its interpretation, as I have illustrated in Section 2.2. when I commented on the negative time-displacements (Von Tchisch, 1885; cf. also James, 1890/1950, p. 411-416; Massaro, 1989, p. 132). First, it is important to note that not only auditory events (i.e., the target tone) but also visual events (i.e., the clock hand) take some time to be perceived. Second, these perceptual latencies may depend on the sensory modality. For example, it is known that participants usually require more time to perceive visual than auditory events, that is, the perceptual latencies of auditory events tend to be shorter than those of visual events (e.g., Jáskowskiet al., 1990; Zampini et al., 2005; see, however, Rutschmann & Link, 1964, for an opposite finding). These two phenomena have implications for interpreting the measure retrieved from a clock paradigm.

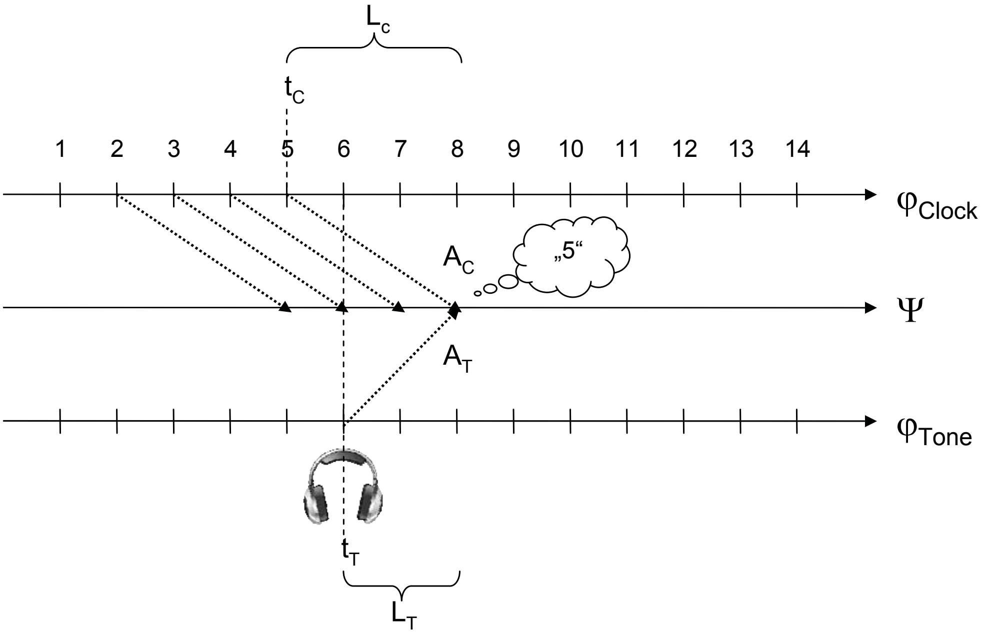

Figure 5. This schematic diagram shows the temporal unfolding of physical and perceptual events in the clock paradigm. φ_{Clock} denotes the physical progress of clock hand rotation and φ_{Tone} denotes the physical progress of target tone presentation. Ψ illustrates how these physical events unfold perceptually in time.

Figure 5 illustrates how physical and perceptual events unfold in time in the clock paradigm. The scale φ_{Clock} depicts the physical progress of the clock hand's position, whereas the scale φ_{Tone} indicates the physical occurrence of the target tone. The scale Ψ represents how these physical events unfold perceptually in time. Specifically, Figure 5 illustrates the situation when a target tone was presented at clock hand position 6, yet the participant reports it to have appeared at position 5. The temporal relations between the physical and the perceptual events can be captured as follows. Let $A_{\text{T}} = t_{\text{T}} + L_{\text{T}}$ be the central arrival time of the target tone, with t_{T}

representing its physical onset and L_T representing the time until it is perceived centrally, that is, its perceptual latency (see Sternberg & Knoll, 1973; Ulrich, 1987). Analogously, let $A_\mathrm{C} = t_\mathrm{C} + L_\mathrm{C}$ be the central arrival time of the clock hand position 5, with t_C representing the physical time when the clock hand arrives at position 5 and L_C representing the time until it is perceived centrally, that is, its perceptual latency. Note, that t_C corresponds to the participant's reported clock hand position, and that therefore t_C indexes the clock position at which both physical events (i.e., target tone onset and clock hand position) are perceived as simultaneous. Thus, the only observable variables in this situation are t_T and t_C. Consequently, the two arrival times are equal in this situation, that is, $A_\mathrm{C} = A_\mathrm{T}$, implying that $t_\mathrm{C} + L_\mathrm{C} = t_\mathrm{T} + L_\mathrm{T}$ or, after rearranging this expression,

$$D = t_\mathrm{C} - t_\mathrm{T} = L_\mathrm{T} - L_\mathrm{C}. \tag{1}$$

This expression corresponds to the time-displacement, which I will call the measure D (i.e., the deviation of the reported clock hand position from the actual clock hand position at target tone onset). The time-displacement or D is usually assessed in a clock paradigm (cf. judgment error, Haggard et al., 2002) and thus also in this study, to infer experimental effects on the perceptual latency of, for example, a tone (e.g., A. J. Sanford, 1974).

It is evident that D can be negative (cf. negative Zeitverschiebung, Wundt, 1911), if the visual latency L_C is longer than the auditory latency L_T (e.g., Jáskowski et al., 1990; Zampini et al., 2005). Literature has reported negative as well as positive values of D (e.g., Haggard et al., 2002; Leatherman, 1940; Pflaum, 1900; A. J. Sanford, 1974). The implicit assumption in all clock experiments, however, is that a manipulation of the target tone within a single experiment affects only the mean of L_T but not the mean of L_C. Monitoring the passage of time on a clock is a process that should, by definition, be devoid of temporal uncertainty. The present experiments proceed from this implicit yet plausible assumption. If temporal preparation diminishes the duration of perceptual processing, that is, the perceptual latency of the target tone, it is hypothesized that mean L_{T} and therefore mean D decrease with the degree of temporal preparation. In other words, participants should become aware of the target tone onset sooner when their temporal preparation is high. In order to substantiate the validity of our paradigm, target tone intensity was also varied in all of the present experiments. When the paradigm is valid the present experiments should replicate the basic pattern of results found by A. J. Sanford (1974), that is, a decrease of D and thus L_{T} with increasing target tone intensity.

II. Experimental Part

In order to investigate whether temporal preparation decreases perceptual latency, four experiments were designed and conducted. All four experiments combined the clock paradigm with a constant foreperiod paradigm and an intensity manipulation. Participants in all four experiments were required to report the perceived clock hand position at the onset of a target tone. Variations in task requirements and experimental setup were introduced to scrutinize specific relevant topics in more detail.

Experiment 1 assessed D but also simple RT, in order to verify the temporal preparation manipulation. Experiment 2 also assessed D and RT, but, in addition, catch trials were introduced, that is, trials without target tone presentation. Through the use of catch trials it should be excluded that participants may not judge the onset of the target tone, but rather infer it from judging the onset of the warning signal. Experiment 3 abstained from the assessment of RT, that is, participants only had to judge the onset of the target tone. This omittance of a speeded response allowed to investigate the influence of temporal preparation on D without a possible confoundation through a concurrent motor response. Finally, Experiment 4 replaced the simple RT task of Experiments 1 to 3 with a Go/NoGo task to gain further insight into the influence of task requirements on the overall direction of time-displacement.

1. Experiment 1

In Experiment 1 an auditory target stimulus was presented which was announced by a warning signal (white noise burst) that preceded the target tone by a FP of 600 or 2,000 ms in separate blocks of trials. Remember that in a constant foreperiod paradigm the function relating RT to FP length is U-shaped, exhibiting an initially sharp RT decrease up to about 200 ms FP length, followed by a slow increase towards an asymptote at about 3,000 ms FP length (see Müller-Gethmann et al., 2003). The present experiments therefore use FPs of 600 and 2,000 ms, which represent FPs that seem to produce a maximum FP effect on RT. Furthermore, a constant foreperiod paradigm was preferred over a variable one, since variable FPs are generally associated with a lower temporal preparation level (see Mattes & Ulrich, 1997), and therefore the FP effect might not be as strong as with constant FPs, at least for the present FP levels.

As in the studies of A. J. Sanford (1971, 1974), participants were required to respond as fast as possible to the target tone onset. After each trial, they additionally had to indicate at which clock hand position the tone onset had occurred. Besides FP, this experiment also varied the intensity level of the target tone in order to replicate the findings of A. J. Sanford and thereby substantiate the validity of the present paradigm. In contrast to the FPs, soft and loud tones were varied randomly within each block of trials. For RT the usual decrease for the shorter FP and the higher intensity level should be observed. Most importantly for the present purpose, however, if temporal preparation affects the duration of perceptual processing, perceptual latency (i.e., D) should decrease with the amount of temporal preparation.

1.1. Method

1.1.1. Participants

Twenty female and four male students participated in this experiment. Their ages ranged between 19 and 31 years (M = 22.9, SD = 2.7). All but two participants were right-handed and all had normal or corrected-to-normal vision. They were told that the experiment was about visual-auditory perception, but were left naïve with respect to the hypotheses of the experiment. Each participant took part in one experimental session and either received €5 or course credit.

1.1.2. Stimuli and apparatus

The experiment was run in a sound-attenuated, dimly illuminated room. A PC controlled the experimental procedure and collected the participants' responses. The number keys, 'enter', and the right 'strg'-key of a standard German keyboard served as response keys (the 'strg'-keys are equal to the 'ctrl'-keys on an US-American keyboard). The experiment was programmed in Matlab® in conjunction with the Psychophysics Toolbox 2.54 (Brainard, 1997; Pelli, 1997).

The clock with all its details is depicted in Figure 6. It was located at the center of a computer screen (VGA screen, Samsung Sync Master 1100 MB, 150 Hz, 1024 × 768 pixel) at a viewing distance of approximately 50 cm. All its elements were presented in black (< 1 cd/m^2) on a white (100 cd/m^2) background. The clock face was a circle with a radius of 1.8°. It was marked with conventional intervals from 5 to 60 (5, 10, 15, etc.). A small filled dot with a radius of 0.13° was employed as the rotating spot (clock hand) and a cross of the size 0.4° marked the center of the clock. The clock characteristics were similar to those typically found in studies employing the rotating spot method (e.g., Haggard et al., 2002; Pockett & Miller, 2007; A. J. Sanford, 1971, 1974).

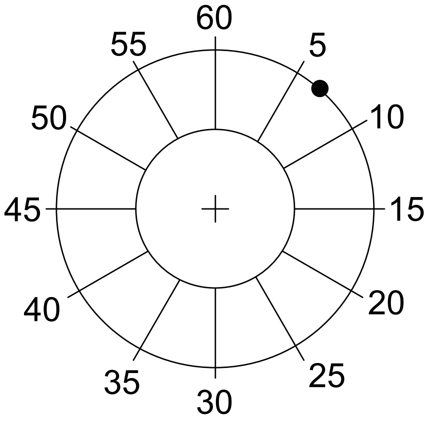

Figure 6. The clock face that was employed in the present experiments.

The warning signal was a 100 ms, 65 dB SPL burst of white noise. The target tones were pure sine waves and had a frequency of 1,000 Hz. Their intensity was either 40 dB SPL (soft tone) or 70 dB SPL (loud tone). Their duration was random, ranging from 1,500 to 2,400 ms. Auditory stimuli were presented binaurally over conventional head phones.

All even clock hand positions between 1 and 60 (2, 4, 6, etc.) were potential onset positions of the target tone. The clock hand revolved with a period of 2,400 ms and thus, two adjacent numbers (e.g., 2 and 3) on the clock face were separated by 40 ms.

1.1.3. Procedure

Figure 7 depicts the time course of one trial. Each trial began with the presentation of the clock face and the cross. The participant initiated the rotation of the clock hand with a key press. The clock hand rotated for an interval of 3,600 ms + X in which X was a random variable that followed an exponential distribution with a mean of 2,400 ms. This random interval was meant to strengthen the functional importance of the warning signal (cf. Müller-Gethmann et al., 2003). After this random rotation duration, the warning signal was presented. In short FP blocks, the onset of the target tone followed 600 ms after the onset of the warning signal whereas in long FP blocks this interval was 2,000 ms. In each trial, the target tone was either soft or loud. After the onset of the target tone, the clock hand kept rotating for a random interval between 1,500 and 2,400 ms. The offset of the target tone coincided with the cessation of clock hand rotation, that is, clock hand rotation and target tone terminated simultaneously at the end of a trial. Afterwards, the clock face disappeared, and a response prompt was shown on the screen. Like the experiments by A. J. Sanford (1971, 1974), this experiment employed a continuous tone that lasted until the end of the trial.[8]

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[8] This avoids a number of possible confounds. Judgements about when a brief stimulus occurs can be influenced by the perceived time of its center ('P-center') rather than its onset (Morton, Marcus, & Frankish, 1976). A brief target tone might also be

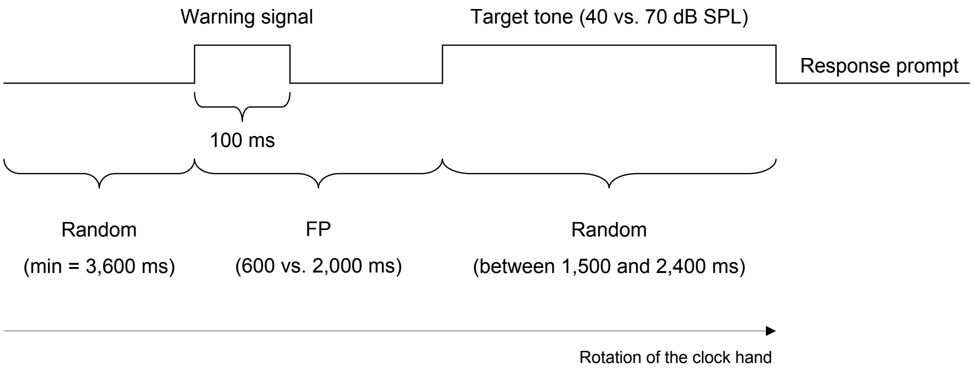

Figure 7. The time course of a single trial in the present experiments.

Participants were told that the warning signal indicated that the target tone was to occur. They were required to watch the revolving clock hand and to respond as fast as possible to the onset of the target tone by pressing the 'strg'-key with their right index finger (right-handed as well as left-handed participants used their right index finger). Furthermore, at the end of the trial they were asked to report the position of the clock hand when they perceived the target tone onset. Participants were prompted to enter their judgment about the clock position. They were encouraged to not only use the marked numbers (e.g., 5, 10, 15, 20, etc.) but also numbers in between (e.g., 23, 34, 41, 56, etc.). The next trial started when initiated by the participant.

The experiment lasted about 45 minutes and consisted of one practice block and four experimental blocks. FP was kept constant within each experimental block but alternated from block to block. Half of the participants started with the short, and the other half with the long FP. Each experimental block consisted of 15 trials at each intensity level, that is, 30 trials in total. Each possible target tone position occurred four times during the experiment, once for each combination of FP and intensity level. The practice block was comprised of six trials per FP. These trials were not included

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perceived as forming a compound stimulus (which might likewise have a P-center) with the warning signal.

in data analysis. No feedback was given, neither during practice nor during the experimental trials.

1.1.4. Design

This experiment factorially combined the two within-subject factors Foreperiod (600 vs. 2,000 ms) and Intensity (soft vs. loud). The dependent variables were mean RT and mean D (cf. Haggard et al., 2002; A. J. Sanford, 1971, 1974), that is, the deviation of the reported clock hand position from the actual clock hand position at target tone onset. Remember, that an increase in D denotes an increase in L_{T}, that is, relatively longer perceptual latencies of the target tone. D comprises a multiplication with 40 ms, that is, the interval between two adjacent numbers on the clock face, to convert the spatial lag between clock positions into a temporal lag.

1.2. Results and discussion

Only trials in which the participant had responded as well as reported a clock hand position were included in further analyzes. Trials with RTs smaller than 100 ms or larger than 1,000 ms were considered outliers. So were then trials with D larger or smaller than $M \pm 3 \cdot SD$ (per factorial condition and participant). Altogether 4.3% of all trials were discarded from RT and D analyzes. Separate ANOVAs with factors Foreperiod and Intensity were performed on mean RT and mean D of the remaining trials.

Figure 8 depicts mean RT for soft and loud target tones as a function of Foreperiod. As one would expect (cf. Niemi & Näätänen, 1981), RT increased with Foreperiod, $F(1, 23) = 4.65$, $p = .042$, validating the successful manipulation of temporal preparation. As one would also expect (Kellas et al., 1969; Mattes & Ulrich, 1997; Miller, Franz, & Ulrich, 1999; A. J. Sanford, 1971, 1974), RT was shorter in trials with loud than in trials with soft tones, $F(1, 23) = 20.63$, $p < .001$. The interaction between the two factors approached significance, $F(1, 23) = 3.00$, $p = .096$, due to a trend for loud

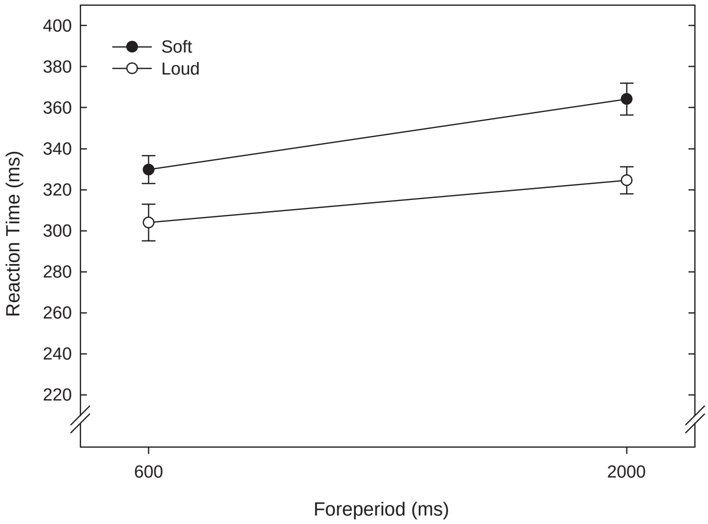

Figure 8. RT results of Experiment 1. Mean RT (ms) for soft and loud target tones as a function of Foreperiod. The error bars indicate ± the standard error of mean for a within-subject design (see Cousineau, 2005).

tones to be influenced by Foreperiod to a smaller extent than soft ones, a result that has also been reported by Kellas et al. (1969) and Niemi (1979).

Theoretically most important, D increased with Foreperiod, $F(1,23) = 5.96$, $p = .023$. This result, depicted in Figure 9, supports the notion that temporal preparation decreases perceptual latency. As one would expect, D decreased with Intensity, suggesting shorter perceptual latency for loud than for soft target tones, although this effect failed to reach statistical significance, $F(1,23) = 2.22$, $p = .150$. Finally, the effect of Foreperiod was modulated by Intensity, $F(1,23) = 9.48$, $p = .005$. For the loud tones D did not differ between the two FP conditions (mean difference = 4 ms, the 95%-confidence interval, CI, ranged from -19 to 11 ms), whereas D for the soft tones did differ between the two Foreperiod conditions (mean difference = 24 ms, 95% CI ranged from -36 to -12 ms).

Taken together, only in the long Foreperiod condition, that is, the con-

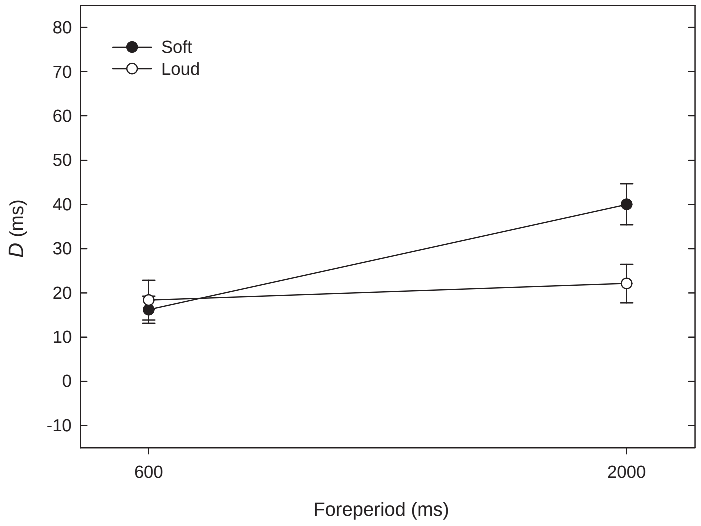

Figure 9. D (the deviation of the reported clock hand position from the actual clock hand position at target tone onset) results of Experiment 1. Mean D (ms) for soft and loud target tones as a function of Foreperiod. The error bars indicate ± the standard error of mean for a within-subject design (see Cousineau, 2005).

dition with little temporal preparation, did the D results replicate those of A. J. Sanford (1971, 1974). Although A. J. Sanford (1971) did not manipulate temporal preparation, his experimental conditions were more comparable to the long Foreperiod than to the short Foreperiod condition (he realized a temporal uncertainty in the range of 1,000–2,000 ms). In accordance with his results, loud tones in the present long Foreperiod condition yielded a lower D than soft tones; the mean difference was 18 ms with a 95% CI that ranged from 3 to 32 ms. Most importantly, however, the present results show that perceptual latency decreases when participants can temporally prepare for a target tone. Interestingly, loud stimuli seem to reduce or eliminate this effect. This might reflect a saturation effect caused by perceptual latency approaching its minimum value in the loud stimulus condition.

Alternatively, temporal preparation might actually have no effect on perceptual latency of the target tone but may improve the ability to switch from one task (i.e., the RT task) to another one (i.e., the perceptual judgment task).[9] Specifically, after selecting and initiating the manual response to the target tone, the participant has to switch attention to the perceptual judgment task in order to note the position of the clock hand. When one assumes that task-switching could occur more quickly in the short Foreperiod condition than in the long one, a smaller D would result in the short Foreperiod condition. Although this explanation cannot be ruled out by the data of Experiment 1, Experiment 3 will show that the relevant result, that is, shorter perceptual latency in the short Foreperiod condition, still holds up even when no manual response is performed before the perceptual judgment. In addition, there exists indirect evidence that participants do not switch attention when they have to compare the central arrival times of auditory and visual events (Ulrich, 1987).

2. Experiment 2

One might assume that in Experiment 1 participants did sometimes not give a judgment about target tone onset but rather judged the warning signal onset and added the perceived FP to this estimate. Such a strategy could have produced the pattern of results in Experiment 1, when one additionally assumes that participants tended to underestimate the short FP more than the long FP. Experiment 2 therefore employed 25% catch trials, that is, trials in which no target tone was presented. These trials required neither a speeded response nor a perceptual judgment from the participants. Such catch trials should prevent participants from adopting a strategy through which they estimate the warning signal's onset instead of the target tone onset.[10]

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[9] I thank an anonymous reviewer of an earlier version of Seifried, Ulrich, Bausenhart, Rolke, and Osman (2010) for this suggestion.

[10] I thank the editor, Dirk Wentura, of Seifried et al. (2010) for bringing up this alternative explanation and for suggesting the catch trial experiment to exclude it.

2.1. Method

2.1.1. Participants

Twenty-one female and three male students participated in this experiment. Their ages ranged between 19 and 36 years ($M = 22.9$, $SD = 4.0$). All participants were right-handed and all had normal or corrected-to-normal vision. They were told that the experiment was about visual-auditory perception, but were left naïve with respect to the hypotheses of the experiment. Each participant took part in one experimental session and either received €5 or course credit.

2.1.2. Stimuli, apparatus, procedure, and design

Stimuli, apparatus, procedure, and design were identical to Experiment 1. The procedure was also identical with the exception that 10 catch trials were included in each of the four experimental blocks. That is, 40 trials were presented per block and in 25% of these trials no target tone was presented. In these trials, participants were neither required to perform the RT task nor the perceptual judgment task. The experiment lasted about 45 minutes and consisted of one practice block and four experimental blocks. The practice block was comprised of 10 trials per Foreperiod condition.

2.2. Results and discussion

The catch trials were not included in the analyzes. The remaining trials were treated as in Experiment 1. Altogether 5.7% of these remaining trials were discarded from RT and D analyzes. Figure 10 depicts mean RT for soft and loud target tones as a function of Foreperiod. As in Experiment 1, RT increased with Foreperiod, $F(1, 23) = 45.62$, $p < .001$, and decreased with Intensity, $F(1, 23) = 149.28$, $p < .001$. There was also an interaction between the two factors, $F(1, 23) = 11.32$, $p = .003$, due to the fact that a smaller Foreperiod effect was found for loud target tones (mean difference = 40 ms) than for soft ones (mean difference = 61 ms, both differences were significant, however, as both 95% CIs exclude zero). This is also in line with Experiment 1 even though the interaction in Experiment 1 only approached significance.

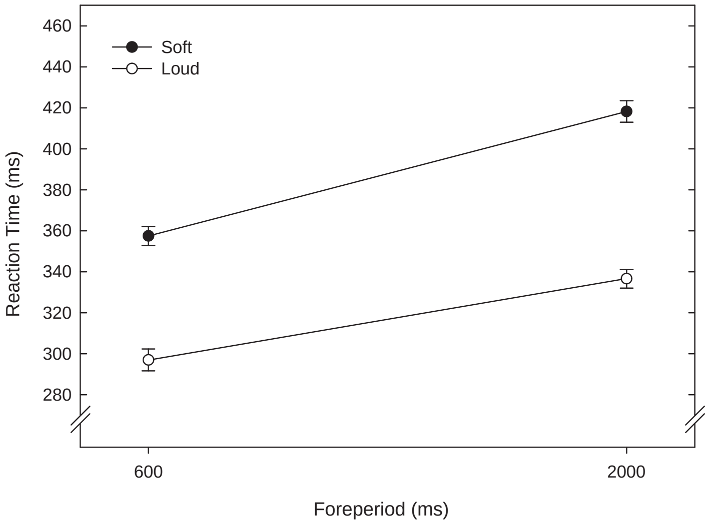

Figure 10. RT results of Experiment 2. Mean RT (ms) for soft and loud target tones as a function of Foreperiod. The error bars indicate ± the standard error of mean for a within-subject design (see Cousineau, 2005).

Figure 11 depicts mean D for soft and loud target tones as a function of Foreperiod. Crucially, also when catch trials were employed, D was smaller for the short Foreperiod condition than for the long one, $F(1, 23) = 31.42$, $p < .001$. Hence, Experiment 2 successfully replicated the result pattern of Experiment 1. This further supports the notion that temporal preparation decreases perceptual latency. Intensity also had an effect on D, $F(1, 23) = 25.54$, $p < .001$, showing again that loud target tones have shorter perceptual latencies than soft target tones. The significant interaction between Foreperiod and Intensity, $F(1, 23) = 9.23$, $p = .006$, shows that a smaller Foreperiod effect was found for loud target tones (mean difference = 29 ms) than for soft ones (mean difference = 46 ms). However, just as for RT, both differences were significant, as both 95% CIs exclude zero.

To sum up, even when 25% of catch trials make it rather futile for partic-

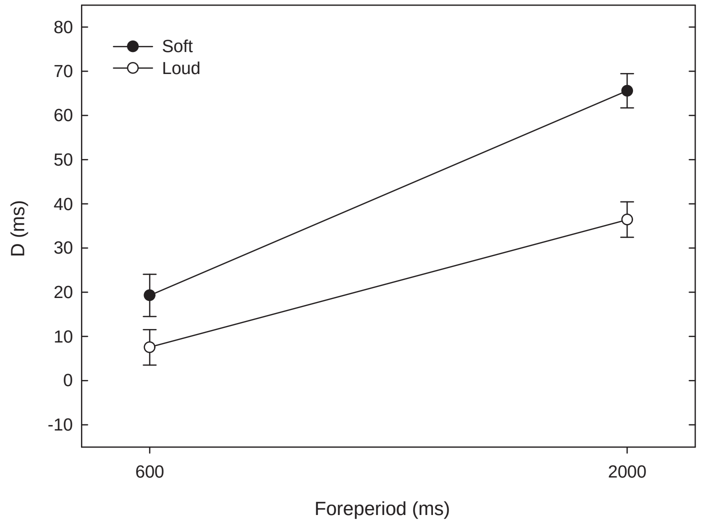

Figure 11. D (the deviation of the reported clock hand position from the actual clock hand position at target tone onset) results of Experiment 2. Mean D (ms) for soft and loud target tones as a function of Foreperiod. The error bars indicate ± the standard error of mean for a within-subject design (see Cousineau, 2005).

ipants to estimate the warning signal onset instead of the target tone onset, a smaller D emerges when the Foreperiod condition allows for high temporal preparation. Hence, the alternative explanation according to which participants would estimate the warning signal onset and add the perceived FP, is rendered rather unlikely. This strengthens the claim that temporal preparation actually decreases the perceptual latency of the target tone. In contrast to Experiment 1, an effect of temporal preparation on perceptual latency was obtained in the present experiment for loud stimuli as well. This was likely due to the incorporation of catch trials, which might have generally increased temporal uncertainty and thus allowed for more influence of temporal preparation even on loud target tones.

3. Experiment 3

The results of Experiments 1 and 2 suggest that temporal preparation decreases perceptual latency. However, there is a caveat to this conclusion due to the fact that participants performed the perceptual judgment task after the speeded response to the target tone onset. It is possible that the effect of FP on D more or less mirrors its effect on RT. More precisely, participants may have anchored their perceptual judgment of the clock hand position to the moment of the key press instead of the target tone onset. If this were the case, the effect of FP on D would not necessarily indicate an influence on perceptual latency, since an effect on D could have resulted from a change in duration of any information processing stage contributing to RT. In order to exclude this possible confound, Experiment 3 was conducted in which participants omitted the speeded response and only performed the perceptual judgment task.

3.1. Method

3.1.1. Participants

Seventeen female and seven male students participated in this experiment. Their age ranged between 20 and 35 years ($M = 24.7$, $SD = 3.6$). All but four participants were right-handed and all had normal or corrected-to-normal vision. They were told that the experiment was about visual-auditory perception, but were left naïve with respect to the hypotheses of the experiment. Each student took part in one experimental session and either received €5 or course credit.

3.1.2. Stimuli, apparatus, procedure, and design

The stimuli, apparatus, procedure, and design were identical to those used in Experiment 1 with the exception that the simple RT task was omitted. The experiment lasted about 40 minutes.

3.2. Results and discussion

The same outlier criteria as before were applied; 1.6% of all trials were discarded from analyzes. Figure 6 depicts mean D for soft and loud target tones as a function of Foreperiod and Intensity. The result pattern closely replicates the one of Experiment 1. As before, D increased with Foreperiod, $F(1, 23) = 21.13$, $p < .001$, strengthening the finding that temporal preparation decreases perceptual latency. The effect of Intensity failed to reach significance, $F(1, 23) = 1.86$, $p = .186$. The Foreperiod effect was modulated by Intensity, $F(1, 23) = 38.01$, $p < .001$. Consistent with Experiment 1, D for the loud tones did not differ between the two Foreperiod conditions (mean difference = 1 ms, 95% CI ranged from -8 ms to 5 ms), but did for the soft ones (mean difference = 25 ms, 95% CI ranged from -33 ms to -18 ms). Taken together, these findings rule out the possibility that the influence of temporal preparation on D is only due to anchoring the perceptual judgment to the key press.

There is, however, a difference between this experiment and Experiments 1 and 2. Whereas the overall D is positive in Experiment 1 ($M = 24$) and 2 ($M = 32$), it is negative in Experiment 3 ($M =$ -13). Thus, the overall mean D of Experiments 1, 2, and 3 was submitted to an ANOVA with the between-subject factor Experiment. This ANOVA revealed a significant effect of the factor Experiment, $F(2, 69) = 4.94$, $p = .010$. Planned contrasts (Tukey test) showed that mean D differed between Experiments 3 and 1 ($p = .047$) and Experiments 3 and 2 ($p = .012$) whereas the means of Experiments 1 and 2 did not differ significantly ($p = .860$). On first sight, one might assume this difference to suggest that participants judged the position of the clock hand at target tone onset after its actual position in Experiments 1 and 2 and before its actual position in Experiment 3. However, remember that D is a difference measure and a negative value does therefore not indicate that participants became aware of the target tone before its actual onset.

The negative D in Experiment 3 is consistent with earlier findings from clock paradigms (Danquah et al., 2008; Leatherman, 1940; Wundt, 1911) and

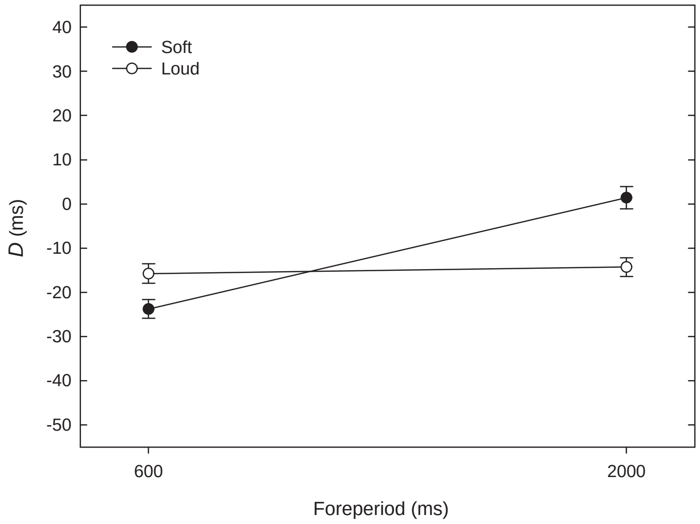

Figure 12. D (the deviation of the reported clock hand position from the actual clock hand position at target tone onset) results of Experiment 3. Mean D (ms) for soft and loud target tones as a function of Foreperiod. The error bars indicate ± the standard error of mean for a within-subject design (see Cousineau, 2005).

is also to be expected, when one takes into account that auditory stimuli are processed faster than visual ones, that is, $L_{\mathrm{T}} < L_{\mathrm{C}}$ (e.g., Jáskowski et al., 1990). The positive D in Experiments 1 and 2 is consistent, for example, with the results of A. J. Sanford (1974). The positive D in Experiments 1 and 2 has to be attributed to the fact that participants had to perform two concurrent tasks in the first two experiments (i.e., simple RT and perceptual judgment). There are at least two alternative accounts why this would lead to a positive D.

First, an interference of the simple RT task with the perceptual judgment task could have slightly postponed the registering of the clock hand position, which tended to increase D in all experimental conditions. Such a constant shift, however, would not change the overall pattern of results. More specifically, the dual-task situation may have shifted D by a constant amount, that is, by the time it takes one to register the clock hand position.

Second, the positive *D* might be the signature of the temporal binding phenomenon (Haggard et al., 2002). According to Haggard et al. (2002), temporal binding refers to the finding that participants tend to perceive their intentional actions and the consequences of these actions as attracted in time to each other. In Experiments 1 and 2 a similar tendency could have emerged. According to this explanation, participants would interpret their key press as a consequence of the target tone and thus perceive the tone onset as shifted towards the key press, which would also tend to increase *D* by a certain amount. Experiment 4 aims to differentiate between these two possible explanations for the positive *D* in Experiments 1 and 2.

4. Experiment 4

In order to investigate whether the positive bias of *D* observed in Experiments 1 and 2 is due to interferences caused by concurrent task processing or by temporal binding, Experiments 1 and 3 were combined into a single experiment. To this end, the simple RT task from Experiment 1 was replaced with a Go/NoGo RT task. This task required participants to respond to a specific target tone but to refrain from responding when a different tone occurred. Nevertheless, the perceptual judgment had to be performed in either case. If the overall positive *D* is due to concurrent task processing, there should be an overall positive shift of *D*, as in Experiments 1 and 2, in both types of trials (Go and NoGo). This is because in both trial types participants are expected to postpone the perceptual judgment due to the required decision of whether to respond or not. By contrast, the temporal binding account suggests a positive bias in Go trials only.

4.1. Method

4.1.1. Participants

Eighteen female and six male students participated in this experiment. Their age ranged between 19 and 37 years ($M = 24.2$, $SD = 5.0$). All but two participants were right-handed and all had normal or corrected-to-normal vision. They were told that the experiment was about visual-auditory perception, but were left naïve with respect to the hypotheses of this experiment. Each student took part in one experimental session and either received €8.5 or course credit.

4.1.2. Stimuli, apparatus, procedure, and design

The stimuli, apparatus, procedure, and design were identical to those in Experiments 1 and 3 with the following exceptions. The target tone was presented monaurally either to the left or to the right ear. Participants had to perform a speeded response only when the target tone was presented to the ear that had been specified in the instruction (Go trials) and refrain from responding when the tone was presented to the other ear (NoGo trials). For half of the participants Go trials corresponded to the left ear and for the other half to the right ear. The perceptual judgment, however, was required in either case (in Go and NoGo trials). The number of trials was doubled compared to Experiments 1 and 3 so that each of the four experimental blocks was comprised of 15 trials per ear at each intensity level, that is, 60 ($2 \times 2 \times 15$) trials in total per block. The practice block contained 12 trials per FP. The experiment lasted about 70 minutes and factorially combined the three within-subject factors Trial Type (Go vs. NoGo), Foreperiod (600 vs. 2,000 ms), and Intensity (soft vs. loud). The dependent variables were RT and D.

4.2. Results and discussion

Only trials with accurate responses (i.e., responding on Go trials and refraining from responding on NoGo trials) were included in further analyzes. As before, trials in which participants did not report the clock hand position were also excluded. Trials with RTs smaller than 100 ms or larger than 1,500 ms were considered outliers and discarded as well as were trials that violated the criterion employed in the previous experiments. The upper RT criterion was increased beyond that in Experiments 1 and 2 due to greater task difficulty. Altogether 5.9% of all trials were discarded from RT and *D* analyzes. ANOVAs with factors Trial Type (for *D*), Foreperiod, and Intensity were performed on RT and *D* of the remaining trials.

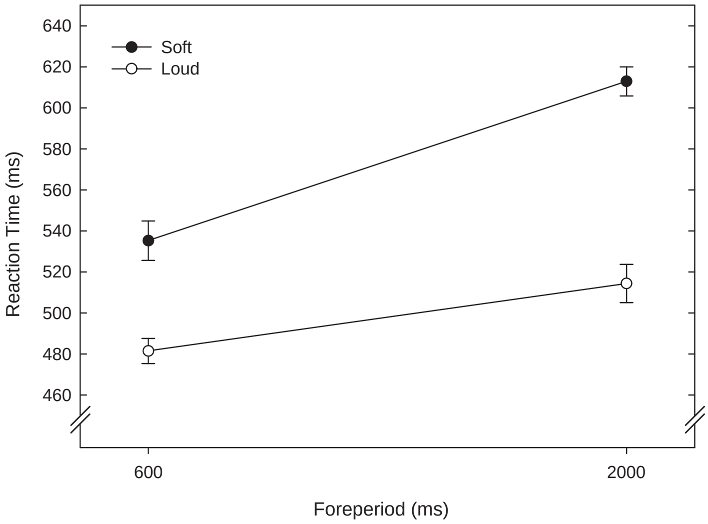

Figure 13. RT results of Experiment 4. Mean RT (ms) for soft and loud target tones as a function of Foreperiod. The error bars indicate ± the standard error of mean for a within-subject design (see Cousineau, 2005).

Figure 13 depicts mean RT for soft and loud target tones as a function of Foreperiod. First, the overall RTs of Experiments 1 and 4 were submitted to an independent *t*-test which revealed RT of Experiment 4 to be longer than RT of Experiment 1, $t(46) = 4.29$, $p < .001$ (two-tailed). This result indicates that the Go/NoGo-task, which imposed the load of response decision on participants, was more demanding than the simple RT task in Experiment 1.

RT increased with Foreperiod, $F(1, 23) = 31.45$, $p < .001$ and decreased with Intensity, $F(1, 23) = 45.88$, $p < .001$, replicating the results of Experiment 1. In addition, the ANOVA revealed a significant interaction between the two factors, $F(1, 23) = 11.38$, $p = .003$. The RT difference between the two Foreperiod conditions was larger for the soft tones (mean difference = 78 ms) than for the loud tones (mean difference = 33 ms), but significant in both cases as the CIs showed (both 95% CIs exclude zero). This corroborates the results of Experiments 1 and 2, although the interaction in Experiment 1 only approached statistical significance.

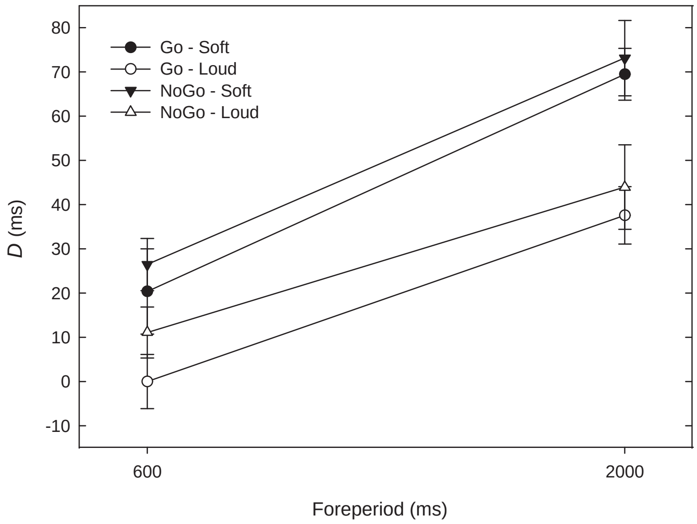

Figure 14. D (the deviation of the reported clock hand position from the actual clock hand position at target tone onset) results of Experiment 4. Mean D (ms) for soft and loud target tones and Go as well as NoGo trials as a function of Foreperiod. The error bars indicate ± the standard error of mean for a within-subject design (see Cousineau, 2005).

Figure 14 depicts mean D for soft and loud target tones as well as both trial types as a function of Foreperiod. Most importantly for the present purposes, D was not significantly influenced by Trial Type, $F(1, 23) = 2.31$, $p = .142$, nor did any interaction including the factor Trial Type approach significance ($Fs < 1$). The overall D was 35 ms in this experiment and positive regardless of trial type. This result suggests that it was not the presence of an overt response, and therefore not temporal binding that shifted D in a positive direction. It rather seems that the requirement of concurrent task processing, which occurred on both Go and NoGo trials, postponed the perceptual judgment task and increased D (cf. for example the finding that the PRP effect is found in Go trials as well as in NoGo trials, Bertelson & Tisseyre, 1969a).

In accordance with the previous experiments, D increased with Foreperiod, $F(1, 23) = 11.87$, $p = .002$. In contrast to Experiments 1 and 3, but in line with Experiment 2, the main effect of Intensity was also reliable in the present experiment, suggesting shorter perceptual latency for loud than for soft target tones, $F(1, 23) = 28.27$, $p < .001$. Still, however, as in the previous experiments, the Foreperiod effect was modulated by Intensity, $F(1, 23) = 8.11$, $p = .009$. The Foreperiod effect was more pronounced for soft tones (mean difference = 48 ms) than for loud tones (mean difference = 35 ms), but significant in both cases as the CIs showed (both 95% CIs exclude zero).

In this experiment, it was possible to assess the false alarm rate, that is, the proportion of trials in which participants responded even though no target tone was presented. The present false alarm rates on NoGo trials were 6.04% for the short Foreperiod condition and 5.97% for the long Foreperiod condition. The difference was not significant, $F(1, 23) < 0.01$, $p = .949$. Thus, no influence of temporal preparation on the false alarm rate could be detected. A change in false alarm rates would have been expected when different response criteria were employed in the short and in the long Foreperiod condition. A presumably lower criterion in the short Foreperiod condition could lead to decreased RT and also to a higher proportion of false alarms.

The fact that such a criterion effect of temporal preparation could not be found strengthens the present idea that temporal preparation directly influences perceptual processing.

Taken together, the results of this experiment show that concurrent task processing generally increases D and they also replicated the results of the previous experiments. The Foreperiod effect on D was also demonstrated in a Go/NoGo paradigm, and thus the temporal preparation effect on perceptual latency can be regarded as a general phenomenon. As in Experiment 2, a significant effect of temporal preparation on perceptual latency was obtained not only for soft but also for loud stimuli and furthermore a criterion effect of temporal preparation could be excluded.

III. General Discussion

This thesis examined whether temporal preparation decreases the time to detect the onset of a stimulus (i.e., perceptual latency). To this end, a clock paradigm (e.g., Haggard et al., 2002; A. J. Sanford, 1974; Wundt, 1911) was combined with a constant foreperiod paradigm (e.g., Niemi & Näätänen, 1981; Müller-Gethmann et al., 2003). Previous studies that investigated the influence of temporal preparation on perceptual processing measured discrimination and detection performance or RT (e.g., Bausenhart et al., 2007; R. Klein & Kerr, 1974; Loveless, 1975; Rolke & Hofmann, 2007). In contrast to these studies, the application of the clock paradigm allowed to measure perceptual latency directly. Therefore, the general hypothesis that temporal preparation decreases the duration of perceptual processes could be examined. Four experiments were conducted which reliably confirmed that perceptual latency decreases under high temporal preparation. This thesis therefore supplements the studies mentioned above and extends them significantly by indicating that temporal preparation not only improves the accuracy of perceptual processing but actually diminishes its duration.

This General Discussion will review the results of the conducted experiments together with their theoretical implications. More specifically, it will address the relation of the present results to temporal orienting research (e.g., Correa et al., 2005; Lange et al., 2003) as well as to the idea of a temporal prior entry effect (Seibold, Fiedler, & Rolke, in press). Then, electrophysiological evidence for a shorter perceptual latency for stimuli under high temporal preparation will be considered (Seibold, Fiedler, & Rolke, in press) and finally, the responsible mechanism for faster perceptual processing (Bausenhart, Rolke, Seibold, & Ulrich, 2010; Seibold, Bausenhart, et al., in press) within the framework of information accumulation models (e.g., Grice, 1968) will be revisited.

Reaction Time results

In all four experiments, RT decreased with increasing FP. This replicates the common FP effect in a constant foreperiod paradigm (e.g., Müller-Gethmann et al., 2003; Woodrow, 1914) and indicates the validity of the present manipulation of temporal preparation. Also in accordance with the respective literature, participants responded faster to loud auditory stimuli than to soft ones (e.g., Miller, Franz, & Ulrich, 1999; A. J. Sanford, 1971). In addition, an interaction between FP and intensity was observed, that is, the effect of temporal preparation was more pronounced for soft tones. It has been shown that the RT benefit due to temporal preparation is smaller when the target stimulus is loud rather than soft or when it is a visual signal (Niemi, 1979; A. F. Sanders & Wertheim, 1973). In contrast to visual signals and soft auditory stimuli, loud tones exert an arousing effect (see Miller, Franz, & Ulrich, 1999) which compensates for low temporal preparation. A. F. Sanders (1975) ascribed this arousing feature to auditory stimuli above 70 dB SPL and proposed that below this intensity level, tones are as sensitive to temporal preparation as visual signals. Since the present stimulus intensities were 40 and 70 dB SPL, the attenuated RT effect for intense targets is in line with A. F. Sanders' account and the relevant literature (e.g., Niemi, 1979).

It is important to emphasize that the present RT results also show that the perceptual latency results do not exclude the possibility of additional effects on post-perceptual stages. Indeed, little or no effect of temporal preparation on perceptual latency for loud tones was observed (see also next paragraph), but a robust effect on RT. Whereas this finding—that is, a larger influence of temporal preparation on RT than on perceptual latency—is compatible with a post-perceptual effect, there are alternative explanations involving a perceptual locus. For example, this dissociation between temporal preparation effects on perceptual latency and RT is similar to various results of the TOJ research describing dissociating effects of stimulus intensity on TOJs and RT (for an overview see Jáskowski, 1996). An analogous dissociation was also observed by A. J. Sanford (1974) in a clock paradigm. Numerous explanations have been suggested to account for this dissociation (for an overview see Miller & Schwarz, 2006), one of them involving different criterions. For example, suppose that noting the clock position and initiating an overt manual response involved different detection decisions, with a higher criterion for the manual response than for the perceptual judgment. Any change in the rate of information accumulation would then produce a larger effect on RT than on D (for a formal analysis of rate effects on RT and TOJ within a diffusion model, see Miller & Schwarz, 2006). Consequently, the dissociating effects observed in the present experiments would indicate that temporal preparation influences the rate of information processing. The mechanisms of temporal preparation will be discussed at greater length in the further progress of this General Discussion.

To sum up, the present RT results are in line with the relevant literature and furthermore show that temporal preparation influences on motor processes must not be excluded.

Perceptual latency results

In order to measure perceptual latency, this thesis employed a clock paradigm in a comparative manner. Accordingly, not the absolute time-displacements were of interest, but the relative comparisons that were drawn between the levels of the manipulated factors. As a general result, this thesis could provide the first behavioral evidence for an influence of temporal preparation on perceptual latency. More specifically, perceptual latency was shorter in the short FP, that is, when participants were highly prepared for target tone occurrence. Furthermore, stimulus intensity also influenced perceptual latency, such that it was shorter for loud target tones (cf. A. J. Sanford, 1974).

An interaction between stimulus intensity and FP, just as for RT, was also observed for D. In Experiments 1 and 3, high temporal preparation significantly decreased the perceptual latency only for soft tones but not for loud tones. Presumably, the perceptual latency of loud tones attained its minimum value because perceptual processing was already at a near-to-optimum level and thus could not be further diminished. Rolke (2008) reported a similar pattern when she investigated the influence of temporal preparation on letter discrimination and found better discrimination performance under high temporal preparation. Specifically, this effect was attenuated for high contrast stimuli compared to low contrast ones. High contrast and high intensity seem to provide less space for an effect of temporal preparation on perceptual processing than low contrast and low intensity. This notion can account for the fact that the perceptual latency of loud tones was not influenced by temporal preparation in Experiments 1 and 3.

In Experiments 2 and 4, however, high temporal preparation significantly decreased D, that is, perceptual latency, for both soft and loud tones, even though this decrease was still more pronounced for soft tones. Probably the presentation of monaurally presented target tones and the employment of a Go/NoGo task (Experiment 4) or of catch trials (Experiment 2) created enough space for a significant latency decrease for loud tones as well. First, the loudness of monaurally presented tones is less than that of binaurally presented tones (e.g., Algom, Rubin, & Cohen-Raz, 1989; Scharf & Fishken, 1970), and binaurally presented tones are known to have a lower detection threshold (Babkoff & Gombosh, 1976). Consequently, perceptual processing of the loud tones may no longer have been at a near-to-optimum level, and thus temporal preparation could still diminish its duration. Second, the employment of catch trials (Experiment 2) or a Go/NoGo task (Experiment 4) could have likewise had such an influence on late perceptual processing of the tones. Since, in Experiment 4 for example, the instruction required participants only to respond to tones presented in a designated ear, the tones had to be localized first. Due to this perceptually more demanding task, temporal preparation could still have diminished the duration of perceptual processing of loud tones.

Summing up, perceptual latency for soft tones always decreased under high temporal preparation. For loud tones, perceptual latency only decreased when specific task requirements created enough space for a temporal preparation effect to emerge. Nevertheless, the results on perceptual latency unequivocally indicate that temporal preparation influences information processing by shortening the duration of perceptual processing.

Temporal attention and prior entry

The present effect of temporal preparation on the duration of perceptual processing can of course also be interpreted with respect to the temporal orienting research (e.g., Correa et al., 2005; Lange et al., 2003). That is, the decrease in perceptual latency can be seen as the consequence of enhanced allocation of attention to stimuli occurring at a particular moment in time. More specifically, since time estimation is better for short FPs than for long ones (Klemmer, 1957; Näätänen et al., 1974), short FPs allowed participants more effective control over temporal attention. Consequently, in the short FP, they could allocate their attention more precisely to the end of the FP, that is, to the time point of target tone occurrence. Or, in other words, in the short FP the onset of the target tone was more likely to occur at a temporal attention peak than in the long FP.

In the temporal orienting paradigms a symbolic cue indicates when to expect the target stimulus (e.g., ‘short’ or ‘long’ for target occurrence after a short or a long interval). Hence, temporal attention is allocated *explicitly* in this paradigm. However, as elaborated above, an *implicit* attention allocation through a constant foreperiod paradigm is also possible (cf. Nobre & Coull, 2010). Temporal orienting research has recently generated broad evidence for improved perceptual processing of temporally attended stimuli. Correa et al. (2005), for example, found increased d' when the target stimulus occurred at expected time points, that is, when it was temporally attended. Even though it is not completely clear whether and how temporal attention and temporal preparation are interrelated, there are ambitions to view them as two sides of the same coin (e.g., Bausenhart et al., 2008; Los, 2010; Nobre et al., 2007).

If one views the present decrease in perceptual latency as a consequence of enhanced attention, the *Law of Prior Entry* (Titchener, 1908) immediately comes to mind (cf. Seibold, Fiedler, & Rolke, in press). According to the original formulation of the Law of Prior Entry by Titchener (1908) attended stimuli are perceived earlier than unattended ones. The Law of Prior Entry has usually been studied with TOJ experiments (e.g., Shore, Spence, &

Klein, 2001; Spence et al., 2001; Stelmach & Herdman, 1991; Vibell, Klinge, Zampini, Spence, & Nobre, 2007). In a typical TOJ experiment by Stelmach and Herdman (1991), a spatial cue directed visual attention to the left or to the right side of the visual field. Then, two stimuli were presented in rapid succession, one at the cued, that is, attended location and one at the uncued, that is, unattended, location. A varying SOA between these two stimuli was introduced and the participants had to indicate which of the two stimuli occurred first.

Based on the dichotomic response pattern ('left first', 'right first'), Stelmach and Herdman (1991) estimated a psychometric function that associated the SOA with the probability of, for example, 'right first' responses (assume that negative SOAs stand for instances in which the left stimulus was shown first). The SOA associated with a probability of .5 for a 'right first' response is called the *point of subjective simultaneity* (PSS), that is, the SOA at which the two stimuli are perceived to occur simultaneously. As a result, the psychometric function, and therefore the PSS, of attended stimuli (presented on the right) was shifted towards the more negative values of SOA. That means, that even though the left stimulus was presented first, the stimuli were perceived simultaneous. Or, in other words, the attended stimulus on the right was perceived earlier, just as the Law of Prior Entry predicts (cf. Stelmach & Herdman, 1991).

The phenomenon of prior entry has not only been shown for visual spatial attention, but also for attentional modulations across modalities (Spence et al., 2001). Furthermore, a non-attentional interpretation of the PSS shift—involving a response bias—has been ruled out (Spence et al., 2001; for an overview see Spence and Parise, 2010). Nevertheless, up to now, one aspect of evidence for prior entry had been lacking, that is, a latency shift of perceptual ERP potentials as the neuronal basis for the behavioral PSS shift. This gap was, however, closed in 2007 by a study from Vibell et al. (2007). These authors used a cross-modal task, in which they shifted attention between the visual and the tactile modality, and participants had to report whether the visual or the tactile stimulus occurred first.

Apart from the typical PSS result, that is, a leftward shift of the psychometric function for attended stimuli, Vibell et al. (2007) observed a significant shift of early visual potentials when the visual stimulus was attended. More specifically, the peak latencies of P1, N1, and N2 occurred earlier when attention had been allocated to the visual stimulus than when it had been allocated to the tactile stimulus. Since the components N1 and P1 (as generated in extrastriate areas; see Clark, Fan, & Hillyard, 1994) are regarded as indexing perceptual processing , it can be concluded that the perceptual processes for the attended stimulus begin earlier and thus also entail the prior entry of this stimulus. The N2 occurs when the registered stimulus features deviate from an expectation (e.g., Fabiani et al., 2007) and can therefore also be interpreted as an index for perceptual processing.

For P1, a correlational analysis even revealed a positive correlation between the latency differences of attended and unattended visual stimuli and the corresponding PSS values. That is, the earlier the P1 peaked for attended compared to unattended visual stimuli, the larger the leftward PSS shift. These findings were the first to undermine the behavioral prior entry effect with electrophysiological data showing that the prior entry effect might be due to earlier “perceptual stimulus analysis in the brain” (Vibell et al., 2007, p. 116).

Although the Law of Prior Entry is usually applied to TOJ tasks, presumably the same attentional mechanism could underly temporal preparation effects on perceptual latency. One could conceive of high temporal preparation as a state of increased attention at the expected time point of target tone presentation. This conception is, for example, put forward by Seibold, Fiedler, and Rolke (in press) when they report their “temporal prior entry effect”. As a consequence of this conception, the question arises whether the decrease in perceptual latency induced by temporal preparation can also be undermined electrophysiologically, as, for example, in the study by Vibell et al. (2007). I will elaborate this question in the following paragraph.

Electrophysiological evidence for decreased perceptual latency under high temporal preparation

The majority of electrophysiological evidence for an influence of temporal preparation on perceptual processing stems from the temporal orienting paradigms. As I have already discussed in the Introduction, several studies could show that temporal attention enhances, for example, the amplitude of the N1 component (e.g., Correa, Lupiáñez, Madrid, & Tudela, 2006; Lange et al., 2006; Lange & Röder, 2006; Lange et al., 2003; L. D. Sanders & Astheimer, 2008). For an instance, L. D. Sanders and Astheimer (2008) employed a temporal Hillyard paradigm, in which a symbolic cue ('short', 'middle', or 'long') indicated when an auditory stimulus would occur. Hence, stimuli could appear at attended or unattended time points. The stimuli could either be standards or deviants and participants had to respond with a button press to the deviants only. Behavioral results showed that participants responded more likely to temporally attended stimuli. Furthermore, as an electrophysiological result, L. D. Sanders and Astheimer observed an amplitude increase of the N1 component for standards presented at temporally attended time points. However, there was no influence of temporal attention on the latency of either the N1 or the P1.

Such latency shifts have rather been observed for later components that are associated with response selection (e.g., Correa, Lupiáñez, Madrid, & Tudela, 2006; Miniussi et al., 1999, cf. Seibold, Fiedler, & Rolke, in press). Correa, Lupiáñez, Madrid, and Tudela (2006), for example, employed a temporal Posner paradigm, in which a symbolic cue indicated when to expect a letter for which a letter discrimination task had to be performed. The authors found faster RTs in validly cued trials, that is, when the letter occurred at the expected time point. Furthermore, greater amplitudes were observed for the P1 and the P300. A latency difference emerged for the P300—that is, it peaked earlier in validly cued trials. A similar result was obtained by Miniussi et al. (1999) who found P300 to peak earlier in valid trials, at least for short SOAs. The P300 is regarded as indexing stimulus evaluation and categorization (cf. Fabiani et al., 2007). Thus, a latency effect on P300 without latency effects on early, perceptual components suggests an influence on rather late perceptual or even central, rather than early perceptual stages of the information processing chain.

A decreased perceptual latency should, however, coincide with shorter latencies of early ERP components that index perceptual processing. A cautious clue on such a latency effect was obtained by Hackley et al. (2007). These authors had participants perform in a choice RT task and manipulated temporal preparation in a constant foreperiod paradigm. Behaviorally, they found decreased RT for the short FP and they also found a small but reliable effect on the latency of N1. Specifically, N1 latency in the short FP was shorter than in the long FP. This latency effect on the N1 component was replicated in an additional experiment of their study and indicates an earlier beginning of information accumulation (see, however, Correa, Lupiáñez, Madrid, & Tudela, 2006; Lange et al., 2003) under high temporal preparation. However, these results cannot be viewed as unequivocal since Hackley et al. also reported contradicting results in this study which rather pointed to later perceptual and even motoric influences of temporal preparation.

In order to further explore whether temporal preparation could decrease the latency of perceptual ERP components, Seibold, Fiedler, and Rolke (in press) employed a constant foreperiod paradigm in combination with an oddball paradigm. More specifically, a visual warning signal announced an upcoming auditory stimulus which occurred after 800 ms in blocks with a short FP and after 1,600 ms the blocks with a long FP. The tonal frequency of the auditory stimuli was varied in order to create standards, deviants, or target stimuli. The standards had the highest probability of occurrence (.8) whereas the targets and deviants occurred more seldom (each .1). Participants had to respond to targets only and furthermore the EEG was recorded throughout the whole experiment.

Seibold, Fiedler, and Rolke (in press) were interested in the so-called oddball N2 (cf. N2a or mismatch negativity, MMN; Näätänen, Simpson, & Loveless, 1982) which is a difference measure derived from a subtraction of the ERPs elicited by the standards and the ERPs elicited by the deviants.

This negativity occurs around 100-250 ms after the onset of the deviant and is suggested to index the detection of oddballs in a standard context, even when these are not task relevant (Folstein & Van Petten, 2008; Näätänen et al., 1982; Seibold, Fiedler, & Rolke, in press). Hence, the oddball N2 should be observed in the current study whenever a deviant is presented. The oddball N2's amplitude has furthermore been reported to correlate with discrimination performance (e.g., Schröger, 1995) and can be seen as an index of auditory perceptual processing.

For RT the usual FP effect was observed by Seibold, Fiedler, and Rolke (in press). That is, participants responded faster in the short FP than in the long one and hence RT decreased under high temporal preparation. Most crucially, however, various latency effects on early ERPs could be observed. First and foremost, the expected influence of temporal preparation on the oddball N2 could be confirmed: The oddball N2 (deviant-standard) exhibited an earlier peak in the short FP, that is, under high temporal preparation. In addition, the N1 and N2 for targets also peaked earlier. Hence, Seibold, Fiedler, and Rolke could show decreased latencies for early perceptual ERP components which substantiates the shortening of perceptual latency by temporal preparation.

The results of Seibold, Fiedler, and Rolke (in press) of shorter ERP latencies under high temporal preparation also pose the question about the neuronal mechanism underlying this finding. As to this matter, Seibold, Fiedler, and Rolke suggest that temporal preparation induces specific top-down mechanisms that in turn facilitate the neuronal processing of the relevant stimuli. Specifically, they propose that for a short time interval temporal preparation could boost the baseline of neuronal activity, which in turn would lead to an earlier emergence of relevant neuronal activation, that is, shorter latencies of perceptual ERP components.

Summing up, there is vast evidence for an influence of temporal preparation on perceptual ERP components. Various studies show that the amplitudes of, for example, N1 and P1 are higher under high temporal preparation (e.g., Correa, Lupiáñez, Madrid, & Tudela, 2006; L. D. Sanders & Astheimer,

2008) which indicates that perceptual processing is enhanced when participants know *when* a target stimulus will occur. Furthermore, through the study by Seibold, Fiedler, and Rolke (in press) there is now also evidence for a shorter latency of the oddball N2, the N1, and the N2 to targets under high temporal preparation. This observation strongly supports the results from this thesis showing a decreased perceptual latency when participants are well prepared for a stimulus. More specifically, perceptual processing seems to begin earlier which would of course result in an earlier availability of the respective stimulus. This notion is in accordance with the early onset hypothesis by Rolke and Hofmann (2007) and Rolke (2008) which will be elaborated in more detail in the last part of this General Discussion.

Mechanisms of the influence of temporal preparation

Although the major goal of this thesis was to assess the effect of temporal preparation on perceptual latency and therefore on the duration of perceptual processing, the present results also provide some clues about the mechanism underlying this effect. In the Introduction, I have introduced criterion models (e.g., Grice, 1968; Luce, 1986; Miller & Reynolds, 2003) that suggest that the internal activation generated by stimulus presentation accumulates over time. In these models, perceptual latency can be regarded as the time from stimulus onset to the time point when the accumulated information reaches a criterion. Perceptual latency therefore depends on the onset time of accumulation, the rate of accumulation, and the criterion level. Changes in any of these three parameters (onset, rate, and criterion) could account for the present pattern of data. Rolke and Hofmann (2007; Rolke, 2008) suggest that under high temporal preparation, information accumulation starts earlier (early onset hypothesis). Temporal preparation might likewise produce a higher accumulation rate (cf. Bausenhart et al., 2008; Correa, Sanabria, et al., 2006) or lower the criterion. In all cases information accumulation would reach the criterion earlier and thus decrease perceptual latency.

Even though neither of these possibilities can be supported definitively as the source of the present findings, these findings do provide some suggestive evidence that criterion level was uninfluenced by temporal preparation. Such a criterion shift would predict a smaller effect of temporal preparation on perceptual latency for loud than for soft tones, because soft tones are assumed to have a slower rate of information accumulation than loud ones (see Luce, 1986, p. 82–87). A difference in rates for soft and loud tones means that both functions diverge with the progress of time. Thus, a criterion shift should, according to intercept theorems, result in a greater difference for the slow rising function than for the fast rising one. Whereas this prediction is consistent with the results from Experiments 2 and 4, it is, however, inconsistent with the results from Experiments 1 and 3 because the effects of temporal preparation on perceptual latency for loud tones were not simply smaller but statistically not significant and quantitatively close to zero.

Setting aside this not completely warranted interpretation of a null effect, temporal preparation had little influence on a measurable criterion in Experiment 4. Specifically, the false alarm rate on NoGo trials for high and low levels of temporal preparation were virtually equal. Though the criteria used for Go/NoGo and detection decisions may not be identical, they might nevertheless be affected similarly by temporal preparation. Consequently, the present thesis suggests that temporal preparation does not influence decisional processes as one might expect if participants lowered their criterion under high temporal preparation.

One the basis of the current results one might rather speculate that it is accumulation onset or rate through which temporal preparation influences the duration of perceptual processing. I already discussed the fact that for loud tones no or an attenuated FP effect on perceptual latency was observed. This may have been due to the fact that perceptual processing of the loud tones was already at a near-to-optimum level and could not be further improved by temporal preparation. This interpretation would be most appealing if intensity as well as temporal preparation influenced the rate of information accumulation. Accordingly, the rate for loud tones would have already been quite high and could not be further increased by temporal preparation. This idea is also supported by the dissociative effects of temporal preparation on perceptual latency and RT (see the paragraph on RT results) which would also suggest that temporal preparation influences the rate. In this vein, Correa, Sanabria, et al. (2006) speculated about temporal preparation speeding up the "refresh rate" (p. 204) of the stimulus detection process.

In contrast to that, however, two quite recent studies (Bausenhart et al., 2010; Seibold, Bausenhart, et al., in press) support the notion that temporal preparation decreases the onset rather than affecting the rate of information accumulation. First, Seibold, Bausenhart, et al. (in press) employed a constant foreperiod paradigm and additionally manipulated the response criterion. The idea was that the factor criterion level should lead to additive effects with the factor foreperiod when FP affects the onset of information accumulation. However, when rate is influenced by FP, the factors criterion level and foreperiod should interact (cf. Figure 2).

Specifically, Seibold, Bausenhart, et al. (in press) presented a visual warning signal and after a long or a short FP a likewise visual target stimulus appeared—or not in catch trials—to which participants had to respond with a simple key press. The authors manipulated the response criterion by varying the proportion of catch trials in one block of trials (0, 25, 50, and 75%). When the number of trials without target presentation rises, participants should become more cautious with their response in order to avoid false alarms. Thus, they should set a higher criterion and RT should increase. In addition, a larger FP effect should be observed with increasing catch trial proportion, if temporal preparation influences the rate of information processing.

Besides the usual FP effect that indicates faster responses for high temporal preparation, a main effect of catch trial proportion emerged. As expected, participants responded faster when catch trial proportion—and therefore their criterion—was low. However, catch trial proportion and FP did not interact. This lack of interaction was confirmed with another manipulation of response criterion, that is, proportion of NoGo trials instead of catch trials. Hence, Seibold, Bausenhart, et al. (in press) concluded that there is no influence of temporal preparation on the rate of information accumulation but rather suggest an influence on the onset.

A further specific investigation on whether temporal preparation influences rate or onset was accomplished by Bausenhart et al. (2010). These authors employed speed-accuracy trade-off (SAT) functions in order to gain insight into the dynamics of perceptual processing under differing levels of temporal preparation. Specifically, an auditory warning signal announced the target stimulus that occurred after a constant FP of 800 or 2,400 ms. The target stimulus required participants to perform in a demanding visuo-spatial discrimination task. However, participants were not to respond directly after target presentation. Rather, a variable SOA (50, 100, 150, 200, 300, 500, 1,000, or 2,000 ms) was introduced between the target and a response signal that prompted participants to enter their response.

From the participant's response a SAT function was generated that associates discrimination accuracy (y-axis) with the available processing time (SOA + RT, x-axis). Then, an exponential function was fitted to the observed data that is characterized through the three parameters intercept, rate, and asymptote. First, the intercept denotes that processing time at which the participant's accuracy rises above chance level (i.e., 50%). With regard to criterion models (e.g., Grice, 1968; Luce, 1986) it can be seen as the onset of information accumulation. Second, the rate denotes how quickly the accuracy asymptote is reached and is indicative of the rate of information accumulation. Intercept and rate thus characterize the dynamics of information processing. Finally, the asymptote shows the maximum accuracy a participant could reach when enough time for stimulus processing is available and therefore stands for improved discriminability.

Bausenhart et al. (2010) fitted eight different functions to the individual data as well as to the averaged data. These functions differed in which and how many of the three parameters were allowed to vary between the two FP conditions. For the individual as well as the averaged data, the best fitting function suggested different asymptotes and different intercepts for the two FP conditions but a common rate. Accordingly, in the short FP the intercept was lower and the asymptote was higher than in the long FP. Bausenhart et al. concluded that temporal preparation influences the dynamics of information processing, but rather by shortening the intercept than by increasing the rate of information accumulation. The higher asymptote and thus higher discriminability under high temporal preparation may, according to Bausenhart et al., either be due to the shorter intercept, or to a better signal-to-noise ratio or enhanced contrast sensitivity. The authors favor the second explanation since, for example, the influence of temporal preparation is reduced when the contrast of the target stimulus is low (Rolke, 2008). These results agree with the present results of decreased perceptual latency under high temporal preparation. Furthermore, they are in accordance with the early onset hypothesis (Rolke, 2008; Rolke & Hofmann, 2007) that assumes an earlier beginning of information accumulation under high temporal preparation.

Summing up, the present data as well as related studies argue against an influence of temporal preparation on the criterion (Bausenhart et al., 2010; Seibold, Bausenhart, et al., in press). Whereas the present experiments are inconclusive about whether onset or rate of information accumulation are influenced since they were not designed to provide such evidence, the studies by Bausenhart et al. (2010) and Seibold, Bausenhart, et al. (in press) rather point to an earlier beginning of information accumulation and thus to the early onset hypothesis (Rolke, 2008; Rolke & Hofmann, 2007). Regardless of the mechanism, however, a change in perceptual latency as observed in this thesis reflects a change in perceptual processing with consequences for post-perceptual processes, as well as for the overall speed and accuracy of performance.[11]

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[11] A correlational analysis on RT and D was performed per participant for Experiment 1. The mean correlation across all participants and conditions was .21, which is significantly different from zero, $F(1,23) = 30.78$, $p < .001$. Therefore RT and D share common variance, as one would expect and thus do not reflect indices associated with (completely) different information processing streams.

Conclusion

To conclude, the present experiments demonstrate that temporal preparation decreases perceptual latency. Closing the circle to the 100-m-sprint example from the Introduction one can say that a runner preparing for the ‘go’ signal (‘steady’) might actually perceive the ‘go’ earlier than without preparation. More generally, orienting attention in time allows faster perceptual processing which should be highly adaptive. Whereas the mechanism of this temporal preparation effect—that is, changes in the dynamics of information accumulation or level of a detection criterion—remains to be determined, the present results provide new and compelling evidence for revising what was once the general consensus on the locus of temporal preparation, that is, that the effects of temporal preparation are limited to late and central stages (e.g., Hackley, 2009; A. F. Sanders, 1980a). Instead, this fundamental process of cognitive control seems to operate at multiple stages within the information processing system, including early perceptual stages.

Abstract

It is a well-known fact that actions can be performed faster and more efficiently when one can prepare for the exact time point when they will be required. In the laboratory, participants express faster reaction times (RT) to a target stimulus when it is preceded by a warning signal. The warning signal is assumed to reduce the participants' temporal uncertainty about the occurrence of the target stimulus because it allows participants to anticipate the target stimulus and thus to prepare for its occurrence.

An important question in the investigation of this *temporal preparation* effect concerns which stages in the chain of information processing from stimulus presentation to response benefit from temporal preparation. Knowing this locus is a prerequisite for the further theoretical development of the concept of temporal preparation. For a long time, the general consensus was that temporal preparation exerts its influence exclusively on motor processing. However, recent studies show that temporal preparation also improves stimulus discrimination and thus suggest an influence also on perceptual stimulus processing. This might be due to a decreased duration of perceptual processes which would in turn predict a shorter perceptual latency—that is, a shorter time to detect the onset of a stimulus—for stimuli experienced under high temporal preparation.

Hence, in order to investigate whether temporal preparation decreases perceptual latency, a clock paradigm was employed in this thesis. In four experiments, participants watched a revolving clock hand while listening to soft or loud target tones under high or low temporal preparation. At the end of each trial, participants reported the clock hand position at the onset of the target tone. The deviation of the reported clock hand position from the actual position indexed perceptual latency. As expected, perceptual latency decreased with target tone intensity. Most importantly, however, high temporal preparation decreased perceptual latency in all four experiments, especially for soft tones. Variations in task requirements excluded several alternative explanations and substantiated a reliable decrease of perceptual

latency under high temporal preparation.

The present findings question an exclusive influence of temporal preparation on motor processing, since they represent direct evidence for the idea that temporal preparation diminishes the duration of perceptual processing. The improved discrimination performance as well as the shortened RT found in previous studies under high temporal preparation might well be due to a shortening of perceptual processes. Thus, these findings provide a compelling foundation for advancing a perceptual theory of temporal preparation.

Zusammenfassung

Handlungsabläufe werden schneller und effizienter ausgeführt, wenn man sich auf ihren Ausführungszeitpunkt genau vorbereiten kann. Im Labor reagieren Versuchspersonen (Vpn) schneller auf einen Zielreiz, wenn diesem ein Warnsignal vorausgeht. Es wird angenommen, dass das Warnsignal die zeitliche Unsicherheit der Vpn über das Auftreten des Zielreizes reduziert und ihnen somit erlaubt, den Zielreiz zu antizipieren und sich auf dessen Erscheinen vorzubereiten.

Eine wichtige Forschungsfrage im Hinblick auf diesen Effekt *zeitlicher Vorbereitung* bezieht sich darauf, welche Stufe in der Informationsverarbeitung von der Reizpräsentation bis zur Reaktion davon profitiert. Diesen Ort zu kennen ist eine Grundvoraussetzung für die weitere theoretische Entwicklung auf dem Gebiet zeitlicher Vorbereitung. Lange Zeit herrschte Konsens darüber, dass zeitliche Vorbereitung exklusiv die motorische Verarbeitung beeinflusst. Neuere Studien zeigen jedoch, dass zeitliche Vorbereitung auch die Reizdiskrimination verbessert und legen daher einen Einfluss auch auf die perzeptuelle Verarbeitung nahe. Dies könnte auf eine kürzere Dauer perzeptueller Verarbeitungsprozesse zurückzuführen sein. Infolgedessen wäre eine kürzere perzeptuelle Latenz—das heißt eine kürzere Zeitdauer bis zur Entdeckung eines Reizes—für solche Reize zu erwarten, auf die man sich gut zeitlich vorbereiten kann.

Daher wurde in dieser Dissertation mit Hilfe eines Uhrenparadigmas untersucht, ob zeitliche Vorbereitung tatsächlich die perzeptuelle Latenz verringert. In vier Experimenten beobachteten die Vpn einen sich drehenden Uhrenzeiger und bekamen währenddessen leise oder laute Zieltöne präsentiert. Die Zieltonpräsentation erfolgte entweder unter guter oder schlechter zeitlicher Vorbereitung. Am Ende jedes Durchgangs berichteten die Vpn, an welcher Position sich der Zeiger befunden hatte, als der Zielton einsetzte. Die Abweichung der berichteten Zeigerposition von der tatsächlichen Position indizierte die perzeptuelle Latenz. Wie erwartet nahm die perzeptuelle Latenz mit der Zieltonintensität ab. Weitaus bedeutsamer war jedoch, dass

gute zeitliche Vorbereitung ebenfalls zu einer Abnahme der perzeptuellen Latenz führte. Dies war in allen vier Experimenten zu beobachten, insbesondere für leise Töne. Durch Variationen der Aufgabenanforderungen konnten diverse Alternativerklärungen ausgeschlossen werden und somit eine reliable Reduktion der perzeptuellen Latenz unter guter zeitlicher Vorbereitung untermauert werden.

Diese Befunde liefern einen direkten Beleg dafür, dass zeitliche Vorbereitung die Dauer der perzeptuellen Verarbeitung verkürzt. Damit stellen sie einen exklusiven Einfluss zeitlicher Vorbereitung auf die motorische Verarbeitung in Frage. Sowohl die verbesserten Diskriminationsleistungen als auch die schnelleren Reaktionszeiten aus früheren Studien könnten sehr gut durch diese Verkürzung perzeptueller Prozesse erklärt werden. Die vorliegenden Befunde stellen daher eine überzeugende Grundlage für die Weiterentwicklung perzeptueller Theorien zur zeitlichen Vorbereitung dar.

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