Preparing to perceive
On the influence of temporal preparation on premotor processing

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Diskutieren von Ideen
Eröffnen von Möglichkeiten
Vermitteln von Wissen
Unterstützen
Daten erheben
Mut machen
Kritisieren
Da sein
Korrektur lesen
und fürs
Miteinander lachen

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1. INTRODUCTION

Already in 1862, Wilhelm Wundt stated „dass wir unsere Aufmerksamkeit keineswegs immer gleichmäßig anzuspannen im Stande sind“ [that by no means we are capable of tensing our attention evenly at all times (author’s translation)] (p. 264). Thereby, he intended to explain intraindividual fluctuations in the “speed of thoughts“, which he had previously accomplished to measure with his famous experimental device, known as the “Wundt clock”. Several years later, this issue of “being attentive at all times” was more systematically investigated by Herbert Woodrow (1914). He was able to demonstrate that warning signals, which temporally precede the occurrence of an imperative stimulus, can greatly alter our state of attentiveness at the moment of stimulus presentation. In the following years, this phenomenon was established in experimental research as “temporal preparation”, and has been extensively investigated by psychologists and neurophysiologists until the present day.

Despite the great deal of experimental work that has been conducted on temporal preparation since then, there remain several open questions concerning this classical phenomenon. One of them, which is central to the present work, is the question about the locus of temporal preparation effects. Whereas according to Wundts (1862) work cited above, one might argue that being attentive at certain points in time alters the speed of perceptual and cognitive processes, another view of temporal preparation has been established in the decades of experimental research following Wundt. Specifically, most empirical evidence to date argues for an influence of temporal preparation on various aspects of motor processing (e.g., Brunia, Scheirs, & Haagh, 1982; Sanders, 1980). These studies thereby led to the widespread conception that temporal preparation effects emerge as a consequence of changes in the motor system. This view, however, has been challenged by more recent studies, which again open up the possibility of a premotor locus of temporal preparation effects (e.g., Müller-Gethmann, Ulrich, & Rinkenauer, 2003). Based on these studies, the present work investigates whether temporal preparation affects premotor and especially perceptual stages of information processing.

The first part of this Introduction gives an overview about basic concepts and experimental paradigms commonly employed in the study of temporal preparation. Following the theoretical foundations of temporal preparation, a detailed overview about relevant empirical studies on the locus of temporal preparation effects is provided. Finally, rationale and aim of the present work are developed against the background of these studies.

1.1. Basic concepts and paradigms

1.1.1. Expectation, uncertainty, and temporal preparation

Anticipating future events is an important ability that enables us to deal with a rapidly changing environment and the associated need to respond quickly, adequately and flexibly to such environmental changes. Factors such as prior knowledge, experience, reasoning, or learning of contingencies between subsequent events enable the formation of expectations about upcoming events and thereby, the prediction of these events. Building up expectations about the future has many consequences. For example, such expectations can change our motivational, cognitive and emotional state, thereby influencing multiple aspects of behavior, as perception, aspiration levels, choice between different alternatives, and learning (e.g., Sanders, 1966). Most important for the present work, expectations enable us also to prepare for upcoming events and respond adequately to them. Requin, Brener, and Ring (1991) emphasized this action-guiding function of expectation and preparation by stating: “Indeed, it is clear that every overt expression of behavior is the product of a series of antedating processes.”(p. 358). These antedating processes can take place even before the occurrence of the event that evokes the action. This can only be accomplished, however, if one has a certain expectation of the event, for example about *when* it will take place or *what* exactly will happen. Only on rare occasions such expectations are completely valid; most of the time, however, they are associated with a certain amount of uncertainty. Depending on the type of expectation, uncertainties can be classified as either *event uncertainty*, that is, uncertainty about what will happen, and *temporal uncertainty*, that is, uncertainty about when something will happen (Requin et al., 1991). Consequently, event uncertainty is associated with the question of which response will be appropriate for a specific upcoming event, whereas temporal uncertainty focuses on when a response will have to be performed. Taken together, expectations about future events are inversely related to the uncertainty about these events: the stronger our expectations, the less uncertain we are.

Importantly, strong expectations about upcoming events and the associated low uncertainty enable preparation for those events, for example, by preselecting and preprogramming an appropriate response to an expected stimulus. Such preparatory activity has often been investigated by employing mental chronometry. A basic assumption of this method is that the time between the presentation of a stimulus and the execution of a related response (reaction time, RT), reflects the time course of all aspects of mental processing necessary for event-related actions: detection and identification of a stimulus, selection of an appropriate response to this stimulus, and finally, motor programming and execution of the selected response (Sanders, 1977, 1980; Sternberg, 1969). Because preparation has been described as “performing in advance what can be performed in advance of a response” (Näätänen & Merisalo, 1977, p. 133), these aspects of processing may be – partly or fully – anticipated and pre-performed if event uncertainty and temporal uncertainty is low. Accordingly, the more advance information about an upcoming stimulus is provided, the more processing steps can take place before presentation of the actual stimulus, and the shorter RT to the stimulus will be (Requin et al., 1991).

To investigate the amount of preparation that can take place in advance of stimulus presentation, one must vary the available amount of information about the upcoming stimulus. A straightforward way to accomplish this is by presenting a warning signal or cue prior to a subsequent target stimulus, to which a response has to be performed. For example, event uncertainty can be reduced by presenting information about the subsequent stimulus that reduces the number of possible response alternatives. As a result, certain aspects of the motor response may be prepared in advance. For example, Rosenbaum (1980) presented target stimuli that required a complex motor response varying in three different response dimensions: movements had to be performed either with the right or left hand, either in the right or left direction and either over a short or long movement distance. Thus, this experimental setup included a total of eight different target stimuli, each requiring a different response. Prior to the presentation of the target stimulus, a cue provided either no information or information about one or more of the required response dimensions. Thus, when informative, the cue enabled participants to prepare certain aspects of the required response in advance, as for example, motor programming of the hand with which the movement later had to be performed. Rosenbaum’s results confirm the notion of advance event preparation: the more response dimensions were specified by the cue, the more aspects of the motor action could be preprogrammed, and thus, the shorter was RT to the target stimulus. Similar evidence for the effect of event uncertainty on advance preparation of motor programs was confirmed in a variety of experimental studies (e.g., Goodman & Kelso, 1980; Hasbroucq, Osman et al., 1999; Miller, 1982; Osman, Moore, & Ulrich, 2003; Rosenbaum, 1983).

Most important for the present work, however, is the use of warning signals that enable the formation of temporal expectancies. Accordingly, in studies on temporal preparation, warning signals do not provide information about the subsequent target stimulus itself, but about the time of its occurrence. Given that the target stimulus requires a forced-choice response, participants do not know in advance of target stimulus presentation which response they will have to perform, and the warning signal does not reduce this uncertainty. Rather, the warning signal reduces the uncertainty about when the target stimulus will occur, and therefore, about when the response will have to be performed. This information is sufficient to enable considerable performance improvements, as for example, shortening of RT. Such performance improvements are typically observable independent of whether warning signals convey the information about the time of target stimulus presentation implicitly or explicitly. The following chapters will introduce the most common paradigms that are used to investigate the effects of implicit or explicit temporal information – foreperiod paradigms and temporal orienting paradigms – and outline some results that are typically obtained with these paradigms.

1.1.2. The foreperiod paradigm

As outlined above, even warning signals that do not convey any explicit information about the time of target stimulus presentation enable temporal preparation. Specifically, such uninformative warning signals may lead to the formation of temporal expectancies about the time of target stimulus occurrence, which in turn, can be used to adjust preparatory activity to the moment of target stimulus presentation. For example, such expectancies can be formed on basis of a temporal contingency between warning signal and target stimulus. Everyday examples for such warning signals are an orange traffic light indicating that it will turn green soon after, or the “ready, steady” that announces a shortly following “go” signal in sprint. As soon as one experiences such a warning signal, he will engage in preparatory activity in order to be able to respond especially fast to the target stimulus. Although these examples somewhat lack comparability with many experimental studies, as they usually occur in situations in which the type of required response is predetermined by situational demands, they demonstrate the importance of anticipation and temporal preparation for everyday life.

Starting with the work of Herbert Woodrow (1914), a great number of experimental studies investigated the effects of such implicit warning signals on RT. Importantly, such warning signals convey information about the time of response signal presentation through their temporal relationship with the target stimulus. Accordingly, manipulation of this temporal relationship enables the implementation of different amounts of temporal preparation. Specifically, the majority of studies on temporal preparation focused on the time interval between warning signal and target stimulus, that is, the foreperiod. The amount of temporal preparation depends heavily on different characteristics of the foreperiod, as for example its duration or its distribution across blocks of experimental trials. The following section will give an overview of these characteristics and their influence on temporal preparation.

As briefly outlined above, the basic foreperiod paradigm involves the presentation of a warning signal that is followed by a defined amount of time – the foreperiod. When foreperiod duration has expired, a target stimulus is presented, and participants have to respond to the target stimulus. The warning signal itself is usually not informative about specific features of the target stimulus. For example, in a two-alternative forced-choice task, the warning signal does not indicate which type of target stimulus will appear at the end of the foreperiod. Thus, the appropriate response can be selected only after the target stimulus has actually been presented. A special case that forms an exception to this is when the target stimulus requires just a speeded simple response (for an overview, see Niemi & Näätänen, 1981). Then, the appropriate response and its corresponding motor program can be prepared in advance of target signal presentation – however, the response that has to be performed later is not indicated by the warning signal itself, but rather by the situational demands, or in other terms, by the task set[1]. Independently of task requirements, however, it has been demonstrated that the mere presence of a uninformative warning signal

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[1] Here, simple reaction task is introduced as a special case in temporal preparation research, because the employment of tasks that require discrimination between different target stimuli and on-line selection of appropriate responses is central to the aim of the present study. Specifically, the present work investigates the effects of temporal preparation on early information processing stages, in which stimulus discrimination and response selection are performed. Nonetheless, it should be emphasized that simple reaction time tasks have frequently been employed in combination with foreperiod paradigms (see Niemi & Näätänen, 1981) and have led to empirically well-founded results as well as to theoretically important conclusions.

announcing a target stimulus shortens RT compared to presentation of a target stimulus alone (Bertelson, 1967; Bertelson & Tisseyre, 1969; Broadbent & Gregory, 1965).

The foreperiod paradigm constitutes a powerful and valuable tool to manipulate the amount of temporal preparation. Thus, it has been employed frequently and successfully to tackle many research questions focusing on the ability to prepare for upcoming events. This widespread use has lead to many variations of the basic foreperiod paradigm, differing for example in characteristics of the warning signal (e.g., Bertelson & Tisseyre, 1969; Davis & Green, 1969; Rodway, 2005), the range of employed foreperiods (e.g., Drazin, 1961; Elliot, 1973; Karlin, 1959; Klemmer, 1956), the duration of foreperiods (e.g., Bertelson & Tisseyre, 1969; Müller-Gethmann et al., 2003; Woodrow, 1914), the distribution of these foreperiods across blocks of trials (e.g., Bevan, Hardesty, & Avant, 1965; Klemmer, 1956; Mattes & Ulrich, 1997), and the probability of target stimulus delivery (e.g., Buckolz & Rodgers, 1980; Drazin, 1961; Näätänen, 1972; Näätänen & Merisalo, 1977). RT research has identified all of these characteristics as important determinants of temporal preparation. Common to all these characteristics is that they influence the uncertainty of a participant about when the target stimulus will occur. The greater the uncertainty about the moment of target presentation, the lower the amount of temporal preparation, and therefore, the longer RT.

Klemmer (1956) compared different experimental conditions in which the mean foreperiod duration was kept constant, but the range of foreperiods could vary over trials around this mean foreperiod duration. For example, in one condition, foreperiod duration always was exactly the mean duration (no variation), whereas in two other conditions, foreperiods were varied around this mean duration with a overall bandwidth of either two or eight seconds. When these conditions were compared only with regard to trials in which the mean foreperiod duration had been presented, Klemmer found that RT increased with the bandwidth of foreperiod variation. Even though mean foreperiod duration was identical in all conditions and therefore, always the best predictor for the upcoming foreperiod duration, increasing the variability of foreperiod durations enhanced the uncertainty about when to expect the target stimulus. As a result, temporal preparation worsened and RT increased with foreperiod variability.

Not only the range but also the absolute duration of the foreperiod influences temporal preparation immensely (see Niemi & Näätänen, 1981 for a review). For example, in the so-called constant foreperiod paradigm, the duration of the foreperiod is kept constant across a block of trials but varied between blocks of trials. A typical finding within this paradigm is that RT increases with increasing foreperiod duration (e.g., Karlin, 1959; Klemmer, 1956; Niemi & Näätänen, 1981; Woodrow, 1914; see figure 1.1). This effect on RT reflects that temporal uncertainty increases with increasing time interval between warning signal and target stimulus, thus hampering temporal preparation for the exact moment of target stimulus presentation. Two supplementing aspects should be noted in connection with this general finding. First, whereas increasing RT with increasing foreperiod duration can be observed over a wide range of foreperiod durations, very short foreperiod durations seem to provide an exception to this rule. Rather, if foreperiod is quite short (up to approximately 200-400 msec), RT usually decreases with increasing foreperiod duration. When a wide range of foreperiod durations is employed, RTs therefore follow an U-shaped function (e.g., Bertelson & Tisseyre, 1969; Müller-Gethmann et al., 2003; Posner & Boies, 1971; Woodrow, 1914). Specifically, a rather steep decrement of RT can be observed as foreperiod increases up to 200-400 msec, and is followed by a slow and steady increase of RT that can last up to foreperiod durations of several seconds. This time course has been interpreted as evidence that the build-up of temporal preparation takes some time, thus leading to slow responses when very short foreperiods do not enable sufficient temporal preparation. Consequently, it has been suggested that foreperiod effects which sometimes are nonetheless observed with very short foreperiods might be rather due to the immediate arousing properties of the warning signal (e.g., Hackley & Valle-Inclán, 2003; Semjen, Bonnet, & Requin, 1973; Ulrich & Mattes, 1996) than to an impact of preparatory processes on stimulus processing. The second important aspect is that there seems to be no generally valid optimum foreperiod duration which is associated with the highest possible level of temporal preparation. Rather, optimum foreperiod duration seems to vary greatly between different experimental setups, for example with specific characteristics of warning signal and target stimulus or according to task difficulty (see Niemi & Näätänen, 1981; Teichner, 1954).

In contrast to this constant foreperiod paradigm, in the variable foreperiod paradigm foreperiod duration varies randomly within a block of trials. This presentation mode does not only result in longer RT compared to the constant foreperiod paradigm (cf., Bevan et al., 1965; Klemmer, 1956; Mattes & Ulrich, 1997), but also in a different pattern of results when regarding the influence of foreperiod duration on RT. Specifically, the typical pattern of RT results seems to be reversed compared to the constant foreperiod paradigm:

increasing the foreperiod duration leads to a reduction in RT (Drazin, 1961; Hohle, 1965; Karlin, 1959; Los, Knol, & Boers, 2001; see figure 1.1). This typical pattern of results can be observed over a rather wide range of foreperiod durations up to several seconds (e.g., Baumeister & Joubert, 1969; Bevan et al., 1965; Elliot, 1973).

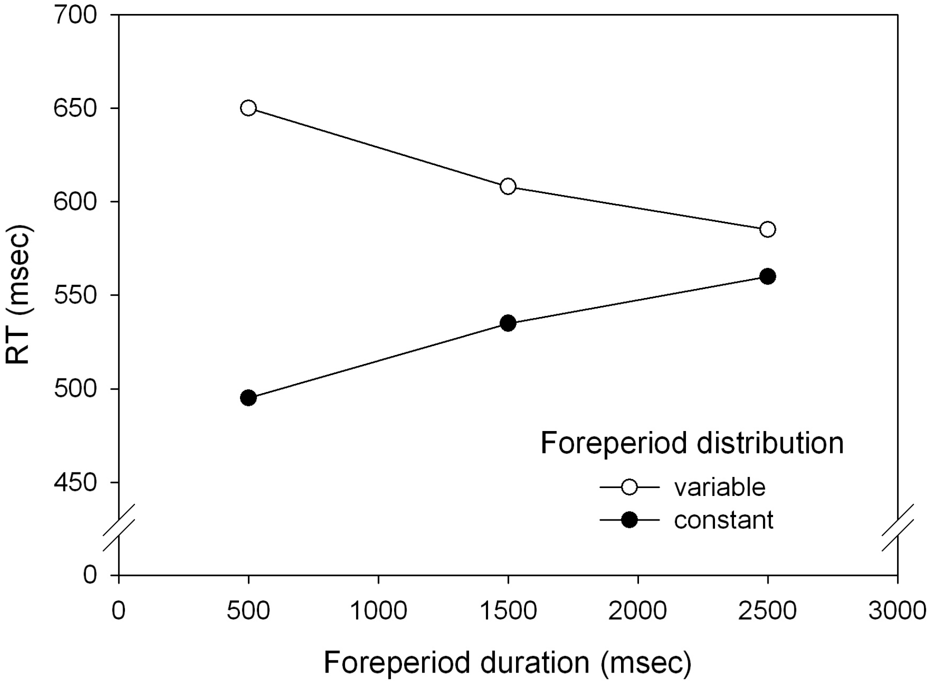

Figure 1.1. Typical reaction time (RT) result in an experiment with constant and variable foreperiods.

An additional typical and well-replicated finding within the variable foreperiod paradigm is the existence of sequential effects (Alegria, 1975a, 1975b; Baumeister & Joubert, 1969; Drazin, 1961; Klemmer, 1956; Los et al., 2001; Los & Van Den Heuvel, 2001; Näätänen, 1970; Woodrow, 1914): The RT observed in a current trial *n* does not only depend on the duration of the foreperiod of the current trial, but also on the foreperiod duration of the previous trial *(n-1)*. More specifically, when the current foreperiod is short and was also preceded by a short foreperiod in trial *n-1*, especially fast responses can be observed. In contrast, when a current short foreperiod duration is preceded by a long foreperiod in the previous trial, responses are slowed down, thus indicating that this situation enables only insufficient temporal preparation. Importantly, these sequential effects are asymmetrical, that is, they depend on the duration of the current foreperiod. In detail, sequential effects are most pronounced for the shortest foreperiod duration, decrease for longer foreperiod durations, and are typically absent for the longest foreperiod duration within a given set of foreperiod durations (see Figure 1.2). This asymmetry seems not to be due to differences of the absolute duration of the foreperiods. For example, it has recently been demonstrated that sequential foreperiod effects can be observed with rather long (1,200-3,600 msec) as well as very short (200-600 msec) foreperiod durations, given that the foreperiods are temporally distinct enough to enable differential preparation for the possible moments of target presentation (Steinborn, Rolke, Bratzke, & Ulrich, 2008). It has been argued that these sequential effects might even constitute the major source of the variable foreperiod effect (i.e., decreasing RT with increasing foreperiod duration), because exactly this pattern of results is expected if one averages RT for different foreperiod durations without respect to the foreperiod duration of the previous trial (see, for example, Los et al., 2001).

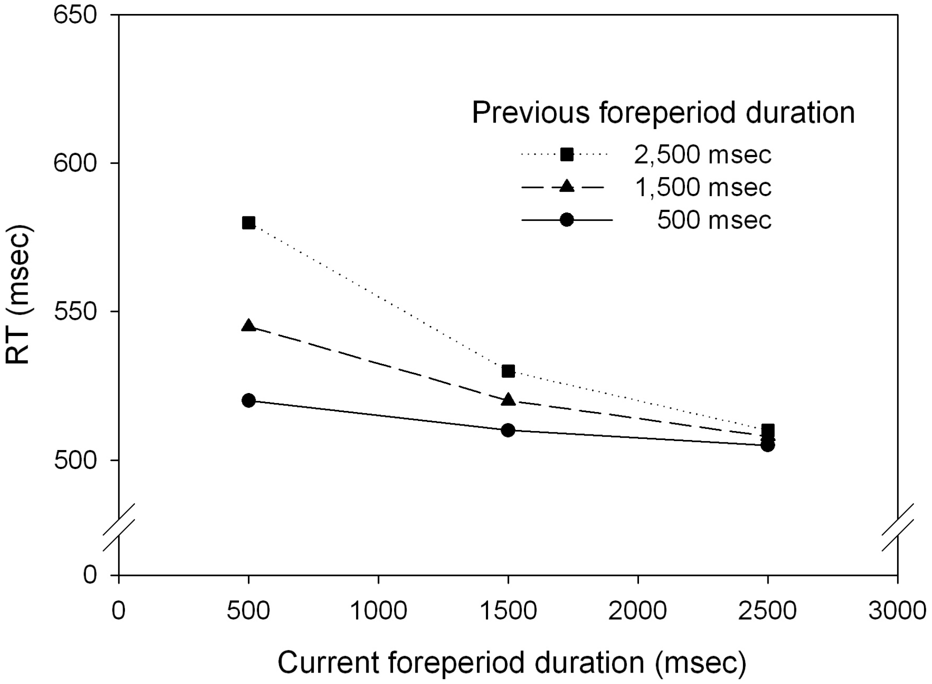

Figure 1.2. Typical sequential effects of previous foreperiod duration on reaction time (RT) results in an experiment with variable foreperiods.

Research on temporal preparation so far focused almost exclusively on foreperiod paradigms. Presumably, the investigation of foreperiod effects and sequential effects has been of major interest in the study of temporal preparation since they can be very reliably observed within a wide range of tasks and experimental setups. These effects also proved to be very fruitful and stimulating for theoretical explanations of the sources of temporal preparation. The present work therefore will also focus on the investigation of foreperiod effects, specifically, by employing the constant foreperiod design. Research within classical foreperiod paradigms, however, was recently supplemented by studies employing explicit temporal orienting as a means to study the effects of temporal preparation. Because this approach yielded some results that are highly relevant to the aim of the present work, the following section shortly introduces the most typical temporal orienting paradigms.

1.1.3. Temporal orienting

As previously described, our expectations about the future and about the timing of upcoming target stimuli can influence our responses to those stimuli considerably. Such expectations can not only be generated implicitly by uninformative warning signals, but also explicitly by informative cues or instructions. Even though these variants found their way into systematic psychological research only recently, an early example for the significance of explicit temporal expectations was already provided by McAdam, Knott, and Rebert (1969). These authors presented target stimuli that were preceded by foreperiod durations of either 1,200 msec or 2,400 msec, and required a speeded simple response from their participants. In addition, participants were asked to predict prior to each trial how long the foreperiod in this trial would be. Stimulus presentation was adjusted according to these predictions, in such way that the predictions proved to be correct in about 70 percent of all trials. The RT results therefore demonstrated an influence of these explicit temporal expectations on performance. Specifically, RT was shortest when a short interval was predicted and subsequently received. A slightly longer RT was observed in trials in which participants predicted and received a long interval. Importantly, in trials in which participants predictions were false, RT was substantially prolonged as compared to trials with correct predictions. Hence, this early study indicated that performance in response to an event is affected by explicit temporal expectations about the event.

In the years following Adams et al.’s (1969) study, the role of explicit temporal expectations has been widely neglected in experimental research. Within the last decade, however, research interest in this topic has renewed, and novel paradigms have been developed that enable the manipulation of explicit temporal expectations, and therefore, a systematic investigation of their effects. In the following, studies concerned with explicit temporal expectations will be subsumed under the label of “temporal orienting”. This name derives from the common interpretation that participants somehow use the information conveyed by the warning signal to orient their attentional resources to the expected time of target stimulus delivery (e.g., Correa, Lupiáñez, & Tudela, 2006; Coull & Nobre, 1998; Miniussi, Wilding, Coull, & Nobre, 1999).

Within temporal orienting research, many studies employed warning signals or temporal cues which carry explicit information about the time of target stimulus occurrence, as for example, the words “early” or ”late” (e.g., Correa, Lupiáñez, & Tudela, 2005; Correa, Lupiáñez, & Tudela, 2006; Coull & Nobre, 1998; Miniussi et al., 1999). Depending on whether these temporal cues correspond to the actual time of target stimulus presentation or not, they are – in analogy to the spatial cues often employed in spatial orienting studies to indicate the position of a subsequently presented target stimulus (e.g., Henderson, 1996; Posner, Snyder, & Davidson, 1980; Yeshurun & Carrasco, 1999) – classified as either “valid” or “invalid”. It has been demonstrated repeatedly that such explicit temporal cues enable the formation of temporal expectations about target stimulus occurrence, which in turn influence performance.

For example, Miniussi et al. (1999) required their participants to perform a speeded simple response to a visual target stimulus. Either 600 msec (short foreperiod duration) or 1,400 msec (long foreperiod duration) prior to the target stimulus, a visual temporal cue was presented. This temporal cue was either a wide or narrow cross, indicating whether the target stimulus would be presented after the short foreperiod duration or the long foreperiod duration. This information provided by the temporal cue was valid in 80 percent of all trials, that is, the information about target stimulus delivery was correct, and invalid in 10 percent of the trials, that is, the warning signal lead participants to expect the wrong duration. The remaining 10 percent of trials were catch trials, that is, no target stimulus appeared at all. The RT results of this experiment indicated that participants actually used the information provided by the temporal cue in order to adjust their preparatory activity to the announced time of target stimulus presentation. Specifically, when foreperiod duration was short, faster responses were observed when the temporal cue previously had announced an upcoming short foreperiod duration than when it had announced a long foreperiod duration.

This modulation of RT as a function of cue validity was not observed for the long foreperiod duration. Later studies with a similar setup, however, were able to generalize this temporal cueing effect also to the long foreperiod duration by employing a higher proportion of catch trials (Correa, Lupiáñez, Milliken, & Tudela, 2004; Correa, Lupiáñez, & Tudela, 2006). Since these explicit cueing studies repeatedly demonstrated that valid compared to invalid temporal cues evoke a reduction in RT, they indicate that participants can actively interpret the temporal information carried by the temporal cues to build up temporal expectancies and, in turn, adjust their preparatory activity flexibly to the moment of target presentation.

Besides explicit temporal cueing, instructions have been successfully used to manipulate temporal expectancies. For example, Lange, Rösler, and Röder (2003) presented two auditory signals which were separated by either short (600 msec) or long (1,200 msec) foreperiod durations. As in the variable foreperiod paradigm, these foreperiod durations varied randomly from trial to trial. In a high percentage of these trials, the second tone was equally loud as the first tone (standard). In some trials, however, the second tone was louder than the first one (deviant). Importantly, participants were instructed to respond to deviants, but only if presented at the end of one of the foreperiod durations. For example, in one block of trials, participants had to respond to deviants presented 600 msec following the first tone, and in another block, participants had to respond to deviants presented 1,200 msec after the first stimulus. Thus, these instructions forced participants to orient their attention especially to the time at which a target stimulus (that is, a deviant at the instructed time interval) might appear. Because overt responses are only measured in few trials and typically only at attended moments, this paradigm is especially useful in investigations of electrophysiological responses to stimuli. Lange et al. (2003) observed an enhancement of specific event-related potentials of the electrophysiological responses to stimuli presented at attended compared to unattended moments in time. Hence, they demonstrated that participants follow the instructions to attend to specific moments in time, and that this temporal orienting alters processing of stimuli presented at these moments. These findings were replicated and extended by subsequent studies employing similar experimental setups or variations thereof (Lange, Krämer, & Röder, 2006; Lange & Röder, 2006; Sanders & Astheimer, 2008).

All of the studies cited above demonstrate convincingly that explicit information about the temporal structure of subsequent events can be used to prepare for these events in order to optimize behavior. Such temporal orienting effects have been studied most extensively by investigating modulations of electrophysiological activity (e.g., Correa, Lupiáñez, Madrid, & Tudela, 2006; Griffin, Miniussi, & Nobre, 2002; Lange et al., 2003; Sanders & Astheimer, 2008). These studies provided important insights into the mechanisms underlying temporal preparation. The respective studies will be described in detail later in this Introduction (in particular, see Chapters 1.4.1.3 and 1.4.2.6).

1.2. When we prepare - Theoretical accounts of the sources of temporal preparation

As has been outlined above, temporal preparation influences performance in RT tasks immensely. Conditions enabling a state of high temporal preparation go together with especially fast responses. It is important to note, however, that reaching and maintaining a state of optimal temporal preparation seems to be effortful and also time-consuming, and therefore can not easily be maintained over time (e.g., Gottsdanker, 1975). Therefore, researchers have been very interested in unravelling the mechanisms that regulate for which moments temporal preparation will be high or low. In the following chapter, an outline of the main theoretical accounts of these mechanisms underlying temporal preparation, namely, *time uncertainty, expectancy*, and *trace conditioning*, is given, before this Introduction will turn to a more specific investigation of the outcomes of temporal preparation. Accordingly, Chapter 1.2 focuses on accounts that provide theoretical explanations for *when* we prepare, whereas Chapter 1.3 will describe theories that concerned with the question of *what* exactly can be prepared, followed by a detailed overview over empirical studies concerned with the localization of temporal preparation effects within the processing stream in Chapter 1.4.

1.2.1. Time uncertainty and expectancy

To explain the influence of constant foreperiods on RT, a common theoretical account refers to the concept of time uncertainty, and relates temporal preparation to current models of time perception (Klemmer, 1956; Treisman, 1964). First, it is assumed that constant foreperiods enable participants to learn the foreperiod duration of the current block. Accordingly, after a few trials of learning, participants can estimate the duration of the current foreperiod, and thus prepare for the expected moment of target presentation as soon as they perceive the warning signal. For example, Treisman (1964) stated that participants tend to anticipate the occurrence of the target stimulus at the end of the foreperiod duration. “Since he [the participant] can not time the end of a time interval exactly, he will expect the stimulus over a range of time about the end of the interval. … The length of this ‘range of expectation’ would be approximately proportional to the inter-stimulus interval…” (Treisman, 1964, p. 17). According to this explanation, longer foreperiod durations would go together with greater ranges of expectation. Because it is assumed that the efficiency of preparation decreases with increasing range of expectation, preparation for the target stimulus would be less efficient when it is presented after a long foreperiod compared to a target stimulus that is presented after a short foreperiod.

This notion of an increasing range of expectation, or in other terms, increasing time uncertainty about target stimulus occurrence, has found wide distribution and has been commonly used to explain the effects of constant foreperiods on performance. There is some convincing empirical evidence for this notion: For example, from studies of time perception, it is well known that human time-keeping ability is imperfect: short durations can be estimated much more accurately than long durations (Gibbon, 1977). Accordingly, when participants try to estimate the duration of the ongoing foreperiod in order to synchronize their preparation with the presentation of the target stimulus, short foreperiod durations will enable a more accurately timed preparation than long foreperiods. This was also demonstrated by Näätänen, Muranen, and Merisalo (1974) who asked their participants in a constant foreperiod paradigm to synchronize their key presses with the presentation of the target stimulus. In accordance with the time uncertainty account, the distribution of the times at which key presses were registered got increasingly broad and flattened out as foreperiod duration was increased. Finally, when the passage of time during the foreperiod is rendered traceable, for example by providing a series of countdown signals between warning signal and target stimulus, accurate estimation of foreperiod duration is greatly improved, and accordingly, RT to the target stimulus is shortened (e.g., Requin et al., 1991; Simon & Slaviero, 1975). Taken together, these studies unequivocally suggest that preparatory activity can be timed more precisely to the moment of target presentation after short than after long foreperiods, resulting in exactly adjusted and therefore fast responses.

In variable foreperiod designs, however, time uncertainty can not be the sole source of temporal preparation effects, as the pattern of results is reversed compared to constant foreperiods. Specifically, RT decreases with increasing variable foreperiod duration. A second source of uncertainty has been suggested to be responsible for this typical pattern of results. In detail, varying the foreperiod randomly from trial to trial produces large variations in the amount of *expectancy* about the time of target stimulus delivery (Elithorn & Lawrence, 1955; Näätänen & Merisalo, 1977; Niemi & Näätänen, 1981). In the variable foreperiod paradigm, foreperiod duration varies randomly from trial to trial, and usually each foreperiod duration is presented with the same frequency within a block of trials, resulting in a rectangular distribution of foreperiod durations. Consequently, at the beginning of each trial, targets might be presented following every possible foreperiod duration with equal probability. During the time course of a single trial, however, the conditional probability of target delivery increases. For example, if the target has not been presented after the shortest foreperiod, the probability increases that it will be presented after one of the longer foreperiod durations. It has been suggested that participants utilize this increase in objective probability to build up expectancies about the upcoming foreperiod duration, and prepare more for moments with a higher probability of target presentation. Accordingly, in the variable foreperiod design, participants are better prepared for target presentation if foreperiod is long rather than short, and thus, RT decreases with increasing foreperiod duration.

Consistent with this notion, Drazin (1961) was able to demonstrate that independent of the absolute duration of foreperiods presented within a block of trials, RT was always shortest for the longest foreperiod duration in the block. More direct evidence for the role of conditional probability stems from studies manipulating the frequency of different foreperiod durations within a block of trials. Increasing the relative frequency of short compared to long foreperiod durations, for example, can greatly reduce the effect of variable foreperiods on RT (Baumeister & Joubert, 1969). Some studies even employed so-called “non-aging” foreperiod distributions, in which the frequency of short foreperiod durations within a block of trials is increased in such a way that the conditional probability of target stimulus delivery remains rather constant throughout the time course of each trial. It has repeatedly been shown that the variable foreperiod effect can be strongly reduced or even eliminated by employing these foreperiod distributions (Frith & Done, 1986; Näätänen, 1970, 1971; Nickerson & Burnham, 1969).

As explained above, a consistently observed feature of the variable foreperiod paradigm is the existence of sequential effects, that is, a dependency of RT on the foreperiod duration of the previous trial. On a first look, the expectancy account can not easily explain these sequential effects. An additional assumption has been made, however, that allows the prediction of such effects. Specifically, it has been assumed that expectancy does not exclusively depend on the conditional probability of the foreperiod in a current trial, but also that participants tend to orient their preparatory activity to the moment at which the target was presented in the previous trial (Drazin, 1961; Karlin, 1959). Thus, when a short foreperiod is followed by another short foreperiod, participants will be especially prepared and respond faster than when a long foreperiod is followed by a short foreperiod. This pattern corresponds to the basic sequential effect of foreperiod duration. The asymmetry of the sequential effect (smaller or absent sequential effect for the longest foreperiod duration) can as well be explained if one considers a strategy of temporal reorienting (e.g., Alegria & Delhaye-Rembaux, 1975; Niemi & Näätänen, 1981). This means that participants can dynamically adjust their expectancy, and therefore also their temporal preparation during the time course of a trial. Specifically, if the target stimulus has not been presented after an expected short foreperiod, participants might notice that their expectancy was incorrect and reprepare for a longer foreperiod duration, therefore enabling a fast response also for the initially unexpected foreperiod. Accordingly, false preparation for a short foreperiod when actually a long one is presented might be less fatal than initial preparation for a long foreperiod when actually a short one is presented. This strategy would result in the typical asymmetric foreperiod effect, because participants would always be relatively well prepared for long foreperiod durations, independent of the previous foreperiod.

The assumption of expectancy and in particular, reorienting, have also found their way into accounts of what was described earlier as the concept of temporal orienting (Chapter 1.1.3), that is, effects of temporal preparation that are evoked by either informative temporal cues or instructions to attend to particular moments in time. First, a cue or instruction would induce expectancy of a particular foreperiod duration, and participants would adjust their preparatory activity to this moment. This might be especially pronounced if the cue is valid in a relatively high proportion of trials, as is often the case in temporal orienting studies (e.g., Correa et al., 2004; Correa, Lupiáñez, & Tudela, 2006; Miniussi et al., 1999). In addition, the possibility of reorienting might have an important influence on the results of temporal orienting studies. For example, and as outlined in Chapter 1.1.3, some studies failed to demonstrate or found strongly reduced effects of temporal cueing in trials with long foreperiods (Coull, Frith, Büchel, & Nobre, 2000; Griffin, Miniussi, & Nobre, 2001; Los & Heslenfeld, 2005; Miniussi et al., 1999). More specifically, if a temporal cue indicates validly that the target will be presented after the short foreperiod, and a short foreperiod is actually presented (valid temporal cue), responses typically will be fast. The same is true for a valid cue indicating a long foreperiod. In contrast, if a cue indicates a long foreperiod, but a short foreperiod is presented (invalid temporal cue), participants will prepare for the long foreperiod and responses will be comparably slow. Most important is the opposite case: if the cue invalidly indicates a short foreperiod, and a long one is presented, participants will notice that the cue was invalid as soon as the duration of the short foreperiod has passed, and they might be able to use this knowledge to reprepare for the long foreperiod duration. Accordingly, despite the invalid cueing they will be able to respond relatively fast after the long foreperiod. As a result, RTs in long foreperiod trials would not differ between trials with valid and invalid cues, and therefore, no cueing effects would be observed after long foreperiod trials. This interpretation received support through the finding that the presence of catch trials, that is trials, in which no target stimulus is presented at all, reinstated the cueing effect for long foreperiod durations, presumably because reorienting is a less effective strategy when the probability of a catch trial is high (Correa et al., 2004; Correa, Lupiáñez, & Tudela, 2006). Therefore, expectancy and reorienting might be major determinants of the effects of temporal orienting on RT.

Apart from these concepts, relatively few theoretical accounts have been proposed to explain temporal orienting effects, probably due to the apparent similarity of temporal orienting to other attentional orienting procedures, as for example spatial cueing, where valid or invalid cues indicate the spatial location of an upcoming target (e.g., Henderson, 1996; Posner et al., 1980; Yeshurun & Carrasco, 1999). Accordingly, the rather descriptive but usually provided account of temporal orienting is that participants somehow direct their attention to the point in time at which a target stimulus is expected, and therefore processing of this target stimulus profits from the allocation of attentional resources when the expected moment coincides with the actual moment of target presentation.

It is important to note that the concepts of time uncertainty and expectancy are also rather descriptive, as they only can predict under which specific conditions temporal preparation will be high or low. Thus, they enable the prediction of performance improvements for certain foreperiod durations presented within certain foreperiod distributions. It remains unclear, however, how exactly such performance improvements are evoked. Specifically, the concepts of uncertainty and expectancy do not specify the underlying processing mechanisms that contribute to the beneficial influence of temporal preparation. As a consequence, it can not be inferred from these concepts which aspects of stimulus processing can profit from temporal preparation, and which aspects remain rather unchanged.

1.2.2. The conditioning account

A competing account of the effects of temporal preparation in foreperiod designs stems from Los and his colleagues (Los et al., 2001; Los & Van Den Heuvel, 2001). This account assumes that the preparation process is based on a mechanism of trace conditioning. Trace conditioning can be regarded as a variant of the paradigm of classical conditioning, in which an associative learning process takes place. During this learning process, an initially neutral stimulus is presented together with a so-called unconditioned stimulus (UCS) that leads to an unconditioned response (UCR). For example, an airpuff to the eye might serve as UCS, as it leads to a reflexogenic eye blink, which therefore is an UCR. As a subject experiences a contingency between a neutral stimulus and the UCS, and thus also between the neutral stimulus and the UCR, the neutral stimulus gets capable of releasing the associated response by itself. Consequently, the neutral stimulus turns into a conditioned stimulus (CS), and the UCR into a conditioned response (CR). In terms of the air puff example, paired presentation of the airpuff with a tone would result in an association of tone and eyeblink. Therefore, the tone would serve subsequently as CS and thus evoke an eyeblink (CR). Trace conditioning, which was proposed by Los and colleagues as a basis for temporal preparation, differs slightly from this basic conditioning paradigm, because here a blank time interval (the trace) separates the CS from the UCS. After a successful conditioning of the CS, a CR develops during the trace that peaks approximately at the moment at which usually the UCS appears. Thus, the trace conditioning paradigm involves a timing component, and therefore is able to explain the evocation of temporally postponed but nonetheless associatively learned responses to a formerly neutral stimulus (for an overview, see Gallistel & Gibbon, 2000).

This trace conditioning paradigm has a strong formal similarity with the classical foreperiod paradigm, and thus, these two paradigms can be related to each other easily (Los et al., 2001; Los & Van Den Heuvel, 2001). Specifically, the warning signal might be seen as CS, which automatically triggers the development of response-related activation (CR) during the foreperiod (the trace). In a constant foreperiod design, after a few trials of learning, this activation is assumed to peak at the moment of the presentation of the target stimulus (UCS). Crucially, a high conditioned activation peak at the moment of target stimulus presentation (that is, at the time a response has to be emitted) enables especially fast responses. The authors assume in addition that the asymptote of this activation peak decreases with longer duration of the foreperiod or trace. This reduction in the peak activation therefore might reflect a decrement in preparatory state as foreperiod duration is prolonged. As a consequence, this account predicts slower responses with increasing foreperiod duration. Thus, the conditioning account can readily account for the effects of constant foreperiods on RT.

Concerning the variable foreperiod paradigm, the predictions of the conditioning account are also in line with the usually observed pattern of results. It is assumed that in a given trial the strength of the conditioned activation for each of the possible moments of target presentation (critical moments) changes dynamically according to the foreperiod that was presented in the previous trial. Specifically, if a target stimulus is presented after a specific critical moment, the associative temporal relationship between warning signal and this critical moment is enhanced (reinforced), and thus activation in the next trial will be especially high at this moment. On the other hand, if at a specific critical moment no target stimulus is presented, the conditioned relationship between warning signal and response-related activation is weakened (extinguished). This, however, is true only for critical moments that are actually bypassed in a trial. Accordingly, extinction will only take place for critical moments after foreperiods shorter than the actually presented foreperiod duration, but not for foreperiod durations longer than the actually presented foreperiod.

For illustration, consider a variable foreperiod paradigm with two foreperiod durations (short vs. long). If the foreperiod in trial *n-1* is long, according to the conditioning view this critical moment will be reinforced. Hence, the activation in the next trial *n* would be high at the end of the long foreperiod duration, thus enabling fast responses if the long foreperiod duration is actually presented. If in trial *n*, however, a short foreperiod is presented, activation at this critical moment will be rather low, as this moment has been subject to extinction in the previous trial. Consequently, RT in the current trial will be rather long. On the other hand, if a short foreperiod in *n-1* precedes the current trial *n*, due to reinforcement the response related activation in trial *n* will peak after the short foreperiod duration. Accordingly, when the target stimulus in trial *n* is presented after the short foreperiod duration, RT will be short. When the target stimulus in trial *n* is presented, however, after the long foreperiod duration, RT will also be rather short, because this critical moment has not been subject to extinction in the previous trial, as it was not presented at all – because the previous trial ended after the short foreperiod.

Taking these different combinations of trials together, the predicted pattern of results closely resembles the effects typically observed in the variable foreperiod paradigm. First, the typical variable foreperiod effect, that is, decreasing RT with increasing foreperiod duration (e.g., Drazin, 1961; Hohle, 1965; Karlin, 1959; Los et al., 2001) results, if one compares predicted RTs for trials with short versus long current foreperiods. Specifically, the trace conditioning model predicts overall longer RT in short foreperiod trials (because in half of the trials rather long RT will be observed as a result of a long foreperiod in the previous trial) than in long foreperiod trials (here RT would be rather short independent of whether foreperiod duration in the previous trial was short or long). Moreover, the RTs predicted for all possible combinations of trials mirror exactly the pattern of sequential effects usually observed in the variable foreperiod paradigm (e.g., Baumeister & Joubert, 1969; Elliot, 1973; Los et al., 2001; Steinborn et al., 2008; Van der Lubbe, Los, Jaśkowski, & Verleger, 2004).

This conditioning view of temporal preparation therefore readily explains the typical patterns of RT performance as well as the presence of sequential effects in conventional foreperiod paradigms without reference to theoretical concepts such as expectancy. Thus, it provides an alternative account to the expectancy-based explanation incorporating conditional probability and reorienting introduced in the previous chapter. As the predictions of trace-conditioning and expectancy are qualitatively and quantitatively very similar, it is hard to find decisive evidence concerning the validity of these accounts.

It is important to note, however, that Los and colleagues (Los & Heslenfeld, 2005; Los et al., 2001; Los & Van Den Heuvel, 2001) do not deny the possibility of a coexistence of trace-conditioning and expectancy-based accounts of temporal preparation. Accordingly, both sources of temporal preparation might be present simultaneously, and even be partly able to override each other. For example, Los and Van den Heuvel (2001) investigated variable foreperiod effects with three different equiprobable foreperiod durations, and included temporal cues in this paradigm that could either be valid, invalid or neutral. They found typical sequential effects in the neutral cue condition. These sequential effects were strongly reduced in the valid cue condition, demonstrating that temporal orienting can override sequential effects. Importantly, in the invalid condition, sequential effects were still present and similar to the neutral condition, suggesting that two mechanisms of temporal preparation were active: one directing temporal attention voluntarily to the invalid cued moment, and one responsible for sequential effects. Therefore, the authors suggested that the observed sequential effects can be better explained by an additional mechanism of trace-conditioning that operates independent of and coexisting to voluntary temporal orienting based on expectancy.

In summary, the main focus of the conditioning account is to provide an explanation for differences in the state of temporal preparation that is based on the principles of trace conditioning. It has been demonstrated that trace conditioning can account well for RT effects typically observed in foreperiod paradigms, that is, constant and variable foreperiod effects as well as sequential effects. An additional process of temporal orienting is needed to account for other known temporal preparation effects, for example as the effects of explicit temporal cueing, because these effects seem to lie beyond the scope of the conditioning account. Similarly to the concepts of time uncertainty and expectancy, the conditioning account does not state explicitly which aspects of stimulus processing should be influenced by temporal preparation. It should be noted, however, that the conditioning account assumes that the learned response consists of response-related activation that develops during the foreperiod. Accordingly, the learned response might be characterized as activation of the motor system, responsible for emitting responses to the target stimulus. Therefore, according to the trace conditioning model it is highly plausible to assume that temporal preparation may affect motor processes. In contrast, according to this account it remains rather unclear how and if premotor stimulus processing, as for example stimulus discrimination or response selection, might be influenced by temporal preparation. In this regard, the conditioning model may be brought easily in accordance with a theoretical account of temporal preparation that assumes a motor locus of temporal preparation, namely, the motor readiness model (Näätänen, 1971). In contrast, a more recent theoretical account of temporal preparation, the early onset model (Rolke & Hofmann, 2007), seems to be at variance with these models because it proposes an influence of temporal preparation in perceptual stages of stimulus processing. The following chapter will introduce these theoretical explanations on the question of what exactly is prepared in more detail.

1.3. What is prepared – Theoretical accounts of the effects of temporal preparation

1.3.1. The motor readiness model

Näätänen (1971) proposed an account for the effects of temporal preparation on RT. He stated that there are permanently fluctuating excitatory and inhibitory motor commands in the motor system. The amount of motor activation at a given point in time corresponds to the difference of excitation and inhibition at this point in time. As soon as this difference, the so called motor readiness, crosses a preset criterion value, namely the motor action limit, a response is emitted (see Figure 1.3).

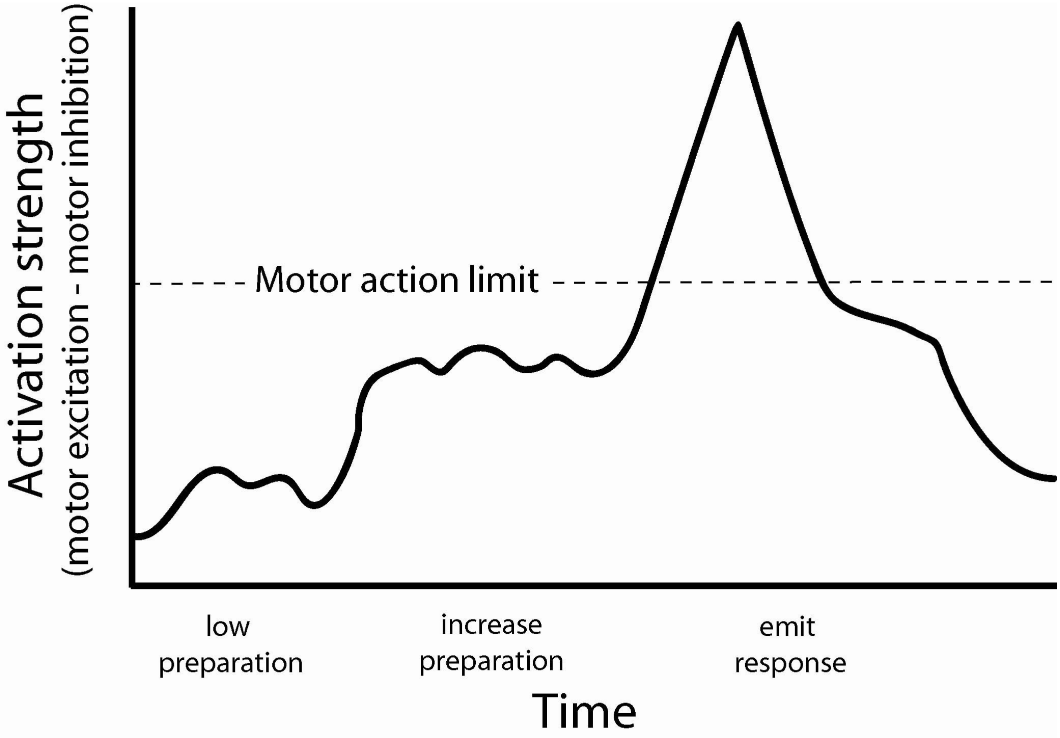

Figure 1.3. The motor readiness model of temporal preparation (modified after Näätänen, 1971). Motor activation strength varies over time and depending on the level of preparedness. If the motor action limit is crossed, a response is emitted.

Importantly, motor readiness is under central control, with the general goal to reach greatest possible motor readiness without crossing the motor action limit erroneously. Keeping motor readiness in the vicinity of the motor action-limit is accomplished by continuous corrections of excitatory and inhibitory motor mechanisms. Most important, motor readiness can also be increased in anticipation of the delivery of a target stimulus (see also Mattes & Ulrich, 1997; Näätänen & Merisalo, 1977). Consequently, the distance between motor readiness and the motor action limit is decreased with increasing temporal preparation. Accordingly, the distance that has to be bypassed by motor activation to evoke a response decreases with improved temporal preparation, and consequently, responses can be emitted especially fast.

The motor readiness model explicitly postulates an influence of temporal preparation on the motor system. Thus, even though this influence of temporal preparation is assumed to be carried and imposed on the motor system by a central cortical process, only the level of motor readiness, and therefore, motor-related response properties should be influenced by temporal preparation. Accordingly, the scope of the motor readiness model might be enlarged to motor variables different from RT (as for example, response force; see Chapter 1.4.1.2). An influence of temporal preparation on premotor processing, however, can not be explained within the framework of the motor readiness model.

1.3.2. Early onset

In contrast to the motor readiness model outlined above, the early onset model (Rolke & Hofmann, 2007) assumes that temporal preparation exerts its influence in premotor processing stages (see also Rolke, 2008). Specifically, this model is based on a criterion model of RT (Grice, 1968; for an overview, see Luce, 1986). The criterion model assumes that after target stimulus presentation, physical stimulus information is converted into internal activation which is accumulated over time. As soon as the amount of accumulated activation reaches a predetermined criterion level, a decision is made and a response can be emitted. Rolke and Hofmann (2007) proposed that under conditions of good temporal preparation, accumulation of the activation can start earlier. As a consequence of such an early onset of the accumulation process, the decision criterion would be reached sooner, and therefore, responses could be made faster than under conditions of low temporal preparation (see Figure 1.4). Therefore, this model can readily explain the typically observed shortening of RT with improved temporal preparation.

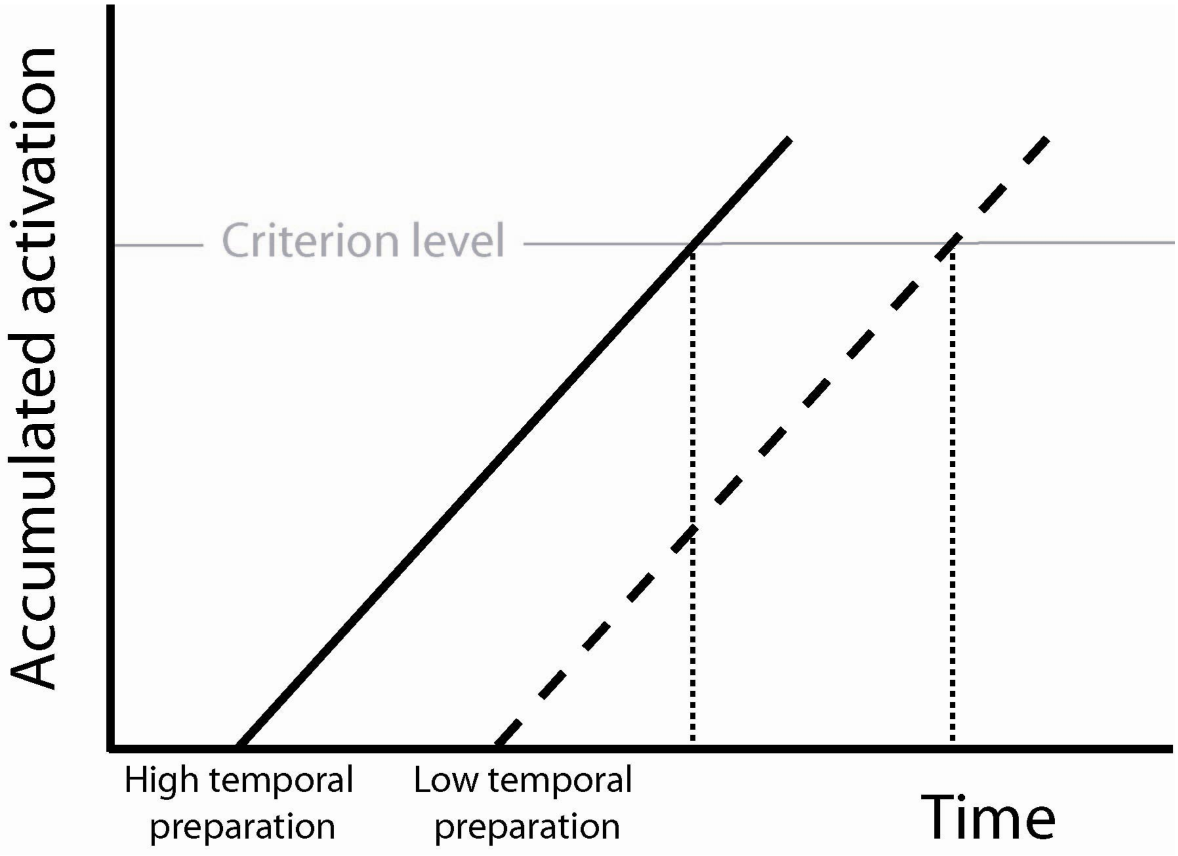

Figure 1.4. The early onset model of temporal preparation (see Rolke & Hofmann, 2007). Internal activation is accumulated over time until a criterion level is reached (dotted lines). Higher temporal preparation enables an earlier start of information accumulation, and thus, the response criterion is reached earlier under conditions of high compared to low temporal preparation.

The accumulated activation in the early onset model is assumed to reflect the amount of information that has been extracted from a physical stimulus input. Importantly, under some conditions, the accumulation process may stop before the criterion level is reached. For example, this might be the case if responses have to be produced very fast or if presentation of the physical stimulus is interrupted at some time during the accumulation process and memory traces of the stimulus are erased. In these cases, decisions about the stimulus have to be made based on the amount of accumulated information that has been reached by the moment at which the accumulation process stopped. Consequently, if good temporal preparation enables the accumulation process to begin earlier, a higher amount of accumulated information would be reached by the time of interruption of stimulus processing when temporal preparation is high rather than low. Presumably, responses that are based on a high amount of accumulated information are more accurate than responses based on less accumulated information. Hence, the early onset model predicts a higher accuracy of stimulus processing when the time available for extracting and accumulation of information about the stimulus is limited. This model therefore suggests that temporal preparation exerts its influence on early stages of information processing that are concerned with the extraction of information from physical stimulus input. Accordingly, and in contrast to the motor readiness model (Näätänen, 1971), the early onset model postulates a perceptual locus of temporal preparation effects.

Given that the early onset model is relatively recent, it is not surprising that most of the existing research on the effects of temporal preparation has focused on the investigation of motor-related variables, as for example activation in the central and peripheral motor system (see Chapters 1.4.2.1 – 1.4.2.4). These studies provide relatively consistent evidence for an influence of temporal preparation on motor processes. The conclusion of a motor locus of temporal preparation is further supported by many behavioural studies employing RT and response force as dependent measures (Chapters 1.4.1.1 and 1.4.1.2). There are, however, also studies that suggest an influence of temporal preparation on premotor processing stages, as for example, studies that demonstrate an influence of temporal preparation on accuracy and on an early proportion of RT (Chapters 1.4.1.3 and 1.4.2.5). Clearly, exact knowledge about which aspects of processing may or may not be influenced by temporal preparation, and of the conditions under which these effects can be observed, is crucial for our understanding of the mechanisms underlying temporal preparation effects. Therefore, the following chapters give a detailed overview over studies providing evidence concerning the locus of temporal preparation.

1.4. Empirical evidence on the locus of temporal preparation

1.4.1. Behavioural studies

1.4.1.1. Reaction time

RT is a measure reflecting the time demands of all stages of information processing taken together. Thus, an effect of temporal preparation on RT per se does not provide any information concerning the question in which processing stage the effect emerged. However, Sternberg (1969) developed the additive factors method as a tool that enables inferences about which processing stage is influenced by a given experimental factor. The additive factors method is based on the assumption that human information processing can be divided into a series of subsequent, distinct, and independent processing stages. For example, a perceptual stage responsible for detection and identification of a target stimulus might forward its output to a central decision stage, in which an appropriate response to the target stimulus is selected. The output of this selection stage is then submitted to a motor stage in which motor programming and finally, execution of the selected response take place. An important consequence of this assumption of distinct, successively operating processing stages is that this architecture enables interferences about the locus of experimental manipulations. Specifically, the additive factors theory predicts that different experimental factors affecting different processing stages must have additive effects on RT measurements. In contrast, if two experimental factors operate at the same processing stage, they should produce an interaction. Accordingly, if the locus of a certain experimental manipulation is known, one can combine this manipulation with another manipulation with unknown locus. Depending on whether an additive or an interactive pattern of results is observed, one can decide whether both factors influence the same or different stages of information processing.

Sanders (1980) employed this logic within a foreperiod experiment to investigate the relationship between preparation and motor processing. Specifically, he manipulated muscle tension by instructing his participants either to tense their muscles at the time they expected the target stimulus, or to relax them completely. The target stimulus itself was a visual light signal that required a reaching movement from a rest button to one of four possible target locations. This procedure enabled Sanders to measure RT – from target stimulus presentation to the moment the rest button was released – as well as movement time – the time between releasing the rest button and pressing the target button. Target stimulus onset was signalled by a visual warning signal that preceded the target stimulus by foreperiod durations of either one or ten seconds, and this foreperiod was varied between blocks of trials. Regarding the effects of instructed muscle tension, Sanders found increased RT and movement time when muscles were relaxed rather than tense. In addition, a typical constant foreperiod effect was observed: RT was shorter in the short compared to the long foreperiod condition. This foreperiod effect, however, seemed to be restricted to RT, because movement time did not differ according to foreperiod duration. Importantly, RT data also showed that foreperiod duration and instructed muscle tension interact: The difference between RT in the tense and the relaxed condition was strongly reduced when foreperiod was long rather than short. This finding was further corroborated in an additional experiment, which, in addition to foreperiod duration and instructed muscle tension, also manipulated relative stimulus-response frequency. Specifically, one of the four target stimuli was presented in 55 percent of all trials, compared to 15 percent for each of the remaining, and thus infrequent, target stimuli. The results basically replicate those of Sanders' first experiment, however, only for the frequently presented target signal: Shorter RT was observed in the tense compared to the relaxed condition, but this difference diminished as foreperiod increased. In contrast, for the infrequently presented target signal, the effect of instructed muscle tension was generally reduced compared to the frequently presented target signal, but not further mediated by temporal preparation. Finally, a third experiment demonstrated additive effects of instructed muscle tension, stimulus-response compatibility, and signal degradation.

Taking these findings and some earlier empirical evidence together, Sanders (1980) developed a detailed model of the different stages of information processing and the variables that can influence each of these stages (see Figure 1.5). Specifically, on basis of the interaction between instructed muscle tension and foreperiod duration he argued that both factors influence a late portion of motor processing. Specifically, Sanders located both variables on a stage called *motor adjustment* stage, which constitutes the transition of central motor processing to the peripheral motor system. Importantly, he interpreted this as evidence in favour of the motor readiness model (Näätänen, 1971). Clearly, the assumption of a motor adjustment stage is closely in line with a dynamic adjustment of motor readiness that serves to regulate the distance between motor readiness and motor action limit, as was proposed by Näätänen. Prior to motor adjustment, Sanders (1980) suggested a *motor programming* stage, in which motor programs are developed in a more abstract fashion and independently of specific muscular states. Moreover, due to the additive effects of instructed muscle tension, stimulus-response compatibility, and signal degradation, Sanders proposed two more independent stages of information processing. First, the *encoding* stage is responsible for detection and identification of the target stimulus, and thus is influenced by variables that render these processes difficult, as, for example, signal degradation. Second, the *choice* or *response selection* stage selects an appropriate response to the perceived target stimulus, and thus, is influenced by stimulus-response compatibility. Due to the complex pattern of interactions between stimulus-response frequency and various other variables, Sanders assigned a special role to this factor by assuming that it may influence each of the processing stages to some extent.

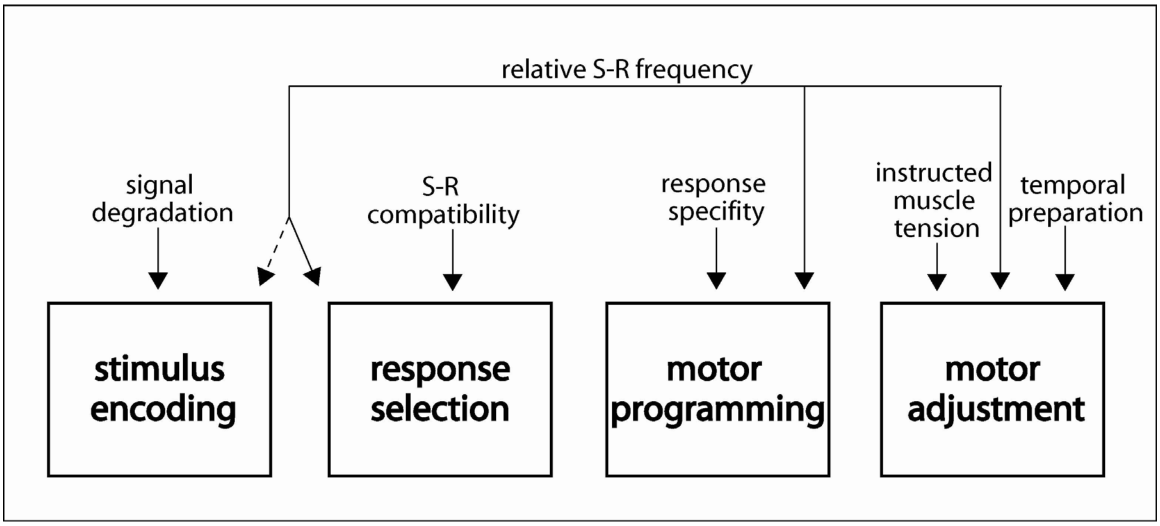

Figure 1.5. Model of distinct processing stages and the locus of various experimental manipulations, including temporal preparation, according to Sanders (1980).

It is important to note that these assumptions derived from Sanders (1980) comprehensive study should be interpreted with care, because it has been demonstrated recently that the specific conditions of instructing muscle tension might have been crucial for the results obtained in Sanders' experiments (Kimura, Imanaka, & Kita, 2002). Specifically, Kimura et al. compared three conditions of instructed muscle tension. In one condition, participants relaxed their muscles. In another condition, and comparable to Sanders (1980) approach, participants self-selected the degree of muscle tension by tensing their muscles just as hard as they subjectively found to be optimal for the subsequent response. In the third condition, the experimenter determined a certain force of muscle tension that should be reached and kept constant throughout the trial. Participants performed a simple RT task under all three conditions. Simple RT in the relaxed condition was significantly longer than in both tense conditions. Interestingly, although the experimental setup guaranteed that the actually implemented muscle tension was matched between the two tense conditions, RT was significantly shorter when the tension level was self-selected by participants than when instructed by the experimenter. A similar pattern of results was found for premotor time, that is, the time between target stimulus presentation and the onset of muscular activity. In contrast, muscle tension did not affect motor time, that is, the time between the onset of muscular activity and the response. These results suggest that the beneficial influence of muscle tension on RT might rather be due to or at least mediated by central processing factors, for example a more efficient allocation of attention to the target stimulus, than to an actual effect of muscle tension itself on preparatory peripheral muscular adjustment.

Nonetheless, Sanders' (1980) conclusion of a motor locus of temporal preparation was corroborated by Spijkers and Walter (1985) and Spijkers (1990), who investigated the relationship between foreperiod duration and motor-related variables other than instructed muscle tension. Specifically, both studies found additive effects of foreperiod duration and movement velocity. In addition, Spijkers (1990) found an interaction of foreperiod duration and the similarity of the movement directions between different response alternatives, that is, response specifity. As movement speed is located in the central motor programming stage (Sanders, 1980), and response specifity exerts its influence in the motor adjustment stage, these results are in close agreement with Sanders' (1980) interpretation. An even more elaborated model stems from Meulenbroek and van Galen (1988), who distinguish three distinct motor substages: motor programming, parametrization, and movement initiation. Participants had to perform a drawing task that varied in number of elements to be drawn, the length of the drawing movement and the direction of the drawing movement. Based on an interaction of foreperiod and the movement length, and additive effects of foreperiod and movement direction as well as number of elements, the authors localized the foreperiod effect in the parametrization stage, in which specific movement parameters of the planned response are assigned to a more abstract motor program previously developed in the programming stage.

The assumption of a motor locus of temporal preparation effects is further supported by studies that found additive effects of foreperiod duration and other variables that are known to unfold their effects in premotor processing stages. For example, foreperiod yielded additive effects with stimulus quality (Frowein & Sanders, 1978), response stimulus intensity (for bimodal stimuli, Bernstein, Chu, Briggs, & Schurman, 1973; for visual stimuli, Niemi, 1979), warning signal intensity (Bernstein et al., 1973; Loveless & Sanford, 1975), the number of response alternatives (Alegria & Bertelson, 1970), and stimulus-response compatibility (Frowein & Sanders, 1978; Posner, Klein, Summers, & Buggie, 1973; Sanders, 1977; Spijkers & Walter, 1985). Since these factors usually are assumed to operate on the perceptual or the response selection stage, the observed additive effects indicate that temporal preparation influences stages located at later processing stages, and thus, motor processing.

There are, however, also some studies employing the additive factors method that found opposite results, providing evidence for a premotor locus of temporal preparation. For example, Niemi and Lehtonen (1982) found interactions between foreperiod duration and target stimulus intensity. This was observed for visual as well as auditory stimuli, however, only when foreperiod duration was varied from trial to trial. In contrast, constant foreperiods did not interact with target signal intensity. Interactions between foreperiod duration and the intensity of auditory – but not visual – target stimuli were also demonstrated by Niemi (1979) and Sanders (1975). As intensity is usually associated with the early processing stage of stimulus identification, these results may be interpreted in favour of a perceptual locus. They should, however, be interpreted only carefully, as it is known that very intense auditory stimuli can also evoke immediate arousal which in turn may increase readiness to respond. Thereby, intense auditory warning signals or response stimuli may overcome the deteriorating influence of a low preparatory state (e.g., Bertelson & Tisseyre, 1969; Mattes & Ulrich, 1997; Sanders, 1977).

There are even some studies that favour a central locus of temporal preparation (Broadbent & Gregory, 1965; Simon & Slaviero, 1975). For example, Simon and Slaviero (1975) investigated the effects of temporal preparation in a simple RT task compared to an two-alternative forced-choice task. Temporal preparation was manipulated by comparing performance in a constant two second foreperiod condition with a condition in which the foreperiod was filled with rhythmic time markers. They observed a more pronounced temporal preparation effect for the two-alternative forced-choice task than for the simple task. As both tasks differ in the need to select an appropriate response to the target stimulus, the authors concluded that temporal preparation influences a central processing stage responsible for stimulus identification and response selection. It should be noted, however, that this conclusion is based on the principles of Donders subtraction method (Donders, 1969). As this method has been subject to strong criticism of its central assumption (pure insertion of additional processing stages; see Külpe, 1893; Luce, 1986), the results of Simon and Slaviero (1975) should be interpreted very carefully.

Broadbent and Gregory (1965) followed another approach to investigate the influence on temporal preparation on central processing. They presented tactile response stimuli that required either two- or four-alternative forced-choice responses, and these responses could be either spatially compatible or incompatible with the location of tactile stimulation. In addition, the target signals were either preceded by a warning signal, which announced the target stimulus with a constant foreperiod of 2 seconds (prepared condition), or there were no warning signals, and the time between two subsequent trials varied unpredictably between 10 and 40 seconds (unprepared condition). Importantly, these authors found an interaction between stimulus-response compatibility and temporal preparation, with the compatibility effect being larger in the unprepared condition. This interaction might be interpreted as evidence for central locus of temporal preparation, as it is assumed that stimulus-response compatibility influences the response selection stage. This result, however, was only significant for two-alternative forced-choice responses, but failed significance for the four-alternative forced-choice response condition. Moreover, temporal preparation was additive with the number of response alternatives, which also is assumed to influence response selection. Whereas the latter effect replicates an additivity of the number of response alternatives and temporal preparation found in a previous study (Alegria & Bertelson, 1970), the observed interaction between stimulus-response compatibility and temporal preparation is at variance with the results of several other studies (Frowein & Sanders, 1978; Sanders, 1977; Spijkers & Walter, 1985). Therefore, this evidence for a central locus of temporal preparation is not unchallenged.

To conclude, the majority of RT findings obtained within the framework of the additive factors method does support the notion of a motor locus of temporal preparation. Some studies, however, also argue in favour of a premotor locus, but these results should only be interpreted with care, as there are alternative interpretations to them that still render a motor locus possible or have failed to be replicated. The additive factors method itself is also subject to some criticism, as its basic assumption of distinct and successively operating processing stages – and thus, the validity of conclusions drawn an basis of this assumption – has been challenged by several authors (see McClelland, 1979; Miller, van der Ham, & Sanders, 1995).

1.4.1.2. Response force

One aspect of overt behavioural responses that is closely related to the motor system is the force with which a response is conducted. Several studies found an effect of temporal preparation on response force, and thus, on the motor system (Giray, 1990; Jaśkowski & Verleger, 1993; Mattes & Ulrich, 1997). For example, Mattes and Ulrich (1997) manipulated foreperiod duration (500, 1750, and 3000 msec) as well as foreperiod distribution (constant vs. variable) in a simple RT task. Typical foreperiod effects on RT were observed: in the constant foreperiod condition, RT increased with increasing foreperiod duration. In the variable foreperiod condition, RT decreased with increasing foreperiod duration. In addition, mean RT was longer in the variable foreperiod condition than in the constant foreperiod condition, reflecting the generally lower expectancy of a certain foreperiod duration when different foreperiods are randomly intermingled rather than kept constant across the trials of a single block. Importantly, a similar pattern of results was also observed with regard to response force, at least for visual, presumably non-arousing stimuli. Responses were executed with less force when constant foreperiods were short, or when variable foreperiods were long. Consequently, high temporal preparation seems not only to enable fast, but also economical and optimally adjusted responses. A similar dependency of response force on temporal preparation was also found in a study by Van der Lubbe, Los, Jaśkowski, and Verleger (2004) which employed variable foreperiods. Interestingly, and in contrast to the RTs obtained within this study, no sequential modulation of foreperiod effects on response force was evident in this study.

Mattes and Ulrich (1997) interpreted their finding within the framework of Näätänen's (1971) motor readiness model, that has been outlined earlier in this Introduction (see 1.3.1). The motor readiness model states that when participants are temporally well prepared for an upcoming target stimulus, the current level of motor activity, that is, motor readiness, is increased. To elicit an overt response, motor activation has to be increased until it reaches a given criterion level for responding, that is, the motor action limit. Since an increase in temporal preparation is assumed to lead to a higher level of motor readiness, a smaller distance between motor readiness and the motor action limit has to be bridged when participants are temporally well prepared. As a consequence, less additional activation is needed to emit a response under conditions that allow good temporal preparation. In contrast, when temporal preparation is low, and thus, the distance to be crossed is high, more additional motor activation needs to be implemented. To ensure that the motor action limit will be reached and a response can be emitted under such conditions of low temporal preparation, it is likely that rather too much than too little additional motor activation will be implemented. This in turn will cause an overshoot of activation when temporal preparation is low, and Mattes and Ulrich (1997) assumed that such an activation overshoot leads to more forceful responses. In contrast, when distance between motor readiness and motor action limit is decreased by high temporal preparation, a smaller and more commensurate amount of additional motor activation can be implemented to elicit the response. Accordingly, there will be less overshoot of activation and thus, less forceful responses when participants can prepare well for the moment of target stimulus representation.

It should be noted that this interpretation of temporal preparation effects on response force as a result of more or less adequate implementation of motor activation can be easily brought in accordance with the results of several studies employing the additive factors method described above (see 1.4.1.1). Specifically, both the notion of Sanders (1980) that temporal preparation influences the motor adjustment stage, and the even more specific interpretation of Meulenbroek and van Galen (1988) that assumes an influence of temporal preparation on the motor parametrization stage, are consistent with the motor activation account: motor adjustment as well as the parametrization stage are responsible for the assignment of specific response parameters (such as activation strength, and thus, force) to a predefined motor program. On a more general level, and theoretically most important, the influence of temporal preparation on response force indicates a motor locus of temporal preparation effects.

1.4.1.3. Accuracy

Despite the great number of behavioural studies investigating the effects of temporal preparation, only relatively few of these studies explored temporal preparation effects on measures of accuracy. Such accuracy measures, however, can be very informative concerning the locus of temporal preparation effects. For example, if temporal preparation improves accuracy in a perceptually demanding task, this might indicate that temporal preparation enhances perceptual processing. The majority of studies in the domain of temporal preparation, however, employed speeded RT instead of accuracy as the main behavioural index of temporal preparation. This is not particularly surprising, given that empirical evidence favoured a motor locus of temporal preparation, and the most prominent theoretical account of temporal preparation effects, the motor readiness model (Näätänen, 1971), assumes such a motor locus as well. From this point of view, RT studies seem to be especially well suited for the investigation of temporal preparation effects, because differences in the speed of motor processing may well be captured in RT, but are rather unlikely to influence accuracy measures[2]. Due to the frequent use of RT studies, however, a possible effect of temporal preparation on the accuracy of premotor processing might have been overlooked. Importantly, in RT studies speed is typically emphasized over accuracy, and the respective tasks are often relatively easy and employ highly discriminable stimuli. Therefore, this type of task places relatively few demands on perceptual processing. Accordingly, in speeded RT tasks, accuracy of responding is typically quite high, and temporal preparation has had rather inconclusive effects on accuracy. For example, some RT studies failed to find an influence of temporal preparation on accuracy (e.g., Alegria & Delhaye-Rembaux, 1975; Sanders, 1975), whereas others demonstrated either improved (e.g., Posner et al., 1973; Spijkers, 1990) or even impoverished accuracy (Bernstein et al., 1973; Bertelson, 1967; Bertelson & Tisseyre, 1969). Therefore, studies requiring speeded responses seem not to be suited for the investigation of effects of temporal preparation on the accuracy of responding.

There are some studies, however, which focussed primarily on the influence of temporal preparation on accuracy measures. To this end, one line of evidence employed detection tasks (Howarth & Treisman, 1958, 1961; Klein & Kerr, 1974; Loveless, 1975; Lowe, 1967; Treisman, 1964; Treisman & Howarth, 1959). For example, Treisman and

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[2] An influence of the speed of processing on the accuracy of performance is possible, however, through speed-accuracy tradeoffs (Luce, 1986; Wickelgren, 1977). For example, if a task demands high response speed, this might be accomplished on the cost of accuracy, because motor responses might have to be emitted before perceptual analysis of the target stimulus or response selection are completed. This however, reflects rather a strategic adjustment of performance to the task requirements than a genuine influence of motor processes on accuracy. Nonetheless, speed-accuracy tradeoffs can be a useful tool to investigate the processes underlying temporal preparation effects (see Experiment 4 in the experimental part of the present work).

Howarth (1959) presented a visual warning signal which preceded an auditory target stimulus by constant foreperiods of different ranges (for example, 1, 3, or 9 seconds in Experiment 1a, and 0, 300, 600, 900, and 1,500 msec in Experiment 2a). During each trial of these experiments, participants heard a sine tone, and the target stimulus that had to be detected was a slight, 30 msec increase in the amplitude of this tone that occurred at the end of each foreperiod duration. Detection thresholds for the target stimulus were estimated according to both the method of limits and the method of constant stimuli. Both methods and employed foreperiod ranges provided a clear picture of results: Detection thresholds increased with increasing foreperiod duration. Accordingly, when temporal preparation decreased, tone amplitude had to be increased relatively more in order to enable participants to detect this increase in loudness. Accordingly, perceptual sensitivity for auditory stimulation seems to be facilitated by temporal preparation. This result was replicated and extended to constant foreperiods of various foreperiod ranges as well as different warning signal intensities and modalities by further studies (Howarth & Treisman, 1958, 1961; Loveless, 1975; Treisman, 1964). In a more recent auditory detection study, foreperiod duration was varied from trial to trial between 0 and 400 msec (Wright & Fitzgerald, 2004). In addition, foreperiod distribution was varied over blocks of trials, in such a way that in each block one of the foreperiod durations was presented in 75 percent of all trials. This enabled participants to build up expectancies about when the target stimulus would be presented. Detection performance varied with these expectancies. Specifically, participants responded more correctly to stimuli presented at or around the expected foreperiod duration. Therefore, this experiment also corroborates the influence of temporal expectations on stimulus detectability. Interestingly, however, detection performance did not vary as a function of foreperiod duration when a rectangular foreperiod distribution was employed. Hence, this study failed to demonstrate a typical variable foreperiod effect on stimulus detectability (see also Howarth & Treisman, 1958).

Three studies also investigated the influence of temporal preparation on stimulus detectability within the visual modality (Klein & Kerr, 1974; Lasley & Cohn, 1981; Lowe, 1967). For example, Lowe (1967) presented a weak visual target very briefly during different intervals of uncertainty. Specifically, participants heard an auditory warning signal and had to detect the potential occurrence of the visual target stimulus within intervals of either 375, 750, 1,500, 3,000, or 6,000 msec following warning signal onset. Lowe demonstrated that stimulus detectability, as measured by d', was highest when the to-be-monitored interval was 750 msec, and decreased for intervals longer or shorter than this. Accordingly, detection of a weak visual stimulus decreases with increasing uncertainty about the time of stimulus presentation. Constraining the generality of these results, however, the specific presentation time of the target stimulus within each of the intervals of uncertainty (i.e., the actual foreperiod duration), however, left detection performance unaffected. Similar results were also obtained in a following study by Lasley and Cohn (1981). Nonetheless, Klein and Kerr (1974) extended these findings to a more typical variable foreperiod paradigm. They randomly intermingled six foreperiod durations ranging from 0 to 1000 msec, and briefly presented a masked visual target on half of the trials. Detectability varied with foreperiod duration, although the observed pattern of results was somewhat atypical of a variable foreperiod effect. Specifically, *d'* increased up to a foreperiod duration of 500 msec, but decreased again, as the foreperiod duration was extended to 1000 msec.

Taken together, these studies suggest that the detection of weak target stimuli is enhanced by temporal preparation. Presumably, this effect does not originate from a motor stage of information processing, but rather points to an improvement of perceptual processes through temporal preparation. For example, the uptake or accumulation of information about the target stimulus might be facilitated by preparatory processes, or, in accordance with signal detection theory (see Macmillan & Creelman, 1991; Wickens, 2001), temporal preparation might lead to a reduction of noise, and thereby render the signal (i.e., the target stimulus) more easily detectable. According to an alternative interpretation, however, this effect might also be located in more central processing stages. Specifically, the warning signal might not influence the perception of the target per se, but rather act as a tool that fosters the decision about signal presence (Posner et al., 1973). For example, at a given point in time, a participant might be insecure about whether the target was really present or not. In this case, he might come more easily to a “target present” decision if the warning signal led him to expect the target at this approximate point in time. In other words, participants might adapt their decision criteria to their state of expectancy (Treisman, 1964)[3]. In accordance with this explanation, it was demonstrated that auditory detection threshold can also be reduced by warning signals that are presented after

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[3] Such a strategy should be reflected in a shift of criterion measures or an increased proportion of false alarms. Unfortunately, many studies failed to report the corresponding values (Klein & Kerr, 1974; Wright & Fitzgerald, 2004) or statistical analyses on these values (e.g., Treisman & Howarth, 1959) that would enable an evaluation of this explanation.

presentation of the target stimulus (Treisman & Howarth, 1959). In this case, warning signals do only provide a temporal marker of the time interval in which the target stimulus might have been presented, however, without enabling advance temporal preparation. Therefore, at least partly, the observed effects of temporal preparation on detection thresholds might be attributable to differences in decisional processes.

Accordingly, the studies on stimulus detectability cited above do not allow a clear decision about which stage of premotor information processing is influenced by temporal preparation. In addition, in some of these studies foreperiod effects were either absent or followed a time course that differed from the commonly observed pattern of foreperiod effects on RT (Klein & Kerr, 1974; Lowe, 1967; Wright & Fitzgerald, 2004). Therefore, it is rather unclear if these results reflect typical effects of temporal preparation. A more promising account to investigate perceptual effects therefore might be to employ tasks that require stimulus discrimination instead of detection, and to monitor not only accuracy but also criterion measures. This was accomplished, at least for the visual modality, by some recent studies. For example, Correa, Lupiáñez, and Tudela (2005) asked their participants to either detect an X or to discriminate whether an X or O was embedded within a rapid serial visual presentation (RSVP) stream of letter distractors. The target stimulus could appear at an early or a rather late temporal position in the RSVP sequence. An explicit temporal cue validly indicated the moment of target presentation in 2/3 of the trials, and was invalid in the remaining trials. The results showed higher values of d' for the detection as well as the discrimination task in validly compared to invalidly cued trials, whereas the criterion measure β did not differ between both cueing conditions. Accordingly, the authors concluded that temporal orienting improves perceptual sensitivity, and hence, influences perceptual processing.

This finding was extended later to the constant foreperiod paradigm (Rolke, 2008; Rolke & Hofmann, 2007). Specifically, Rolke and Hofmann (2007) employed a backward masking procedure and required their participants to judge whether the masked target stimulus (a Landolt square) contained a small spatial gap on either the right or the left side. Short constant foreperiods did not only accelerate RT, but improved also the accuracy of spatial gap discrimination. No influence of foreperiod duration on the response criterion was observed. Importantly, it is assumed that backward masking selectively influences processing in perceptual processing stages, for example, by interrupting stimulus processing and overwriting visual memory traces of the target stimulus (Kahneman, 1968;

Sperling, 1963). Because temporal preparation compensated – at least to some extent – this interrupting effect of masking, this finding argues strongly for an influence of temporal preparation on perceptual processing. In the following, a similar facilitating influence of temporal preparation was also demonstrated in a letter discrimination task (Rolke, 2008). Accordingly, it can be concluded that temporal preparation within the constant foreperiod paradigm enhances perceptual processing also for complex visual stimuli that require the integration of several spatial features.

In summary, the studies cited above demonstrated influences of temporal preparation on the accuracy of performance in perceptually difficult detection or discrimination tasks. Especially some recent studies employing discrimination tasks within the visual modality argue convincingly for a perceptual locus of this effect. These results thus can not be accounted for by the motor readiness model (Näätänen, 1971). Therefore, Rolke and Hofmann (2007) formulated the early onset hypothesis (see Chapter 1.3.2) to explain how temporal preparation may affect perceptual processing. Obviously, there seems to be an apparent inconsistency between these two theoretical assumptions and the respective lines of evidence (i.e., RT and response force measures, which argue mainly in favour of the motor readiness model, on the one hand, and accuracy measures on the other hand). These explanations, however, do not necessarily exclude each other. Rather, temporal preparation might influence different stages of processing in parallel, and an observed effect of temporal preparation within a perceptual processing stage does not rule out an additional effect on response selection or motor processing and vice versa (Rolke & Hofmann, 2007). Consistent with this assumption, Correa et al. concluded that "It makes sense, then, to expect that temporal attention, analogously to spatial attention, can flexibly enhance processing at different stages, according to the most relevant demands of the task at hand" (Correa et al., 2005, p. 334).

1.4.2. Neurophysiological studies

The majority of behavioural results reviewed above are suggestive of a motor locus of temporal preparation effects. In addition, and somewhat inconsistently with this conclusion, some studies also open up the possibility of an additional influence of temporal preparation on premotor (especially perceptual) processing stages. This influence, however, may be restricted to situations in which the respective processing demands are especially high. These conclusions based on behavioural studies were supplemented by a great deal of research on electrophysiological correlates of processing. Consistent with the prepotent notion of a motor locus of temporal preparation, the majority of these studies focussed on electrophysiological instances of motoric processing stages such as electromyographic activation, reflex amplitudes, motor evoked potentials, and the contingent negative variation. More recently, however, investigations of the lateralized readiness potential and post-stimulus evoked potentials also provided some evidence for a premotor locus of temporal preparation. Hence, electrophysiological investigations contribute important evidence on the locus and the mechanisms underlying temporal preparation effects. Eventually, these findings also have led to a renewed research interest in temporal preparation effects. Therefore, the following chapters provide an overview about electrophysiological evidence relevant to the locus of temporal preparation effects.

1.4.2.1. Electromyographic activation

Electromyography is a technique for evaluating and recording the activation signal of muscles. Accordingly, the electromyogram (EMG) reflects the activation of the peripheral motor system, as for example, muscle activation that precedes an overt behavioural response such as a key press. The onset of the EMG of such an overt response can therefore be used to bisect RT into an early and a late phase. The early phase, called premotor time, is the interval between target stimulus presentation and the onset of EMG activity, whereas the late phase, called motor time, is the time interval between EMG onset and the overt response.

Some experimental studies used this way of partitioning RT in order to localise the effects of temporal preparation within the processing stream. Some of these studies failed to demonstrate an effect of temporal preparation on motor time, even though RT varied clearly with the amount of temporal preparation (Botwinick & Thompson, 1966; Sanders, 1980). Because the shortening of RT must therefore be due to a shortening of processes that occur prior to EMG onset, that is, in the premotor time, Botwinick and Thompson (1966) interpreted their results as evidence for a premotor locus of temporal preparation. In contrast, Hasbroucq, Kaneko, Mouret, and Seal (1995) as well as Tandonnet, Burle, Vidal and Hasbroucq (2003) demonstrated a small but significant shortening of motor time with improved temporal preparation. Accordingly, temporal preparation also seems to speed up the duration of motor processes. These effects, however, were rather small relative to the effects of temporal preparation on RT. For example, Tandonnet et al. (2003) reported that short as compared to long constant foreperiods shortened motor time in a choice response task by 3 msec, but the foreperiod effect on RT was 20 msec, and thus, much larger. Accordingly, the observed shortening of motor time alone can not account for the effects of temporal preparation on RT. Indeed, most of the foreperiod effect on RT in Tandonnet et al.'s study was captured in premotor time, which was 16 msec shorter in short foreperiod trials than in long foreperiod trials. [4]

These studies therefore suggest that temporal preparation predominantly affects processing in information processing stages located prior to peripheral muscular activity associated with the overt motor response. Possibly, there is also an influence of temporal preparation on the motor execution of the response, however, this influence seems to be very small. Even if one might therefore be led to conclude that foreperiod primarily influences premotor time, and thus results in a shortening of premotor processing stages, as for example perception and response selection, this conclusion can not be drawn safely. In this regard, the term 'premotor time' is particularly misleading, because preceding the onset of response related muscle activity, more centrally located motor processes take place, as for example motor programming. Therefore, an influence of temporal preparation on premotor time might also stem from a shortening of such more central motor processes. Accordingly, EMG onset is not particularly suited to differentiate between an influence of temporal preparation on premotor processes such as perception and response selection on the one hand, and motor processes on the other hand.

1.4.2.2. Reflex amplitudes

Another empirical approach to localize the effects of temporal preparation within the information processing chain employed reflex amplitudes as an indicator of spinal excitability, and thus, peripheral motor processing. For example, Brunia, Scheirs, and Haagh (1982) presented an auditory warning signal that was followed by a visual target stimulus after a fixed foreperiod of four seconds. Four groups of participants were asked to respond to the target signal by performing a plantar flexion of their right foot, their left

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[4] The effects of foreperiod durations on premotor and motor time do not add up to the observed effect of foreperiod duration on RT. This might be due the fact that these values are derived from averaged data.

foot, or a button press with their left or their right index finger. At various points during the foreperiod and also after target stimulus presentation, in all participant groups an Achilles tendon reflex was elicited by mechanic stimulation in both legs simultaneously. EMG measurements documented the electromyographic activation in the muscles involved in the to-be-performed response as well as in the corresponding muscles of the nonresponding leg. The amplitudes of the reflex responses showed a characteristic modulation during the foreperiod. A first, small activation peak was found for the involved as well as the noninvolved leg approximately 200 msec after warning signal presentation. Later in the foreperiod, the amplitudes of the evoked reflexes decreased until time of target stimulus presentation, and then increased again sharply. Most important, however, reflex amplitudes between the involved and the noninvolved leg differed during this decrease. Throughout the foreperiod, reflexes elicited in the noninvolved leg yielded higher amplitudes than reflexes elicited in the involved leg. This difference even increased shortly before target stimulus presentation, but reversed after target signal presentation. Then, the elicited reflex amplitudes were higher in the leg involved in the intentional response. In the control conditions, in which the responses had to be conducted with either the left or the right hand, no differences in reflex amplitudes between the legs could be observed.

These findings were interpreted as evidence for an influence of immediate arousal and temporal preparation on motor processing. Specifically, the authors suggested that the first, small activation peak that occurred shortly after warning signal presentation reflects the influence of arousal induced by the warning signal. This arousal is supposed to be nonspecific, because it develops in the involved as well as in the noninvolved muscles, and thus, is independent of the requirements of the subsequent response. This interpretation gains additional support in the finding that such an immediate increase of reflex amplitudes (although with a slightly smaller peak amplitude) follows the presentation of a warning signal even when no target stimulus is presented (Semjen et al., 1973), or when no response to the target stimulus is required (Scheirs & Brunia, 1985).

The persisting difference in reflex amplitudes between the involved and the non-involved leg, however, seems to reflect a more specific preparatory process. Specifically, the simple task employed in this study allowed motor preprogramming of the response, and thus, motor preparation of the leg involved in the response. The decrease of reflex amplitudes in this leg compared to the uninvolved leg thus seems to result from an inhibitory preparatory process. This inhibition leads to a suppression of disturbing external influences on the muscles later involved in the response process. Presumably, this suppression evolves through presynaptic inhibition of the Ia afferents to the motoneurons that are involved in the reflex as well as the intentional response. Functionally, this mechanism might serve as a temporary protection against premature responding, because the predefined motor program could easily be set into action by such disturbing external influences. This mechanism seems to be deactivated during and after target stimulus presentation, as indicated by the reversal of the effect: higher reflex amplitudes can then be observed in the involved leg compared to the noninvolved leg. This might reflect that at the time the response actually has to be executed, there is a selective activation of the motoneurons that are responsible for the response.

Even though some studies questioned if the difference between the involved and the uninvolved muscle really stems from an inhibitory mechanism, or merely from an absence of activation in the involved compared to the noninvolved muscle (Brunia, 1983), many studies demonstrated patterns of reflex amplitudes that indicate an influence of immediate arousal and temporal preparation on the peripheral motor system. These studies employed not only the mechanically evoked Tendon reflex (Brunia, 1983; Brunia et al., 1982; Scheirs & Brunia, 1982), but also, for instance, the electrically evoked Hoffmann reflex (Manning & Hammond, 1990; Requin, Bonnet, & Semjen, 1977), or the eye blink reflex (Boelhouwer, Teurlings, & Brunia, 1991; Low, Larson, Burke, & Hackley, 1996; Sollers & Hackley, 1997; Zeigler, Graham, & Hackley, 2001).

In evaluating the significance of these studies for the localization of temporal preparation effects, however, it should be emphasized that these studies investigated the time course of preparatory inhibition during a given fixed foreperiod, and mainly found variations in the amplitude of reflexes elicited during the foreperiod. As spinal excitability clearly is associated with the motor system, these results argue for a motor locus of temporal preparation. For one thing, however, it has been assumed that the origin of these modulations of spinal excitability might be rather supraspinal (Manning & Hammond, 1990; Requin et al., 1977). Second, most of these studies employed one fixed foreperiod, and thus, they do not allow a direct comparison between conditions with different levels of temporal preparation. As a consequence, it can hardly be investigated if those prepraration-related changes that lead to differences in spinal excitability go together with changes in processing duration of intentional behaviour, as shown by RT studies. Accordingly, covariation between the amplitudes of reflexes and RT measures is rather small (Requin et al., 1977; Semjen et al., 1973). In addition, measures of RT in these studies should be interpreted only with care, as the voluntary response may be biased by the elicitation of reflexes during preparation of the response. Indeed, Semjen et al. (1973) showed that RT varies as a function of the point in time during the foreperiod at which the reflexes were evoked.

Another reflex study conducted by Manning and Hammond (1990) partly overcomes these criticisms as these authors varied temporal preparation explicitly. In one experiment, foreperiod was kept constant at one second in one block of trials, and varied from one to four seconds in another block of trials. Hoffman reflexes were elicited at various time points during the foreperiods, and participants had to perform a simple RT task. A typical pattern of RT was observed: responses in the constant foreperiod condition were faster than responses in the trials of the variable foreperiod condition with foreperiod duration of one second. Importantly, it was demonstrated that the amplitude of the reflexes elicited during the fixed foreperiod was consistently smaller than in the variable foreperiod. Accordingly, good temporal preparation not only accelerates RT, but this acceleration also goes together with an attenuation of reflex amplitudes, and thus, preparation-related inhibition seems to be stronger when temporal preparation is high.

A second experiment in Manning and Hammonds' (1990) study focused explicitly on the excitatory influences of temporal preparation that occur after target stimulus onset. A target stimulus was presented following either fixed or variable foreperiods of one or four seconds, and participants were required to perform a simple RT task. Hoffman reflexes were elicited at various time points between target signal and the overt response. Importantly, this time window can be further dissociated in two phases – a premotor phase, during which reflex amplitudes and thus, spinal excitability remain rather constant, and a motor phase that is characterized by the strong increase in reflex amplitudes shortly before the overt response. It is assumed that the premotor phase reflects the duration of premotor processing stages such as stimulus detection and response selection, whereas the motor phase is associated with the execution of the voluntary response. The results showed that the duration of the motor, but not of the premotor phase was influenced by temporal preparation: constant foreperiods led to a shorter motor phase than variable foreperiods. In addition, for constant as well as variable foreperiods, short foreperiods led to a shorter motor phase than long foreperiods. Although this result was somewhat unexpected in the variable foreperiod condition, it was highly correlated with the RT measures that showed a very similar pattern. Since both RT and the duration of the motor phase are latency measures, these results indicate that the shortening of RT by temporal preparation is accompanied by a shortening of late, motor processes.

It should be noted, however, that these influences of temporal preparation on motor processing should still be interpreted with care, as most of the studies cited above required simple tasks from their participants. As noted earlier, simple tasks might be regarded as a special case of temporal preparation, as response selection is not necessary (Donders, 1969), and they allow motor preprogramming of the correct response. Accordingly, preparatory influences on motor processing in these studies might have rather developed as a consequence of the combination of temporal and motor preparation than of temporal preparation alone. Consistent with this criticism, some studies that did not require simple tasks failed to replicate the typical result patterns described above. For example, Requin, Bonnet and Semjen (1977) measured H reflex amplitudes during the foreperiod in a two-alternative forced-choice paradigm, which required either a flexion or an extension of the foot, and varied response probability of these movements. Specifically, one of the responses was required in 75 percent of all trials compared to 25 percent for the other response. The authors still found inhibition of reflex amplitudes during the foreperiod, but this inhibition was less pronounced, and there was no influence of response probability on the amount of inhibition of spinal excitability. Even in go/no-go tasks that allow preprogramming of the correct response but require signal discrimination, a lack of differential inhibition between the involved and the uninvolved leg was observed (Scheirs & Brunia, 1985; Semjen et al., 1973). Therefore, these studies indicate that preprogramming of the response, und thus motor preparation, might be an important determinant for a modulation of spinal excitability during the foreperiod. Accordingly, the evidence for a motor locus of preparation found in reflex studies should be interpreted with care, as it might not withstand in situations that require a choice between responses.

1.4.2.3. Transcranial magnetic stimulation and motor evoked potentials

Another approach, based on a logic quite similar to the measurement of reflex amplitudes, employs transcranial magnetic stimulation (TMS) methods. TMS allows a focused, noninvasive and painless stimulation of the cerebral cortex. Specifically, a brief current pulse is applied to the scalp and evokes a fast change in magnetic field, which in turn evokes an electric current in cerebral cortex. This electric field excites the cortex, and thereby can lead to either excitatory (e.g., muscle activity) or inhibitory effects (e.g., delay of voluntary movements). Importantly, because the anatomical location of these effects depends strongly on the specific cortical area at which the TMS was implemented, this procedure enables mapping of cortical areas to motor or perceptual functions. For example, when specific areas of the motocortex are stimulated, motor evoked potentials (MEPs) can be registered in the muscles corresponding to the respective cortical area.

Hasbroucq, Kaneko, Akamatsu, and Possamaï (1997) used TMS to elicit MEPs in the flexor digitorum superficialis, a forearm muscle that is involved in flexion movements of the fingers, such as key presses. TMS was implemented in a constant foreperiod design, either at the time of warning signal presentation or at the time of target stimulus presentation. Foreperiod duration was either 500 msec or 2,500 msec. To measure behavioural foreperiod effects, participants had to perform a choice RT task with their index and middle finger (both served by the stimulated muscle) after presentation of the target stimulus. A typical constant foreperiod effect was observed: responses were faster in the short foreperiod condition than in the long foreperiod condition. Importantly, the amplitudes of the MEPs in the muscle involved in the manual response were influenced by temporal preparation as well. When TMS coincided with the onset of the warning signal (baseline), MEP amplitude did not differ between both foreperiod conditions. In contrast, MEP amplitudes differed between foreperiod conditions when TMS was implemented at the time of target stimulus presentation. Specifically, in the short foreperiod condition, MEP amplitude at target stimulus onset was reduced as compared to baseline amplitude. In the long foreperiod condition, MEP amplitudes did not differ from baseline. The author argued that this decrease in corticospinal excitability at the end of short foreperiods reflects the state of temporal preparation, with a higher level of preparation reached at the end of short constant foreperiods.

In a second experiment, Hasbroucq et al. (1997) investigated the time course of this preparation-related decrease in excitability. Therefore TMS was implemented at various points during a 500 msec foreperiod. Specifically, MEPs were evoked either 500, 333, 167, or 0 msec before the target stimulus was presented. The amplitude of these potentials decreased progressively during the foreperiod until 167 msec before target stimulus onset, and then remained stable until target stimulus presentation. It was concluded that this decrement in corticospinal excitability during the foreperiod reflects the existence of a preparatory mechanism that serves to increase the sensitivity of motor structures for the forthcoming motor command. Presumably, this is accomplished by an active filtering of task-irrelevant cortical afferents to the motor structures involved in the voluntary motor response. Accordingly, the decreasing MEP amplitudes during the foreperiod observed by Hasbroucq et al. (1997) might be a direct consequence of such a filtering mechanism. Presumably, this mechanism would lead to an improved signal-to-noise ratio in the involved motor structures, and thereby facilitate the interpretation of the forthcoming excitatory command that elicits the voluntary response. More recent studies replicated and generalized the existence of effects of temporal preparation on corticospinal excitability and extended the theoretical assumptions of the underlying mechanisms by emphasizing that temporal preparation effects might even consist of a complex interplay of inhibitory and excitatory cortical activation (Davranche et al., 2007; Sinclair & Hammond, 2008; Van Elswijk, Kleine, Overeem, & Stegeman, 2007). For example, it was suggested that the inhibition of the corticospinal pathway is accompanied by a preparation-related enhancement of cortical activation, and thus, serves especially to suppress premature responses that could otherwise be emitted prematurely by this enhanced activation (Davranche et al., 2007).

This interpretation is in close agreement with the results obtained in reflex studies reviewed above (see Chapter 1.4.2.2). Indeed, an experimental comparison of the effects of both forms of stimulation (TMS and H reflexes) during the foreperiod led to a similar, however not identical, pattern of results (Hasbroucq, Kaneko, Akamatsu, & Possamai, 1999). Both MEP and reflex amplitude decreased during a constant 500 msec foreperiod, but the time course of these decrements differed slightly. This underlines the possibility of different sources of the observed inhibitory effects. Specifically, the authors suggested that the reflex amplitudes might be suppressed by a presynaptic inhibition of the motoneurons' afferents involved in the reflex circuit, whereas the reduced MEP amplitudes might be the result of an activation of cortical inhibitory pathways.

Nonetheless, the cortical pathways that are inhibited by temporal preparation are part of the motor system. Therefore, the results outlined above demonstrate a motor locus of temporal preparation. Importantly, many of these results were obtained while employing two-alternative forced-choice tasks (Davranche et al., 2007; Hasbroucq et al., 1997; Hasbroucq, Kaneko et al., 1999). Such tasks require target stimulus discrimination as well as on-line selection and programming of an appropriate response to the target stimulus.

Therefore, the results of these studies cannot be attributed to a mere influence of temporal preparation on motor preprogramming of the appropriate response. This assumption was further corroborated by a study that investigated the effects of temporal preparation and event preparation simultaneously (Hasbroucq, Osman et al., 1999). Specifically, these authors demonstrated a decrement of MEP amplitudes during a constant foreperiod of 1000 msec. The magnitude of this decrement, however, was not more pronounced when the warning signal did not only provide information about the time of target stimulus occurrence, but also provided information about the required response, and thus, enabled event preparation by reducing the number of possible stimulus-response alternatives. Importantly, behavioural measurements demonstrated that temporal preparation and event preparation both independently reduced RT, and thus both manipulations were successful. The authors concluded that while temporal preparation exerts its effects on the cortico-spinal pathway, event preparation mainly influences more central cortical structures, responsible, for example, for response selection.

This study, however, also showed that TMS by itself also influenced RT. Specifically, RT in trials with TMS was longer than in trials without TMS, and this was more pronounced the later in the foreperiod TMS was implemented. A control experiment revealed that this influence on RT depends probably on the stimulation by TMS itself rather than on a potential influence of the noise bursts that usually accompany the implementation of TMS. Thus, the presence of TMS during the foreperiod seems to evoke either an immediate disruption of temporal preparation, or a slowing or postponement of stimulus processing. Other studies suggested in addition that TMS itself might act as a warning signal, or even evoke immediate arousal (Hasbroucq, Kaneko et al., 1999). As a consequence, experiencing TMS during the foreperiod might overwrite the effects of the actual warning signal and hence, of the foreperiod. Accordingly, observed RTs in TMS trials probably do not reflect typical preparatory processes. It is important to note that this does not deny the interpretation of a motor locus of temporal preparation, however, it can not be safely concluded that these motor effects are also responsible for the preparation-related shortening of processing duration, as usually observed in RT studies.

Such a possible influence of on-line TMS during the foreperiod was avoided, however, in a study by Vallesi, Shallice and Walsh (2007). These authors aimed at investigating the role of different brain regions, especially the right dorsolateral prefrontal cortex, in temporal preparation. To this end, they measured baseline RT in a variable foreperiod paradigm in one block of trials. Then, they implemented off-line TMS for 20 seconds over either the right or left dorsolateral prefrontal cortex, or the right angular gyrus. This procedure evokes a reduced excitability of the stimulated cortical area which outlasts the duration of TMS stimulation by about 20 minutes. After this manipulation, the variable foreperiod effects were measured again. Importantly, and independent of whether a simple or a two-alternative forced-choice task was required from participants, the variable foreperiod effect was strongly reduced compared to baseline by preceding TMS over the right dorsolateral prefrontal cortex, but not by TMS over the left dorsolateral prefrontal cortex or the right angular gyrus. Interestingly, the sequential effects that are typically observed within the variable foreperiod paradigm, were not influenced by TMS, neither over the right or left dorsolateral prefrontal cortex, nor over the right angular gyrus.

Thus, these findings point to the right dorsolateral prefrontal cortex as a major anatomical source of temporal preparation effects in a variable foreperiod design (see also Nagel et al., 2008, for a similar conclusion based on the effects of TMS on saccadic latencies). As this brain region has been associated with processing of temporal information (Lewis & Miall, 2003; Rao, Mayer, & Harrington, 2001), this might be seen as evidence for an endogenous monitoring of the course of time and the associated conditional probability of response signal delivery assumed by classical theories of temporal preparation effects (see Chapter 1.2.1). Most important for the purpose of the present work, this result opens up the possibility of a contribution of premotoric structures to temporal preparation effects. It should be noted that this does not rule out the evidence for a motor locus of temporal preparation obtained in previous studies employing TMS (e.g., Davranche et al., 2007; Hasbroucq et al., 1997; Hasbroucq, Kaneko et al., 1999), but rather suggests that these motor effects might be mediated or even evoked by a modulation of earlier processing stages. Moreover, the results of Vallesi, Shallice and Walsh (2007) also indicate that the typical variable foreperiod effect and sequential effects do not originate from the same anatomical area. On basis of these results, the authors concluded that at least two anatomically and functionally different mechanisms contribute to sequential and variable foreperiod effects. Theoretically important, this conception is at variance with the conditioning account of temporal preparation proposed by Los and colleagues (Los et al., 2001; Los & Van Den Heuvel, 2001), that assumes trace conditioning as a common basis for both effects.

In summary, the results of TMS studies demonstrate that temporal preparation reduces excitability in the cortico-spinal pathway, and thus, influences the motor system. These influences were interpreted as evidence for a protection mechanism that serves to avoid premature responding during the foreperiod. Therefore, the results of these studies are in close agreement with the results of reflex studies cited earlier (see Chapter 1.4.2.2). This motor locus of preparation effects, however, does not allow the conclusion that preparation effects are purely motoric in origin. Recent studies suggest, for example, that temporal preparation also goes together with increased cortical activation, and demonstrate a major involvement of the right dorsolateral prefrontal cortex.

1.4.2.4. Contingent negative variation

The studies cited in Chapters 1.4.2.1 to 1.4.2.3 regarding EMG, reflex amplitudes, and MEP share the common approach to measure the influence of temporal preparation on a rather peripheral component of motor processing, that is, electrical activity in muscles of effectors responsible for motor responses. Even though at least MEPs are evoked by cortical stimulation, and therefore supraspinal in origin, a more direct approach to localize temporal preparation effects consists of a direct investigation of cortical activity associated with temporal preparation. The method of electroencephalography (EEG) allows such a measurement of electrical activity produced by the brain, as this activity can be recorded directly from electrodes placed on the scalp. EEG is noninvasive and enables documentation of brain activity with a very high temporal resolution, but unfortunately rather poor topographical resolution (for an overview, see Jänke, 2005).

Overall brain activity measured by EEG reflects the activity of many different areas, processes, oscillatory rhythms, and artifacts. Therefore, activity related to certain events can only be observed when many EEG segments are averaged time-locked to the respective event, thereby averaging out the randomly distributed background EEG activity. The resulting averaged waveforms allow the investigation of so-called event related potentials (ERPs). ERPs are defined as independent transient electric potential shifts that can be measured prior to, during, or after a perceptual or motor event. Typically, ERPs can be reliably measured in different individuals, are derived from separable sources and indicate one or multiple ongoing processing steps (Jänke, 2005; Luck, 2005). So far, investigation of ERPs has provided much relevant evidence on the locus of temporal preparation, and thus, some of the respective results are presented the following chapters, starting with the contingent negative variation described already by Walter, Cooper, Aldrige, and McCallum (1964).

Walter et al. (1964) recorded EEG signals and discovered a slow negative deflection of the electrical brain activity that develops between the presentation of a warning signal and a target stimulus. Interestingly, this negative potential occurred only if participants had to respond to the target stimulus, and not if no response was required. For example, the authors randomly intermingled trials in which the warning signal was presented without a subsequent target stimulus within a block of trials in which both signals occurred. As a consequence, the amplitude of the negative potential was reduced gradually over trials. Furthermore, an immediate suppression of the negative deflection was observed when participants were informed explicitly that no target stimulus would be presented anymore. On the basis of these results, the authors concluded that this negativity depends strongly on the contingency between warning signal and target stimulus, and thus, they named it the 'contingent negative variation' (CNV). Further results revealed, however, that not the contingency between warning signal and target stimulus itself, but rather the contingency between warning signal and the need to respond was crucial for observing the CNV. Specifically, after participants had learned a given foreperiod duration for some trials, a CNV could still be observed when just a warning signal was presented and participants were instructed to respond at the approximate moment at which they would expect the target stimulus. Although this shows that the CNV can be modulated strongly by participants' expectations and that it is associated closely with planning of voluntary movements, Walter et al. (1964) demonstrated that it can also be observed for classically conditioned reflex responses. Accordingly, the CNV has been regarded as electrophysiological correlate of the preparation of motor responses.

In the following, development of a CNV during the foreperiod has been repeatedly demonstrated, and this phenomenon has proved to be very influential for many research questions centered on the topic of preparatory processing. An important feature of the CNV that was detected subsequently to the research of Walter et al (1964) is that this negative wave is not a unitary phenomenon. Specifically, if the foreperiod between warning signal and imperative stimulus is long enough, it can be observed that the CNV is composed of at least two temporally distinct negative deflections. A first negativity, termed early CNV or orienting (O)-wave (Gaillard, 1976; Loveless & Sanford, 1974) develops shortly after the warning signal. The second negativity, termed late (or terminal) CNV or expectancy (E)-wave, develops prior to the expected occurrence of the target stimulus.

The early CNV has been recognized as part of the orienting response of the individual towards the warning signal. This interpretation is supported by studies that demonstrated that the amplitude of the early CNV is sensitive to the characteristics of the warning signal. For example, Loveless and Sanford (1975) varied the intensity of an auditory warning signal that was presented throughout constant foreperiods of either 1, 3, or 8 seconds und ended with the presentation of a visual target stimulus. It was found that the amplitude of the early CNV (measured between 400 and 700 msec following warning signal onset) increased with increasing warning signal intensity. A similar intensity effect was also found for RT, with faster responses accompanying more intense warning signals. This effect was independent of foreperiod duration, and thus probably due to immediate arousal triggered by the warning signal. Somewhat unexpected, foreperiod duration had also a slight influence on the early CNV: the amplitude of this potential was higher in the one-second foreperiod condition than in the longer foreperiod conditions, which did not differ from each other. This finding, however, might be attributable to the fact that the early CNV within a one-second foreperiod was most probably overlapped by the late CNV component. As the amplitude of this late component strongly decreased with foreperiod duration, an overlap of both CNV components in the short foreperiod would have resulted in an increased early CNV amplitude as compared to longer foreperiod durations. The dependency of the early CNV on characteristics of the warning signal was repeatedly replicated, for example by demonstrating an influence of the modality of the warning signal (Gaillard, 1976) and of the information content of the warning signal (Gaillard & Perdok, 1980) on the early CNV. Specifically, it was shown that early CNV amplitude is higher for auditory than for visual warning signals, and higher for warning signals that are informative about the subsequent task requirements than for uninformative warning signals.

More important for the purpose of the present study, however, is the late CNV component, because this potential has been interpreted as a direct electrophysiological correlate of temporal preparation in motor structures. Convincing evidence for this notion stems for example from a study that investigated whether the late CNV depends rather on expectancy of the target stimulus alone or on the need to prepare a motor response to the target stimulus (Gaillard, 1977). To this end, Gaillard presented auditory warning signals which preceded an also auditory target stimulus by a fixed foreperiod of 3 seconds. To manipulate expectancy of the target stimulus, three different conditions of target stimulus probability were randomly intermixed. Specifically, the frequency of the warning signal (high, medium or low pitch) indicated from trial to trial if the target stimulus would appear at the end of the foreperiod either with 90, 50, or 0 percent probability. In addition, motor preparation was manipulated with a speed-accuracy tradeoff instruction. The participants had to respond to the target stimulus with a simple key press, and were either told to respond as fast as possible, even on the cost of some errors (speed condition), to respond fast but with as few errors as possible (accuracy condition), and to withhold their response until at least one second after target stimulus presentation (detection condition).

The amplitude of the late CNV as measured 200 msec prior to target stimulus onset was influenced by both factors: target stimulus probability and instruction. The main effect of instruction was due to the development of a late CNV in the speed and, somewhat less pronounced, in the accuracy conditions, but not in the detection condition. Similarly, a late CNV only developed when the warning signal indicated that a response signal would appear subsequently with 90 or 50 percent probability, but not if the warning signal indicated that no response signal would follow. Importantly, instruction and probability also produced an interaction: no effects of target stimulus probability were found when the subjects' task was to delay their response. Hereby, it is especially interesting to see that even when the target stimulus was presented with a very high probability of 90 percent (and thus, expectancy of the target was high), no late CNV developed if only a delayed response was required. These results indicate that a late CNV develops prior to presentation of the target, whenever a fast motor response contingent on target stimulus presentation has to be prepared. In contrast, an early CNV deflection could be observed under all experimental conditions, and was only influenced modestly by the instruction. This finding thus supplements the assumption of a functional independence of the two CNV components.

The role of instructions (e.g., Gaillard, 1980; Loveless, 1975; Loveless & Sanford, 1974) and expectancy (e.g., Besrest & Requin, 1973; McAdam et al., 1969; Trillenberg, Verleger, Wascher, Wauschkuhn, & Wessel, 2000) as a determinant of the late CNV component was further investigated by a series of studies that consistently demonstrated the sensitivity of the CNV amplitude to these factors. For example, McAdam et al. (1969) let their participants predict which of two foreperiod durations would be presented in the next trial, and adjusted stimulus presentation in such a way that participants predictions were valid in about 70 percent of all trials. CNV amplitudes varied with participants' predictions: If participants had predicted a short foreperiod, but a long one was presented, CNV amplitude was smaller than when a long foreperiod had been predicted and presented subsequently. Thus, temporal expectancies about target stimulus occurrence influenced the amplitude of the CNV.

As was elaborated earlier, one of the most prominent ways to manipulate temporal expectancies is the variable foreperiod paradigm. Accordingly, one might expect that the amplitude of the late CNV is sensitive to foreperiod duration in this paradigm. Indeed, this was demonstrated in several studies (e.g., Besrest & Requin, 1973; Trillenberg et al., 2000). Trillenberg et al. presented foreperiod durations of 1,300, 1,950 and 2,600 msec according to three different foreperiod distributions: a rectangular and thus aging distribution, a nonaging distribution, and a Gaussian distribution, in which the median foreperiod duration was presented in the majority of trials. As expected they found patterns of RT that are typical for these distribution types: responses grew faster with increasing aging foreperiod, remained stable across foreperiods within the nonaging distribution, and were fastest for the median foreperiod duration within the Gaussian distribution. Thus, RT in all conditions depended strongly on the conditional probability of target stimulus presentation. Importantly, a very similar pattern was also found for the late CNV amplitude. In the nonaging condition no effects of foreperiod were observed for late CNV amplitude, in the aging distribution a monotonical increase of amplitudes with foreperiod duration was found, and in the Gaussian distribution, CNV amplitude was higher for the median and the long foreperiod duration than for the short foreperiod duration. Accordingly, it can be concluded that the amplitude of the late CNV component reflects differences in temporal preparation in the variable foreperiod paradigm.

Typically, RT in the variable foreperiod design is not only affected by the duration of the current foreperiod, but also by the duration of the previously presented foreperiod (see Chapter 1.1.2). Recently, such sequential effects have been demonstrated also for the amplitude of the late CNV (Los & Heslenfeld, 2005; Van der Lubbe et al., 2004). In these studies, CNV amplitude at each possible (critical) moment of target presentation was investigated depending on the foreperiod duration of the previous trial. Similar to the sequential effects usually found for RT, CNV amplitude typically was higher at a given critical moment when this moment was preceded by a foreperiod shorter than or equally long as the foreperiod in the previous trial.

Los and Heslenfeld (2005) did not only vary foreperiod duration, but their warning signal also provided either neutral or valid information about the current foreperiod duration. If the warning signal indicated that the target signal would be presented after the short foreperiod, CNV amplitude at this critical moment was enhanced compared to the condition, in which a long foreperiod was announced by the warning signal. Therefore, this study indicates that temporal orienting by explicit cueing studies may as well influence CNV amplitude. Theoretically important, however, even when the valid cue indicated that a long foreperiod would be presented in the current trial, sequential dependency of CNV amplitude on the foreperiod duration of the previous trial could be found for the critical moment corresponding to the short foreperiod duration. Thus, sequential effects were not fully suppressed even if the valid cue removed any uncertainty about the time of target stimulus presentation. Los and Heslenfeld concluded from this finding that two rather independent processes contribute to temporal preparation: A first component enables intentional preparation based on explicit expectancies evoked by the temporal cues, and a second component corresponds to unintentional preparatory processes due to sequential effects.

Even if expectancy of the target stimulus does not vary, however, temporal preparation can affect the amplitude of the late CNV. Specifically, an influence of foreperiod duration on CNV amplitude has also been repeatedly demonstrated within the constant foreperiod paradigm (Gaillard & Näätänen, 1973; Gaillard, 1976; Loveless & Sanford, 1975; McAdam et al., 1969; Müller-Gethmann et al., 2003). These studies employed constant foreperiods within the range of 50 msec up to 8 sec, and consistently demonstrated an decrease of the amplitude of the late CNV component with increasing foreperiod duration. Accordingly, the extent of motor preparation as indicated by the late CNV seems to depend not only on target stimulus probability, but also on the pure amount of time uncertainty about target stimulus presentation. This dependency of CNV amplitude on temporal regularity was also demonstrated in an alternative paradigm that enables the induction of temporal regularities. Präamstra, Kourtis, Kwok, and Oostenveld (2006) implemented such temporal regularities by presenting a serial choice RT task. In this study, 15-21 target stimuli followed each other and were separated by a constant time interval (in this study, either 1.5 or 2 seconds, varied between series of target stimuli). Thus, in each of these series, temporal expectation about the time of presentation of the next target stimulus was implemented over time. Independent of the absolute duration of the intervals between subsequent target stimuli, CNV amplitude was always highest shortly preceding the next target stimulus, thus demonstrating that participants learned the temporal regularity of the task and adjusted their motor preparation to the respective moments of target stimulus presentation. Importantly, the temporal interval between the next-to-last and the last stimulus was always 1.75 seconds and thus deviated from the temporal structure of the remaining stimulus series. Even though participants reported that they did not get aware of this violation of temporal structure, RT was longer in these deviating trials, and CNV amplitude peaked at the moment the target stimulus would have been expected if it had been presented at the regular, expected time. When the presented interval was longer than expected, CNV amplitude showed a pronounced drop at the expected moment, even if the target stimulus had not been presented yet. Thus, it can be concluded from these studies that the introduction of temporal regularities leads to a synchronization of the late CNV with the expected moment of target stimulus presentation, and if this synchronization is rendered difficult by increasing time uncertainty, CNV amplitude reaches smaller peak values (see also Praamstra & Pope, 2007).

The studies cited above demonstrate convincingly that temporal preparation as implemented by variable or constant foreperiods, foreperiods of previous trials, by informative temporal cues, or by induction of temporal regularities, has an influence on the late CNV component, with enhanced temporal preparation corresponding to a higher amplitude of this negative deflection. Importantly, many studies could demonstrate that CNV amplitude and RT are correlated (Gaillard & Näätänen, 1973; Los & Heslenfeld, 2005; McAdam et al., 1969; Trillenberg et al., 2000). This further corroborates the idea that the CNV reflects the state of temporal preparation, and might even be responsible for foreperiod effects on RT. Because the late CNV usually develops when a motor response has to be produced following target stimulus presentation, it has been concluded that it reflects motor preparation. The neuroanatomical locus of this potential seems to support this conclusion. Specifically, and in contrast to the early CNV component, that is most pronounced over frontal electrode positions, the late CNV has a more central-parietal scalp distribution (Brunia & van Boxtel, 2001; Gaillard, 1976; Loveless & Sanford, 1974, 1975). This is quite consistent with the idea that the late CNV reflects preparatory processes taking place in premotor and motor cortical areas.

In line with this conclusion, many studies have pointed out the remarkable similarity between the late CNV component and the readiness potential (e.g., Gaillard, 1977; Gaillard, 1980). The readiness potential is a slow negative potential shift that precedes any voluntary movement (Kornhuber & Deecke, 1965). In contrast to the CNV which is typically measured within a foreperiod paradigm, and computed time-locked to the presentation of the target stimulus, the readiness potential is investigated for movements independent of target stimulus presentation, and accordingly, averaged time-locked to the overt response. Despite these paradigmatical differences, however, systematic comparisons have led to the view that both potentials may be regarded as functionally equivalent. Specifically, form and topographical midline distribution of both potentials appear very similar, and if the response hand – in case of the CNV – can be preselected, both potentials show a topographical lateralization with more pronounced negativity contralateral to the responding hand[5], indicating a preparatory activation of hand-specific motor areas (e.g., Gaillard & Perdok, 1980; Gaillard, 1980). These results therefore underline the relationship between CNV amplitude and the motor system.

This view of the CNV as an indicator of preparatory processes taking place in the motor system, however, has not remained unchallenged. For example, at least partly, the late CNV component may also be due to negativity that develops in advance of expected relevant stimuli. This so-called stimulus preceding negativity (SPN) can be observed independent of overt responses and thus, can not be explained in terms of motor preparation (Brunia & van Boxtel, 2001). In addition, a high density electrical mapping study by Dias, Foxe, and Javitt (2003) suggested that the CNV is likely to contain a significant contribution of nonmotor structures, as the anterior cingulate cortex and – in close agreement with the TMS study by Vallesi et al. (2007) described in Chapter 1.4.2.3 – of the dorsolateral prefrontal cortex. Finally, some studies suggest that the CNV might as well reflect nonmotor sources of activity such as effort (Wascher, Verleger, Jaśkowski, & Wauschkuhn, 1996) or memory activity (Ruchkin, Canoune, Johnson, & Ritter, 1995).

In summary, the amplitude of the late component of the CNV has been shown to vary with temporal preparation in a variety of paradigms. Because of its contingency on motor responses, its similarity with the readiness potential, its correlation with RT, and its topographical distribution with a maximum over central and parietal electrodes, it has been

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[5] This lateralization of the readiness potential will play an important role in Chapter 1.4.2.5 as this feature is a very useful tool to localize the effects of empirical manipulations within the stages of information processing.

concluded that the late CNV reflects preparatory activity in the motor system. Hence, this argues for a motor locus of temporal preparation. Some studies, however, cast doubt on this conclusion. Also, it is important to note that CNV amplitude, similar to reflex amplitudes and MEP amplitudes described in the previous chapters (but see Manning & Hammond, 1990), is typically investigated during the foreperiod, and thus, prior to target stimulus presentation. Therefore, it may well reflect preparatory activity that occurs in advance of target stimulus presentation. In the majority of cases, the studies cited above employed either simple RT tasks, warning signals that were informative about the subsequent response, or tasks in which participants responded with two fingers of one hand (for exceptions, see Gaillard & Näätänen, 1973; Gaillard & Perdok, 1980; Trillenberg et al., 2000). Accordingly, in these studies, specific motor preparation of the response, or at least, the responding hand, was probable before the target stimulus has been presented. What the CNV does not reflect, however, are changes in target stimulus processing that occur after presentation of the target stimulus. Such changes, if existing, may still be premotor in origin. In the following chapter, an electrophysiological method will be described that, in contrast to the CNV, enables the investigation of temporal preparation effects that follow target stimulus presentation.

1.4.2.5. Lateralized readiness potential

As was described above, the readiness potential (RP) is a negative deflection that develops prior to a voluntary movement (Kornhuber & Deecke, 1965). Importantly, this potential is not symmetrical, but lateralized with a more pronounced negativity in the hemisphere contralateral to the responding hand than in the ipsilateral hemisphere. To derive an index of this lateralization, this negativity is measured over electrode positions C3'and C4', which lie over the handspecific areas of the primary motor cortex. The index of lateralization, i.e., the so-called lateralized readiness potential (LRP), is computed by subtracting the average waveform at the ipsilateral electrode position from the waveform at the contralateral electrode position. As a result of this subtraction process, activation patterns that do not reflect specific activation of the responding hand cancel each other out, and a hand-specific pattern of activation results (e.g., De Jong, Wierda, Mulder, & Mulder, 1988; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). An idealized LRP curve is depicted in Figure 1.8. As an increase in amplitude of the LRP curve indicates that the contralateral hemisphere is more active compared to the ipsilateral hemisphere, it is assumed that the onset of the LRP deflection reflects the moment in which the reponding hand has been selected and specific motor preparation of the this hand begins. Accordingly, and because the source of the LRP is presumably located in primary motor cortex (Kristeva, Cheyne, & Deecke, 1991; Miller, Riehle, & Requin, 1992; Okada, Williamson, & Kaufman, 1982; Osman & Moore, 1993) the LRP has been used as a specific measure of motor activation at a central level (for an overview, see Coles, 1989; Eimer, 1998).

Some studies investigated the LRP in experimental situations in which participants had preknowledge about the responding hand, for example, because responses were always conducted with two fingers of the same hand, or because precues or blocked instructions specified in advance of the trial with which hand the response should be executed (e.g., De Jong et al., 1988; Gratton et al., 1988; Los & Heslenfeld, 2005; Van der Lubbe et al., 2004). In this case, the LRP develops during the foreperiod of the trial, and hence was termed the foreperiod LRP. Interestingly, and partly similar to the CNV, the amplitude of the foreperiod LRP was demonstrated to vary with temporal preparation, as indexed by effects of explicit temporal cuing and variable current and previous foreperiods on this measure (Los & Heslenfeld, 2005; Van der Lubbe et al., 2004). These results can be interpreted as further evidence for a motor locus of temporal preparation.

More important for the present purpose, however, is another variant of the classical experimental design. In this variant, responses have to be conducted with either the right or the left hand depending on the target stimulus, and no prior information about the response hand is provided. In this case, the RP develops after target stimulus presentation, and prior to the response (e.g., Hackley & Valle-Inclán, 1999; Müller-Gethmann et al., 2003; Osman, Moore, & Ulrich, 1995). In this situation, selection of the response hand can not take place prior to the presentation of the target stimulus, but proceeds online during stimulus processing. Accordingly, the onset of the LRP within this experimental setup marks the point in time at which the target stimulus has been detected, identified and an appropriate response to the target stimulus has been selected, because motor preparation and thus, development of the LRP can start only after these processes have been completed. The LRP onset can therefore be used as an electrophysiological landmark that allows a distinction between premotor and motor processing.

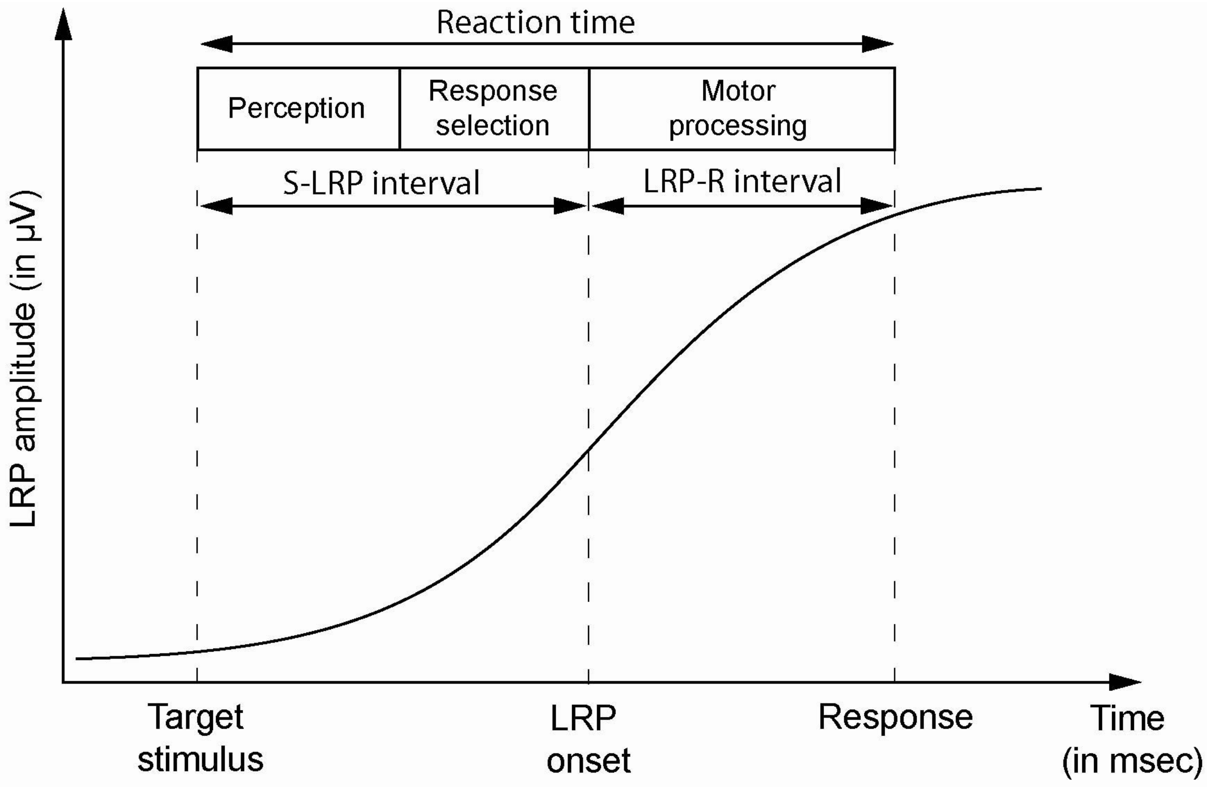

Figure 1.8. Schematic depiction of S-LRP and LRP-R interval and their relation to the duration of premotor (perception and response selection) and motor processing.

To this end, LRP onset is computed according to two different averaging methods: first, the LRP is computed time-locked to the overt response, and the time of LRP onset relative to the response is determined. The interval between the onset of this response-locked LRP and the response (LRP-R interval) thus marks the duration of processes that occur after response selection has been completed, that is, the duration of motor processes. Second, the LRP is computed time-locked to the presentation of the target stimulus, and the LRP onset is determined relative to target stimulus presentation. The interval between target stimulus presentation and onset of the stimulus-locked LRP (S-LRP interval) therefore marks the duration of processes that occur before the completion of response selection, that is, premotor processing. Importantly, S-LRP interval and LRP-R interval are latency measures that index the duration of early and late processing stages, respectively, and thus bisect the total time of stimulus processing which is measured by RT (see Figure 1.8). Therefore, it can be concluded that if an experimental manipulation affects RT, this influence should also be observable either in one or both LRP intervals (see also Mordkoff & Gianaros, 2000). Accordingly, the LRP has been repeatedly used to localize the effects of various experimental manipulations within the information processing stream (e.g., Dudschig & Jentzsch, 2008; Fiedler, Schröter, & Ulrich, 2009; Jaśkowski, Kurczewska, Nowik, Van Der Lubbe, & Verleger, 2007; Osman et al., 2000; Osman et al., 1995; Schröter & Leuthold, 2008, 2009).

Müller-Gethmann et al. (2003) also employed this method of RT bisection, and used it in order to localize the effects of temporal preparation. Specifically, in their first experiment, participants heard an either low-pitched or high-pitched target tone and performed a speeded two-alternative forced-choice response on this target stimulus by responding with the index finger of either their right or left hand. A visual warning signal preceded the target stimulus by a broad range of constant foreperiod durations (ranging from 50 msec to 6,400 msec). No warning signal was presented in a control condition. In a second, otherwise identical experiment, warning signal and target stimulus modalities were interchanged. The results of both experiments were quite similar: the observed RT revealed a typical constant foreperiod effect: RT decreased with foreperiod duration up to foreperiods of about 400 msec, and then slowly increased with increasing foreperiod duration. In addition, RT in conditions with warning signal (with exception of the longest foreperiod duration) was shorter than without warning signal. Theoretically most important, very similar effects of temporal preparation were obtained for the stimulus-locked LRP: The duration of the S-LRP interval decreased until a foreperiod of 200 (Experiment 2) or 400 msec (Experiment 1), and then increased again during the remaining foreperiod durations. High positive correlations (r = .83 and r = .93 in Experiments 1 and 2, respectively) between RT and S-LRP interval further underlined the similarity of the time course of preparation between both measures. In contrast, the duration of the LRP-R interval varied only weakly (Experiment 1) or not at all (Experiment 2) with foreperiod duration. The authors concluded from these results that temporal preparation in the constant foreperiod design influences predominantly the duration of premotor processing stages, whereas the duration of motor processing seems to be largely unaffected by temporal preparation.

Temporal preparation effects on the S-LRP interval and lack of such effects on the LRP-R interval were found also in other studies. For example, within a constant foreperiod design, Hackley, Schankin, Wohlschlaeger, and Wascher (2007) found an earlier onset of the stimulus-locked LRP in a 600 msec foreperiod condition compared to a 3,000 msec foreperiod condition, whereas the duration of the LRP-R interval was not affected by foreperiod duration[6]. Smulders (1993) compared a condition in which subsequent target stimuli were presented with a fixed interstimulus interval with a condition in which this interval varied from trial to trial. Slower responses and a prolonged S-LRP interval were found in the variable interstimulus interval condition than in the fixed condition, but no such influence was found for the LRP-R interval. Similar results were found also in an experiment in which two different preparation conditions were randomly intermixed: A shorter S-LRP interval was observed in trials in which a warning signal preceded the target stimulus by a very short (30 msec) fixed foreperiod, as compared to trials in which no warning signal was presented (Hackley & Valle-Inclán, 1998, 1999). Due to the short foreperiod duration used in these studies, however, the obtained effects on the LRP are more likely due to immediate arousal triggered by the warning signal, than to temporal preparation per se (see also Hackley & Valle-Inclán, 2003).

The LRP studies cited above consistently argue for a premotor locus of temporal preparation. This notion, however, is not unchallenged. In a constant foreperiod design with foreperiod durations of 500 and 2,500 msec, Tandonnet, Burle, Vidal, and Hasbroucq (2003) required a two-alternative forced-choice response from their participants and used surface Laplacian estimation which increases the spatial resolution of the recorded EEG signals. The authors computed the LRP time-locked to the onset of EMG activation in the hand muscle involved in the overt response. Even though they replicated the typical finding that this response-locked LRP onset was not influenced by foreperiod duration, an additional analysis suggested an influence of temporal preparation on motor processes. Specifically, they investigated the pattern of activation and inhibition over the primary motor cortices in both hemispheres separately and found that foreperiod duration affected the start of response-related activation. Accordingly, short foreperiods were accompanied by a shorter time interval between the onset of negativity in the hemisphere contralateral to the responding hand and the onset of the EMG. As this negativity corresponds to motor preparation of the response, this result indicates that temporal preparation influences the duration of motor processing stages.

Interestingly, and in addition to this contralateral negativity, a positive deflection was observed over the primary motor cortex of the ipsilateral hemisphere. This positivity was

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[6] This study aimed at an even more fine-grained localization of the effects of temporal preparation and accomplished this by additional investigation of another lateralized EEG component, the N2pc. This potential can be categorized as a post-stimulus event related potential, and thus, the results derived by Hackley et al. (2007) concerning this component are described in detail in Chapter 1.4.2.6.

interpreted as an electrophysiological correlate of inhibition of the nonresponding hand, which might be implemented in order to avoid erroneous responding with the wrong hand. It should be noted that this idea of such a combination of excitatory and inhibitory motor processes preceding overt responses is closely in line with interpretations derived from reflex and TMS studies (see Chapters 1.4.2.2 and 1.4.2.3). In contrast to the contralateral negativity, the ipsilateral positive deflection was not affected by foreperiod duration. According to the authors, this might be the reason for the lack of effect of foreperiod duration on the LRP-R interval. If the ipsilateral positivity begins earlier than or simultaneous with the contralateral negativity, onset of the LRP might be caused by this positivity alone. Accordingly, if the positivity is unaffected by temporal preparation, LRP onset would be independent of temporal preparation, too. Therefore, Tandonnet et al. (2003) concluded that an existing effect of temporal preparation on the motor system might be nonevident in the LRP-R interval, due to the subtraction procedure used to compute the LRP.

Importantly, the influence of temporal preparation on the onset of contralateral negativity over the primary motor cortex was replicated in a later study (Tandonnet, Burle, Vidal, & Hasbroucq, 2006). In addition, the amplitude of this negativity also varied with foreperiod duration: short constant foreperiods lead to a reduced amplitude of this negativity compared to longer foreperiods. Theoretically important, this result might be interpreted as electrophysiological evidence for the extended version of the motor readiness model (Mattes & Ulrich, 1997; Näätänen, 1971; see also chapters 1.3.1 and 1.4.1.2), according to which less motor activation would be implemented in the short foreperiod condition, because only a small distance from the current motor activation to the motor action limit has to be bridged when temporal preparation is good.

In summary, the LRP enables a bisection of RT in an early premotor and a late motor portion. This feature has been used repeatedly to localize the effects of temporal preparation within the information processing stream. These studies unequivocally indicated that temporal preparation influences the duration of the S-LRP interval, which indexes the duration of premotor processing. In contrast, the LRP-R interval seems to be unaffected by temporal preparation. Therefore, it has been concluded that temporal preparation exerts its influences exclusively on perceptual or central processing stages. This interpretation, however, is in contrast to the majority of results that were obtained in reflex studies, TMS studies, and within the CNV paradigm (see Chapters 1.4.2.2 – 1.4.2.4).

A possible explanation for this might be that both the S-LRP and the LRP-R interval are latency measures that reflect the duration of stimulus processing, whereas in investigations of reflexes, MEPs, and the CNV merely their amplitudes during preparatory processing taking place in the foreperiod were regarded. Therefore, the results of LRP studies seem to be especially conclusive in localizing the effects that temporal preparation exerts on the latency of stimulus processing. The absence of a temporal preparation effect on the LRP-R interval, however, should only be interpreted with care, as the subtraction procedure employed to compute the LRP might possibly mask existing influences of temporal preparation on motor processing.

1.4.2.6. Post-stimulus event related potentials

As outlined above, the CNV and the RP are components that reflect preparatory activity that develops prior to an upcoming perceptual or motor event. Because these components typically occur prior to target stimulus presentation, they can be classified as pre-stimulus ERPs[7]. As outlined above, such pre-stimulus EEG deflections undoubtedly reflect preparatory processes. They are, however, not informative about if and how on-line processing of a target stimulus is altered by temporal preparation. Therefore, recent research has been more interested in the influence of temporal preparation on post-stimulus ERPs, that is, ERP components which typically observed time-locked and in relatively close temporal succession to the presentation of a target stimulus. Post-stimulus ERPs are often characterized according to their polarity (negative or positive deflections), amplitude, latency, and scalp distribution. By convention, early ERPs are typically named according to their polarity and approximate latency or their ordinal position of occurrence (for an overview, see Jänke, 2005; Luck, 2005). For example, N400 describes a negative voltage deflection with a latency of about 400 msec after the presentation of a stimulus, and P2 is the second positive deflection of the EEG trace. The other most important examples for such components are the N1, P1, N2 and the P3 (see Figure 1.9).

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[7] An exception to this classification is provided by situations in which RP (and accordingly, also the LRP) is investigated in alternative forced choice reaction tasks (see Chapter 1.4.2.5). In this recently often employed setup, the RP develops online during target stimulus processing, and therefore, it may also be classified as post-stimulus potential.

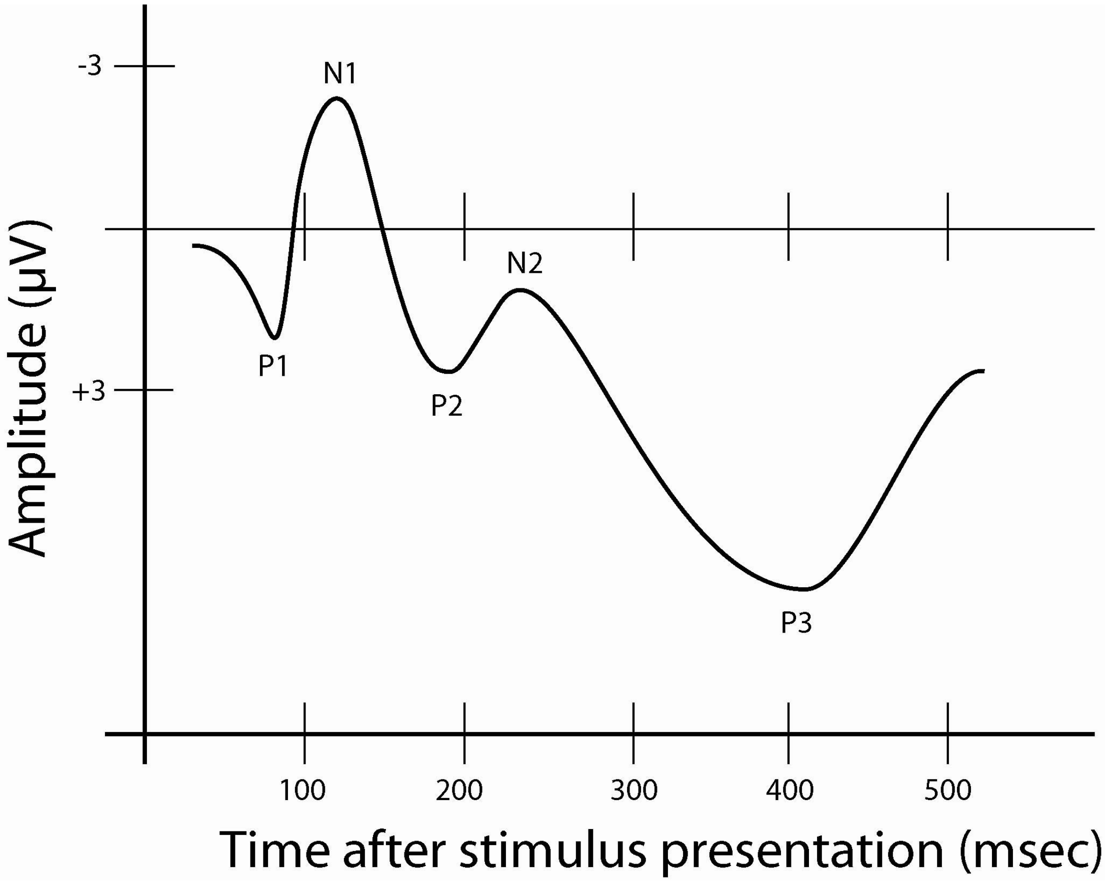

Figure 1.9. Idealized illustration of post-stimulus ERP components P1, N1, P2, N2 and P3.

Importantly, P1 and N1 are relatively early deflections that most probably originate from sensory cortices, and therefore, it has been assumed that their amplitude and latency reflect perceptual processing of a stimulus. Modulation of the amplitudes of these components has also been used as an index of early attentional selection processes influencing perception (e.g., Griffin et al., 2002). Somewhat less clear is the localization of P2 and N2, and therefore their functional significance. However, N2 amplitude is sensitive to the presentation of deviating or unexpected stimuli, seems to originate from extrastriate areas and can also be modulated by spatial attention (e.g., Lange et al., 2006). Finally, P3 is not coupled to a specific sensory system, and originates from various sources, for example, in prefrontal and temporal cortex as well as the hippocampus. It is commonly interpreted as an index of processes coupled to working memory functions, and has therefore been linked to more central processing stages. Specifically, this component is most pronounced for task relevant stimuli that breach previously generated expectations and therefore require extinction and updating of short term memory (cf. Jänke, 2005).

Accordingly, post-stimulus ERPs seem especially appropriate to identify the influences of temporal preparation on successive steps of on-line stimulus processing. Rather surprisingly, only few studies so far used this methodology to localize temporal preparation effects, and these were almost exclusively conducted within the framework of temporal orienting rather than traditional foreperiod setups. The first of these studies was conducted by Miniussi et al. (1999, see also Chapter 1.1.3), who employed a task requiring the speeded detection of a target stimulus. Prior to the target stimulus, informative warning signals were presented which indicated the following foreperiod duration (short vs. long) validly in 80 % of the trials. A typical pattern of temporal orienting effects was found for RT: when foreperiod duration was short, faster responses were observed for validly compared to invalidly cued trials. Probably due to a strategy of temporal reorienting, no effects of cue validity were obtained for target stimuli presented after the long foreperiod duration.

Most important, however, explicit temporal cueing modulated also ERP components. Specifically, for short foreperiods, valid cues shortened the latency of the P3 evoked by the target stimulus and enhanced its amplitude over midline and posterior areas. This influence was interpreted as reflecting preparation and synchronizing of motor processes or temporal sharpening of decisional and response processes. There was also a modulation of the N2, resulting in higher amplitudes of this component for invalid compared to valid trials. As the N2 is found in go/no-go tasks, it has been assumed to be related to response inhibition processes. Miniussi et al. speculated that within their paradigm, however, the amplitude modulation might rather reflect a violation of expectations about target stimulus delivery and the associated response requirements. Most important, however, the latency and amplitudes of the earlier components P1 and N1, which are traditionally linked to perceptual processing, remained unchanged by cue validity. Therefore, the results of this study have been interpreted as evidence for a postperceptual locus of temporal orienting effects.

Another study also reported a mainly postperceptual influence of temporal preparation processes within temporal orienting paradigms (Griffin et al., 2002). These authors conducted two temporal orienting experiments. In Experiment 1, after each of two possible foreperiod durations visual stimuli consisting of concentric squares appeared to the left and right of fixation. A target was present if a square within one of these stimuli was missing. In Experiment 2, only one stimulus was presented, either with a square missing (target) or not. In both experiments, participants had to perform a speeded response as soon as they detected the presence of a target and withhold their responses if no target was present. In addition, explicit cues were presented at the beginning of each foreperiod, and contained valid information about when the target stimulus would be presented in 75 % of the trials. RT results demonstrated that participants were able to flexibly orient their attention to the time indicated by the explicit cue. Importantly, only ERPs to nontarget stimuli presented after the short foreperiod were analyzed, therefore enabling a comparison between identical conditions of stimulation but different states of temporal preparation.

In their second experiment, Griffin et al. (2002) found similar results as Miniussi et al. (1999). P1 as well as N1 were not influenced by temporal orienting, the amplitude of the N2 was enhanced when participants had been cued to the long foreperiod duration, and the latency of the P300 was shortened when participants were cued to the short foreperiod duration. Again, these results indicate that perceptual processing is rather unaffected by temporal orienting. In contrast, the authors reasoned that later processes related to the go/no-go task or detection of deviations of temporal expectancy (N2) as well as response decisions and motor related preparation (P300) may be influenced by temporal orienting. It should be noted that the results of Experiment 1 were not as clear-cut: here, temporal orienting to the short foreperiod evoked a diffusely distributed enhancement of N1 amplitude, increased N2 amplitude and prolonged P300 latency. These rather uncommon results might be due to the fact that in this experiment, probability of foreperiod duration was not sufficiently balanced between cueing conditions, and stimuli were always presented bilaterally, therefore requiring also some spatial orienting[8]. Nonetheless, it can not be ruled out that under these conditions, some influence of temporal preparation on perceptual processing might be present.

This seems to be supported by the finding of synergistic effects of temporal and spatial expectations (Doherty, Rao, Mesulam, & Nobre, 2005). Specifically, in this experiment, participants had to mirror the movement of a ball which crossed a computer screen from left to right at either regular or irregular temporal intervals. In addition, the ball moved either in a linear trajectory over the screen or "jumped" in an irregular fashion

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[8] In another experimental condition, Griffin et al. (2002) cued the spatial instead of the temporal position of the target stimuli. In contrast to temporal orienting, it was shown that spatial orienting can enhance the amplitudes of P1 and N1. This does not only demonstrate the power of Griffin et al.'s experiments to detect potential modulations of these components, but also points out an influence of spatial orienting on early perceptual processing.

over different vertical positions across the screen. Having travelled in such a way across the largest part of the screen, the ball disappeared behind a vertical bar on the screen, and reappeared again on the other side of the bar. When the ball reappeared, participants had to detect whether it contained a black dot or not, and to respond as fast as possible if the dot was present. It was assumed that participants would use the initial movement of the ball to build up expectancies about when and where the ball would reappear. Clearly, such expectations would only be valid when the initial movement was temporally regular and / or spatially linear. Interestingly, the authors found some evidence for a synergistic effect of spatial and temporal expectations. While temporal expectations alone had no effect on the amplitude of the P1, combined spatial and temporal expectations yielded a higher P1 amplitude than spatial expectations alone. Therefore, this study suggests that temporal preparation might only be efficient in influencing perceptual processing when joined by orienting of spatial attention. Interestingly, this study also showed a rather unexpected attenuation of the N1 amplitude by temporal expectation, which was present only at posterior electrodes, but typical N2 attenuation and a shortening of P3 latency. These effects were only present in go-trials. Therefore, it was concluded that temporal preparation alone exerts its influence predominantly on rather late processing stages that are concerned with response inhibition, decision making and response execution. In combination with spatial expectations, however, also earlier, perceptual processing might be enhanced by temporal preparation.

The attenuation of the N1 amplitude through temporal expectation found by Doherty et al. (2005) contrasts, however, with the cueing-related enhancement of N1 amplitude observed in Griffin et al.'s (2002) Experiment 2. A key feature responsible for this difference might be the employment of temporal movement regularities to induce temporal expectation by the former study and explicit temporal cues by the latter study. This was empirically underlined within a variant of Doherty et al.'s (2005) moving ball paradigm (Correa & Nobre, 2008). In this study, the ball moved always in regular steps, but – varying from trial to trial – in different paces from left to right. In valid conditions, the respective pace was maintained during the time the ball disappeared behind the occluder, therefore yielding different durations of the "occlusion foreperiod". In invalid cases, however, the pace of the ball changed behind the occluder, in such a way that the ball appeared either earlier or later than expected. Again, participants had to respond when the ball contained a small dot after it reappeared from behind the occluder. RTs indicated that participants indeed used the rhythm induced by the ball movement to prepare, and accordingly were faster in the valid condition, especially when foreperiod was short, and following longer foreperiods, especially in invalid trials. The basic ERP results of Doherty et al. (2005) were replicated. P1 was neither influenced by validity nor occlusion foreperiod duration, but N1 amplitude in the invalid condition was attenuated progressively by longer foreperiod durations. Also, N2 amplitude was attenuated and P3 latency was decreased with increasing temporal preparation, following the same pattern of results as RT. Therefore, this study demonstrated again consistent influences of temporal preparation on later stages of stimulus processing indexed by N2 and P300, and replicated the negative influence of temporal preparation on N1 amplitude when rhythmic regularities are used to implement temporal expectations.

It seems problematic to derive clear conclusions regarding a perceptual locus of temporal preparation from the inconsistent modulations of N1 amplitude reported above. More convincing evidence, however, was brought forward by Correa, Lupiáñez, Madrid, and Tudela (2006) who hypothesized that the need to perform a target stimulus discrimination, and therefore, rather high perceptual demands, might be crucial for observing a modulation of perception-related ERP components. Accordingly, they employed a temporal orienting paradigm with a centrally located target stimulus, consisting of an X or O, on which participants had to perform a choice RT task. In different blocks of trials, participants were cued with 75 % validity to expect the target after the shortest or the longest of three possible foreperiod durations. As validity effects on RT were most pronounced at the short foreperiod, only ERPs to validly and invalidly cued targets presented after the short foreperiod were compared. Consistent with former studies (Griffin et al., 2002, Experiment 2; Miniussi et al., 1999) employing the temporal orienting paradigm, N2 amplitude was attenuated and P300 latency was shortened by valid temporal cueing. Most interesting, however, was that valid temporal cueing evoked an enhanced amplitude of P1 compared to invalid cueing. Accordingly, the authors concluded that temporal orienting is capable of enhancing visual perceptual processing, given that the task is perceptually demanding. This result seems especially convincing, as all stimuli were presented foveally at fixation, and therefore, no on-line shifts of spatial attention were needed during the trial. Therefore, the observed effects of cue validity can be convincingly attributed to an influence of temporal orienting alone.

Interestingly, temporal orienting effects on ERPs related to perceptual processing in the auditory modality have been observed more consistently than in vision. For example, Lange et al. (2003) presented auditory stimuli at the end of one of two randomly intermingled foreperiod durations. Participants were instructed to attend selectively to the end of one of the foreperiods and to respond only to sounds which were presented at this attended interval and deviated in loudness from more frequently presented standard sounds. ERPs to standards were compared according to whether they were temporally attended or not. Lange et al. (2003) thereby were able to demonstrate that temporal attention enhanced not only P3 amplitude, but also N1 amplitude. This finding of a perceptual locus of temporal orienting effects within the auditory modality was consistently replicated by later studies (Lange et al., 2006; Sanders & Astheimer, 2008), and even extended to the tactile modality (Lange & Röder, 2006).

Closely in line with this more consistent modulation of perceptual processes in audition, some researches have argued that temporal information might be a highly relevant criterion for attentional selection in the auditory modality, and play an important role, for example, in speech segregation and music perception (Astheimer & Sanders, 2009; Tillmann & Lebrun-Guillaud, 2006). In contrast, and probably due to its retinotopic organization, the visual system might primarily rely on spatial information, and make additional use of temporal information only if spatial information is insufficient and / or the task is perceptually highly demanding (Correa, Lupiáñez, Madrid et al., 2006; Griffin et al., 2002; Lange et al., 2006).

Even though preparation-related modulations of the amplitudes of early ERP components as P1 and N1 suggest strongly that temporal preparation exerts some influence in early, perceptual processing stages, it is somewhat unclear how these amplitude modulations can be interpreted with respect to typically obtained RT results. For example, Doherty et al. (2005) reported a small negative correlation of RT and P1 peak amplitude, with greater amplitudes going together with faster responses. Such a relationship, however, was not existent for N1 and N2. In contrast, both P300 peak amplitude and latency correlated with RT, with short latencies and high amplitudes going together with fast responses. Therefore, the question remains open whether N1 amplitude, which is most consistently influenced by temporal preparation, is related to the speed of processing. Rather, it might reflect a preparatory adjustment of excitability of the respective sensory cortex (Lange & Röder, 2006), thereby improving the quality of perception, but not necessarily the speed of processing.

Despite this unclear interpretation of the functional significance of early ERP amplitudes, another factor constrains the interpretation of early ERPs: these components might be superimposed and therefore strongly biased by the offset of the target-preceding CNV (e.g., Hackley et al., 2007). Because the CNV varies dramatically with the state of temporal preparation (see Chapter 1.4.2.4), this can hamper the interpretation of preparation effects on the latencies and amplitudes of early ERPs. Therefore, Hackley et al. followed another approach to determine the locus of temporal preparation. As outlined in Chapter 1.4.2.5, they employed a constant foreperiod design with a two-alternative forced-choice response and computed the S-LRP and the LRP-R interval. This procedure revealed convincing evidence for a premotoric locus of temporal preparation, because only the duration of the S-LRP interval varied with temporal preparation.

Importantly, in this experiment the target stimulus was presented either to the left or right of fixation, therefore enabling the additional computation of the N2pc. The N2pc refers to a lateralized negative deflection with its maximum amplitude at a posterior site contralateral to the hemifield that contains a target stimulus. Occurrence of a N2pc indicates that perceptual analysis of the visual display has progressed far enough to determine the side of target presentation. Because the N2pc is a subtraction measure just as the LRP, it is largely independent of possible contaminating influences of overlapping potentials. By means of N2pc and LRP latency measures, the authors accomplished to split RT in three portions, i.e., the interval between target presentation and the onset of the N2pc, the interval between onset of N2pc and the onset of the stimulus-locked LRP, and the interval between the onset of the response-locked LRP and the response. Even though a small but significant effect of foreperiod duration on N1 latency and amplitude suggested that perceptual processes might somewhat benefit from temporal preparation, only the interval between N2pc and the onset of the stimulus-locked LRP was reliably influenced by temporal preparation. Specifically, short foreperiods led to a shorter duration of this interval, and this effect accounted for a large proportion of the overall effect of foreperiod duration on RT. No significant effects of temporal preparation were found for the intervals between target presentation and N2pc onset, and between the onset of the response-locked LRP and the response. Hackley et al. (2007) concluded from this result that temporal preparation speeds primarily late perceptual processes (occurring after target localization), response selection, or early motor processes, and leaves the duration of early perceptual processes as well as motor processes largely unaffected.

Some supporting evidence for this notion can also be found in the lack of a temporal preparation effect on the latency of the recognition potential (Rudell & Hu, 2001). This potential occurs when recognizable, meaningful images or words are perceived, typically has a latency of less than 300 msec, and an occipital focus. Therefore, it has been related to rather early, nonmotoric processes. It was demonstrated that the latency of this potential did not differ according to whether a warning signal was presented or not. In contrast, the latency of longer latency positive deflections (probably related to the P300) as well as RT was shortened by the presence of a warning signal. Therefore, this study also supports the notion that the effects of temporal preparation on processing speed presumably originate in central rather than early, perceptual or late, motoric stages of information processing.

To sum up: whereas effects of temporal preparation on the latency of P300 and amplitude on N2 have been relatively consistently demonstrated by temporal orienting studies, N1 amplitude was sometimes enhanced (e.g., Hackley et al., 2007; Lange et al., 2003; Sanders & Astheimer, 2008), unaffected (Miniussi et al., 1999) and in other cases even attenuated (Correa & Nobre, 2008; Doherty et al., 2005) by temporal preparation. This might be at least partly due to methodological differences in the way temporal orienting was manipulated. Only one study demonstrated an influence of temporal preparation on P1, the ERP component which can be most confidently be related to early perceptual processing (Correa, Lupiáñez, Madrid et al., 2006). Nonetheless, taken together these studies suggest that under specific conditions temporal preparation can alter perceptual processing. Only one of these studies, however, was conducted within the classical foreperiod paradigm (Hackley et al., 2007). Importantly, based on the latency of subtraction measures which rule out a potentially disturbing influence of other overlapping ERP components, this study suggested nonetheless that the major part of temporal preparation effects on RT can be accounted for by a speeding of central rather than perceptual or motor processing stages.

1.5. Overview and aim of the present experiments

In the previous chapters, an overview over studies that demonstrate strong influences of temporal preparation on a variety of behavioural and electrophysiological measures has been presented. These findings demonstrate that temporal preparation is a ubiquitous phenomenon that can affect various aspects of human behaviour. Despite the high number of empirical investigations of temporal preparation effects, however, still many questions remain open. For one thing, a rather inconsistent picture emerged concerning the stages of information processing that may be affected by temporal preparation. To give a short summary, the majority of behavioural results obtained within the framework of the additive factors method favour a motoric locus of temporal preparation effects (e.g., Sanders, 1980; Spijkers & Walter, 1985). This conclusion is backed up by studies that demonstrate preparation effects on response force (e.g., Mattes & Ulrich, 1997; Van der Lubbe et al., 2004). In addition, a variety of electrophysiological measures further supports the notion of a motor locus of temporal preparation. For example, motor related variables such as reflex amplitudes (e.g., Brunia et al., 1982; Requin et al., 1977), MEPs (e.g., Davranche et al., 2007; Hasbroucq et al., 1997), and the CNV (e.g., Gaillard & Näätänen, 1973; Loveless & Sanford, 1975) have been demonstrated to vary with the degree of temporal preparation. Taking these findings together, it is not surprising that the view of a motor locus of temporal preparation has been widely acknowledged in psychological research, and has governed empirical investigations as well as theoretical reasoning about temporal preparation for a long time.

This motor view of temporal preparation has utterly neglected, however, the findings of some early studies that demonstrated an influence of temporal preparation on stimulus detection, and thereby suggested a perceptual locus of temporal preparation (e.g., Klein & Kerr, 1974; Lowe, 1967). Only in the last decade, research showed a renewed interest in the possibility of an influence of temporal preparation on premotor stages of information processing. Indeed, three lines of evidence made important empirical contributions to this topic. First, LRP studies suggested that temporal preparation evokes a shortening of the premotor portion of RT (e.g., Hackley & Valle-Inclán, 2003; Müller-Gethmann et al., 2003). Second, perceptual discrimination tasks demonstrated that spatial resolution within the visual modality was enhanced by temporal preparation (e.g., Correa et al., 2005; Rolke & Hofmann, 2007). Third, investigation of post-stimulus ERPs showed that – even though somewhat inconsistently – early perception-related potentials can be enhanced by conditions that enable temporal preparation (e.g., Correa, Lupiáñez, Madrid et al., 2006; Lange et al., 2003). All these results contrast with the traditionally assumed motor locus of temporal preparation effects.

These recent empirical findings also imposed a problem on the most common theoretical explanation of temporal preparation effects, that is, the motor readiness model (Näätänen, 1971). This model postulates that temporal preparation influences the motor system by enhancing motor activation. This notion can explain preparation effects on RT as well as on force, and can also be easily brought into accordance with modulations of spinal and sensorimotor cortical excitability observed in electrophysiological studies. This model, however, is not capable of explaining temporal preparation effects in premotor processing stages. Consequently, the early onset model has been proposed to account for temporal preparation effects on perceptual processing (Rolke & Hofmann, 2007). According to this model, accumulation of information about a stimulus can start earlier when one is temporally prepared for the presentation of this stimulus. Even though this account provides a plausible and viable explanation of temporal preparation effects on perceptual processing stages, so far there is no direct evidence for the notion of early onset.

Based on these empirical findings and theoretical assumptions, three major questions for the present work emerged. In which processing stage are temporal preparation effects located? Is temporal preparation associated with a genuine improvement of the accuracy of perceptual processing? And finally, what mechanism is responsible for temporal preparation effects? In the following, a brief overview is given about how the present work addressed these issues empirically.

First, the chronophysiological evidence for a shortening of the premotor RT portion obtained within LRP studies contrasts sharply with RT results derived from behavioural studies within the framework of the additive factors method, which argue for a motor locus of temporal preparation effects on RT. Importantly, both lines of evidence employ latency measures, that is, they investigate temporal preparation effects on the speed of processing. The contradictory results obtained for these latency measures can not easily be explained, and therefore, independent evidence is needed to distinguish between a motor or premotor locus of temporal preparation effects. Even though many studies investigating reflex amplitudes, MEPs, and the CNV support the notion of a motor locus, it should be noted that there seems to be no straightforward relation between these amplitude measures and processing speed. Therefore, although these studies indicate a motor locus of temporal preparation effects, it is not clear if these effects also constitute the source of the typically observed preparation-related shortening of RT. Therefore, Experiment 1 of the present work aims at obtaining further and independent evidence regarding the locus of temporal preparation effects on the speed of responses. To this end, the psychological refractory period (PRP) paradigm was used (see Pashler & Johnston, 1998). Similar to the LRP, the PRP paradigm enables the bisection of RT in a premotor and a motor phase. By investigating which of these portions of RT is affected by temporal preparation, one can therefore determine the locus of temporal preparation effects.

The second open question that is tackled by the present work is concerned with a potential influence of temporal preparation on perceptual processing. Besides some early research on stimulus detectability, recent studies demonstrated a beneficial influence of temporal preparation on the discrimination of spatial stimulus properties within the visual system. Obviously, if this effect of temporal preparation on spatial resolution reflects a genuine improvement of processing in perceptual stages, beneficial influences of temporal preparation should be also evident for (a) different perceptual tasks and (b) within different modalities. To test these assumptions, five experiments were conducted to investigate whether temporal preparation influences the temporal resolution within the visual system, and pitch discrimination within the auditory modality, respectively. To further extend the already existing studies requiring stimulus discrimination, which employed d’ as an index of processing accuracy, the present work follows another psychophysical approach. Specifically, adaptive and non-adaptive methods have been employed to determine perceptual thresholds for the discrimination of temporal order and pitch (e.g., Kaernbach, 1991). Accordingly, if temporal preparation improves perceptual processing, discrimination thresholds should decrease with increasing temporal preparation.

To anticipate the results of these experiments: they allow rather clear-cut conclusions about the locus of temporal preparation effects. Specifically, the PRP study shows that the temporal preparation effect on RT is located exclusively in the premotor portion of RT, and the experiments assessing discrimination thresholds demonstrate a beneficial influence of temporal preparation on perceptual processing. Based on these results, the third open question emerged: By which mechanism can such a beneficial influence be accomplished? Contingent on the finding that processing in premotor processing stages is speeded by temporal preparation, it seems reasonable to expect an influence of temporal preparation on dynamic aspects of stimulus processing. For example, temporal preparation might enhance the rate of information accumulation in the perceptual system, or – as stated by the early onset model – enable an earlier onset of information accumulation. The final experiment of the present work is directly aimed at this theoretically important issue.

Specifically, a speed-accuracy tradeoff (SAT) procedure was employed in which the speed demands for responding are manipulated in order to obtain the SAT function underlying RT performance (e.g., Wickelgren, 1977). The investigation of temporal preparation effects upon specific parameters of these SAT functions enables determining whether dynamic aspects of stimulus processing are affected by temporal preparation. Indeed, such an influence on response dynamics could be demonstrated in the final experiment of the present study. More specifically, temporal preparation seems to lead to an earlier onset of accumulation of evidence about a perceptual event.

2. EXPERIMENTAL PART

2.1. Temporal preparation influences early stages of information processing: Evidence from the psychological refractory period paradigm[9]

As was outlined in the Introduction, an unresolved issue of theoretical importance concerns the locus of temporal preparation within the processing stream from input to the corresponding response. A review of the relevant studies provided a somewhat mixed picture: Several studies employing the additive factor method (Sternberg, 1969) have concluded that a manipulation of temporal preparation changes the speed of motor processes (e.g., Sanders, 1980; Spijkers & Walter, 1985). This conclusion has been supported by several other studies which assessed foreperiod effects on measures other than RT, such as response force (Mattes & Ulrich, 1997; Van der Lubbe et al., 2004), reflex amplitudes (Brunia et al., 1982; Requin et al., 1977), transcranially evoked motor potentials (Davranche et al., 2007; Hasbroucq et al., 1997), and the CNV (Gaillard & Näätänen, 1973; Loveless & Sanford, 1975). According to this prevailing view, an enhancement of temporal preparation shortens the late motoric portion of RT.

Other theorists, however, hold that temporal preparation operates at an earlier level. Especially convincing is the evidence from recent chronopsychophysiological studies that challenged the notion that temporal preparation operates exclusively or primarily at a late motoric level (Hackley & Valle-Inclán, 1998, 1999; Müller-Gethmann et al., 2003; Smulders, 1993). These studies employed the LRP to bisect RT into an early and a late stage. Contrary to the prevailing view, the results of these studies have shown that a enhanced temporal preparation shortens the early but not the late portion of RT. Hence, these studies support the conclusion that temporal preparation facilitates the speed of rather early processes. As noted above, response force and other amplitude measures provide indisputable evidence that temporal preparation does influence late motor processes. Hence, what the LRP data indicate is simply that temporal preparation effects on the *speed* of response initiation are due to some other, earlier mechanism.

In the experiment reported below, the psychological refractory period (PRP) paradigm was used to obtain further and independent evidence regarding the locus of temporal

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[9] The data reported below have been published in: Bausenhart, K. M., Rolke, B., Hackley, S. A., & Ulrich, R. (2006). The locus of temporal preparation effects: Evidence from the psychological refractory period paradigm. *Psychonomic Bulletin & Review, 13*, 536-542.

preparation effects on the speed of response initiation (Pashler, 1994; see Pashler & Johnston, 1998, for a review of this paradigm). This paradigm was originally developed to resolve the temporal microstructure of dual-task interference, but more recently, it has also been employed to localize the effects of several experimental manipulations (McCann & Johnston, 1992; McCann, Remington, & Van Selst, 2000; Miller & Reynolds, 2003; Pashler, 1989; Ruthruff, Johnston, & Van Selst, 2001; Ruthruff, Miller, & Lachmann, 1995).

The PRP paradigm requires participants to perform two successive yet temporally overlapping RT tasks. For example, in the experiment reported below, the first target stimulus (S1) required color discrimination. Specifically, a red or green square appeared on the monitor. Depending on the color, participants were asked to press a key with the middle or index finger of the left hand. The second target stimulus (S2) was a high-pitched, medium-pitched or low-pitched tone, which appeared shortly after S1. Participants were asked to respond to the tone with the other hand, indicating with the index, middle or ring finger whether the tone was low-, medium-, or high-pitched, respectively.

The standard PRP finding is that RT for S2 (RT2) increases dramatically as the stimulus onset asynchrony (SOA) between S1 and S2 decreases. Although various accounts of this PRP effect have been proposed (e.g., Meyer & Kieras, 1997; Navon & Miller, 2002; Tombu & Jolicœur, 2003), there is strong evidence for the assumption that the PRP effect emerges from a response selection bottleneck (e.g., McCann & Johnston, 1992; Pashler, 1984, 1994; Sommer, Leuthold, & Schubert, 2001; Welford, 1952). Accordingly, response selection for S2 cannot begin until the response selection process for S1 has finished. Specifically, this bottleneck model assumes that response selection constitutes a single-channel process, which cannot serve both tasks simultaneously. This central processor receives its input from perceptual processes and forwards its output to motor processes. These pre- and post-bottleneck processes proceed without interference from the other task.

The bottleneck model involves an effect-propagation property (see Miller & Reynolds, 2003), which can be employed as a tool to assess the locus of temporal preparation (Figure 2.1)[10]. First note that at short SOAs (e.g., 50 msec), the perceptual outcome resulting from S2 processing cannot be fed into the central processor (the bottleneck) until this processor has selected the first response and forwarded this information to the motor system. At long SOAs, no such S2 processing delay is present. This bottleneck model therefore can account for the

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[10] The "effect-propagation" paradigm is one of two methods by which PRP can be used to localize effects. An alternative, and more common method, is the "locus-of-slack" paradigm. See Miller and Reynolds (2003) for a lucid explanation of the two methods.

typically observed PRP effect (increasing RT2 with decreasing SOA). Crucially, at short SOAs, any experimental manipulation (e.g., of temporal preparation) that would affect the duration of Task 1 perceptual processing or response selection will be propagated to Task 2 processing and thus affect RT2 accordingly.

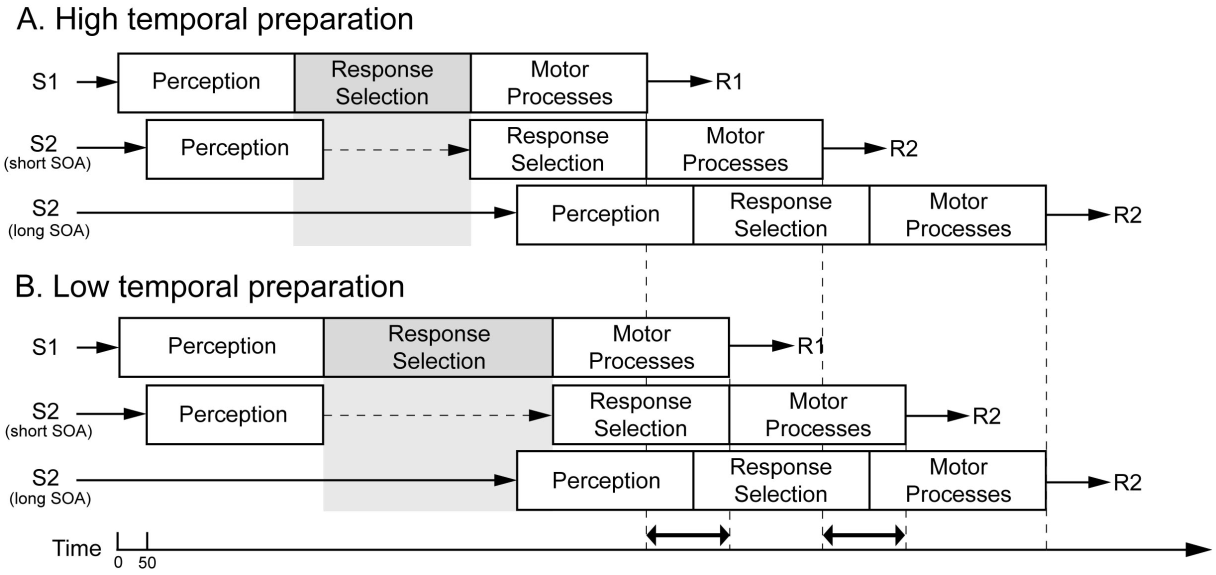

Figure 2.1. Illustration of the effect propagation property of the bottleneck model. This figure depicts dual-task processing in accordance with the bottleneck model for trials with short and long stimulus onset asynchrony (SOA) and for trials with high (Part A) and low (Part B) temporal preparation. It is assumed that temporal preparation affects the duration of **premotor processing stages** (perception and response selection). *Part A:* The upper sequence illustrates the duration of perceptual processing, response selection, and motor processing for Task 1. The durations of these stages do not depend on the SOA. The middle sequence shows the same processing chain for Task 2 at a short SOA. Note that response selection for Task 2 cannot begin until response selection for Task 1 has finished; this waiting period is represented by the gray background. The third sequence of Part A depicts Task 2 processing at a long SOA. Here, response selection for Task 2 can immediately begin after Task 2 perception has finished. *Part B:* This is identical to Part A except that, due to low temporal preparation, a longer premotor processing in Task 1 emerges. A comparison of Part A and B illustrates that an increase in RT1 associated with lower temporal preparation would completely propagate to RT2 at a short SOA. At a long SOA, however, this effect on RT1 would no longer be propagated to RT2 (cf. dashed vertical lines).

For example, suppose an experimental manipulation prolongs premotor stages of information processing (i.e., perception and response selection) of Task 1 by some time (Figure 1B). At short SOAs, the initiation of the central bottleneck process by Task 2 will also be delayed, and RT2 would consequently be prolonged by this amount of time. At long SOAs, however, Task 2 needs not to wait until the central processor is finished with Task 1 processing and effect propagation should no longer occur. Therefore, if temporal preparation affects early processes of Task 1, effect propagation to RT2 should be observed at short but not at long SOAs. It is important to note that this pattern of results is predicted independent of whether the experimental manipulation affects the duration of the perceptual processing stage, the central processing stage, or both stages in common.

If, however, the experimental manipulation operates on motor processes, no such effect propagation should be observed for RT2 at either short or long SOAs (see Figure 2.2). This is because the prolongation of RT1 emerges in the motor processing stage, and this stage can proceed in parallel with Task 2 processing. Consequently, any motor effect of an experimental manipulation on RT1 would not affect the waiting time for Task 2 processing. Therefore, only the typical PRP effect, that is increasing RT2 with decreasing SOA, but no effect propagation for RT2 would be expected if a Task 1 manipulation affects the motor processing stage.

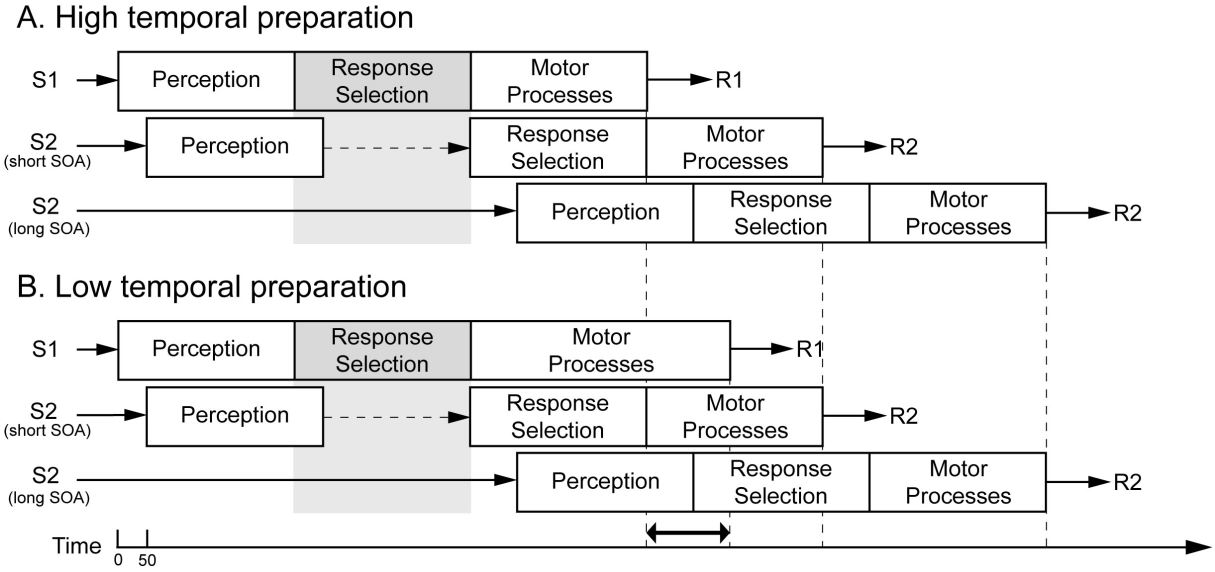

Figure 2.2. Illustration of the effect propagation property of the bottleneck model. This figure depicts dual-task processing in accordance with the bottleneck model for trials with short and long stimulus onset asynchrony (SOA) and for trials with high (Part A) and low (Part B) temporal preparation. It is assumed that temporal preparation affects the duration of **motor processing stages.** *Part A* is identical to part A of Figure 2.1. RT in Task 2 should be prolonged following a short SOA due to the waiting period associated with Task 1 response selection. *Part B:* This is identical to Part A except that, due to low temporal preparation, longer motor processing in Task 1 emerges. A comparison of Part A and B illustrates that an increase in RT1 due to prolonged motor processing associated with lower temporal preparation would not propagate to RT2, neither at a short nor at a long SOA (cf. dashed vertical lines).

2.1.1. Experiment 1

To assess whether temporal preparation shortens the duration of premotor or motor processing stages, temporal preparation for S1 in a PRP paradigm was manipulated. To this end, and similar to the experiments conducted by Müller-Gethmann et al. (2003), a constant foreperiod paradigm was employed. To enable the exclusion of potential alternative explanations of the results, altogether three groups of participants were tested. One third of the participants performed the above mentioned dual-task condition. This condition assessed whether or not a manipulation of temporal preparation on S1 produces an effect propagation to RT2. Another third of the participants were instructed to ignore S2 and to perform Task 1 only. This single-task condition served as a control condition to determine the size of the foreperiod effect and to assess potential accessory effects (Hackley & Valle-Inclán, 1998, 1999) of S2 on RT1, which could hamper the interpretation of the results in the dual-task condition. The third group of participants received the same stimuli as the other two groups, but they ignored S1 and performed Task 2 only. The purpose of this single-task condition was to determine possible direct effects of the warning signal on Task 2 processing, thereby providing a baseline against which propagation effects in the dual-task condition could be assessed. It was anticipated that direct effects of foreperiod manipulation would be modest in size, on the assumption that S1 would serve as a more useful predictor of S2 onset than the earlier warning signal.

2.1.1.1. Method

Participants

Forty-seven women and seven men participated (mean age = 24.3 years). According to self-report, all but three were right-handed, and all had normal or corrected-to-normal vision.

Stimuli and apparatus

An IBM-compatible computer presented stimuli, and recorded responses and RT. All visual stimuli were presented in the center of the screen on a blue background (2.5 cd/m^2) and viewed from a distance of approximately 50 cm. The fixation cross (2×2 mm, 110 cd/m^2) and the warning signal (an asterisk with a diameter of 9 mm, 110 cd/m^2) were white. S1 was a filled red or green rectangle (6×9 mm, 25 and 70 cd/m^2). S2 was either a low-, medium-, or high-pitched tone (800, 1,000, or 1,200 Hz), presented binaurally over headphones at approximately 70 dB(A). There were separate response panels for each hand with response buttons for each finger. Two buttons on one panel were for the middle and index finger of the left hand (Task 1), and three response buttons on the other panel were assigned to the index, middle, and ring finger of the right hand (Task 2).

Procedure and design

The time course of an experimental trial is depicted in Figure 2.3. Each intertrial interval started with the presentation of the fixation cross, which was displayed for an interval of (1,000 + X) msec, where X was a random variable that followed an exponential distribution with a mean of 2,000 msec. This random interval was introduced to emphasize the importance of the warning signal as a temporal reference for preparation (e.g., Müller-Gethmann et al., 2003). At the end of the intertrial interval, the fixation cross was replaced by the warning signal (asterisk) for 200 msec. At warning signal offset, the fixation cross reappeared and was again replaced after 600, 1,400, or 3,000 msec by S1. Thus, the foreperiod duration between the onset of the warning signal and S1 was either 800, 1,600, or 3,200 msec for any given block of trials. S1 remained on the screen for 200 msec and was then replaced by the fixation cross, which stayed on until the trial was over. At a variable SOA of either 50, 200, or 800 msec following S1 onset, S2 appeared for 200 msec. In case of an incorrect response, the word “FEHLER!” (Error) appeared in the lower part of the screen for 500 msec at the end of the trial.

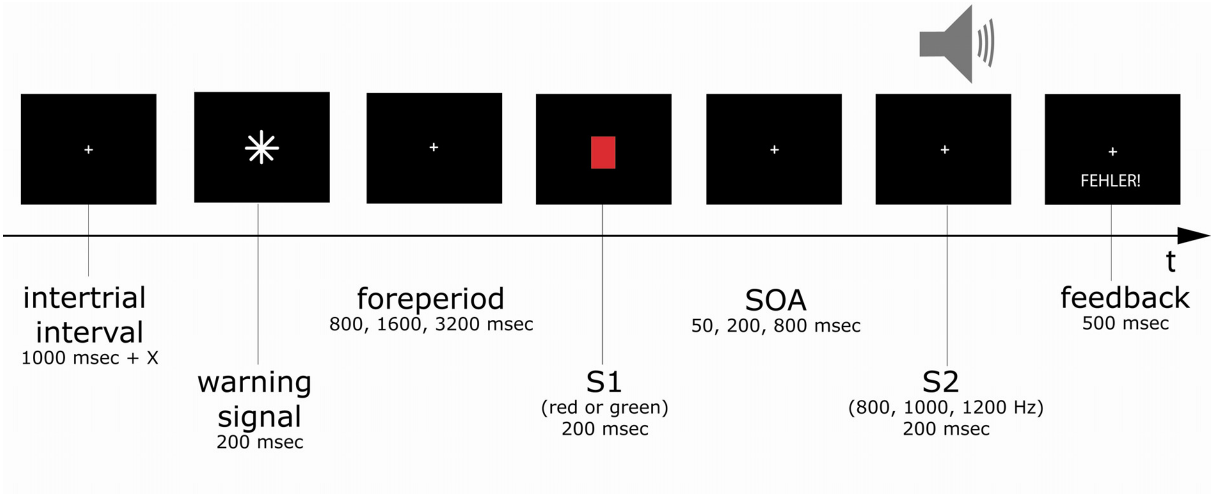

Figure 2.3. Time course of an experimental trial in Experiment 1.

A single session lasted about 1.5 h and consisted of 15 blocks. Foreperiod duration was kept constant over five consecutive blocks of 36 trials each. Order of the three foreperiod conditions was balanced across participants in each group. The first block of each foreperiod condition was considered practice and was discarded from data analysis. After each block, participants received performance feedback concerning mean RT and percentage of errors.

For the single- and the dual-task conditions, the experiment factorially combined foreperiod duration (800, 1,600 vs. 3,200 msec) and SOA (50, 200 vs. 800 msec). This yielded a total of 48 experimental trials per participant for each factorial combination of experimental conditions.

2.1.1.2. Results

RTs shorter than 150 msec or longer than 1,500 msec were considered outliers and their corresponding trials were discarded. Specifically, 0.3% of all trials were eliminated in the visual single-task condition, 0.3% in the auditory single-task condition, and 4.8% in the dual-task condition (RT1: 1.2%; RT2: 4.6%). Separate repeated measures analyses of variance (ANOVA) with the factors foreperiod duration and SOA were conducted on mean RT and percentage of correct responses (PC). Parallel analyses in which fast and slow outliers were not omitted yielded results similar to those reported below. In all analyses, p-values were, whenever appropriate, adjusted for violations of the sphericity assumption using the Greenhouse-Geisser correction.

Single-task conditions

The results of the single-task conditions are summarized in Figure 2.4, which depicts mean RT and PC for both conditions as a function of foreperiod duration and SOA. An ANOVA on PC for the *S1 single-task condition* revealed only a main effect of SOA, $F(2,34) = 9.6$, $p = .002$, due to more incorrect responses at the shortest SOA. No further significant results for PC were obtained, ps > .162. The ANOVA on RT for this single-task condition revealed that the manipulation of temporal preparation was successful, because foreperiod duration produced a strong effect on RT, $F(2, 34) = 45.2$, $p < .001$. As one should expect, mean RT increased with foreperiod duration due to decreasing temporal preparation. Mean RT increased slightly yet significantly with SOA, $F(2,34) = 4.8$, $p = .017$. Crucially, the two factors produced no significant interaction on RT, $F < 1$, indicating that the task-irrelevant S2 did not modulate the observed effect of temporal preparation in Task 1.

An ANOVA on PC for the *S2 single-task condition* revealed no significant effects, Fs < 1. An ANOVA on RT revealed no significant effect of SOA, $F < 1$. As expected, the direct effect of foreperiod duration on RT was modest in size, $F(2,34) = 5.07$, $p = .034$. Presumably, the temporally proximal S1 (50-800 msec SOA) constituted a more useful warning signal than the more distal (850-4,000 msec SOA) asterisk. This assumption is consistent with previous research showing that the presence of a proximal warning signal can eliminate the foreperiod effect of an earlier warning signal (Low et al., 1996). Most important and analogous to the S1 single-task condition, SOA and foreperiod did not interact, $F < 1$. These findings imply that, should an SOA by foreperiod interaction be observed in the dual-task condition, it could reasonably be attributed to effect propagation.

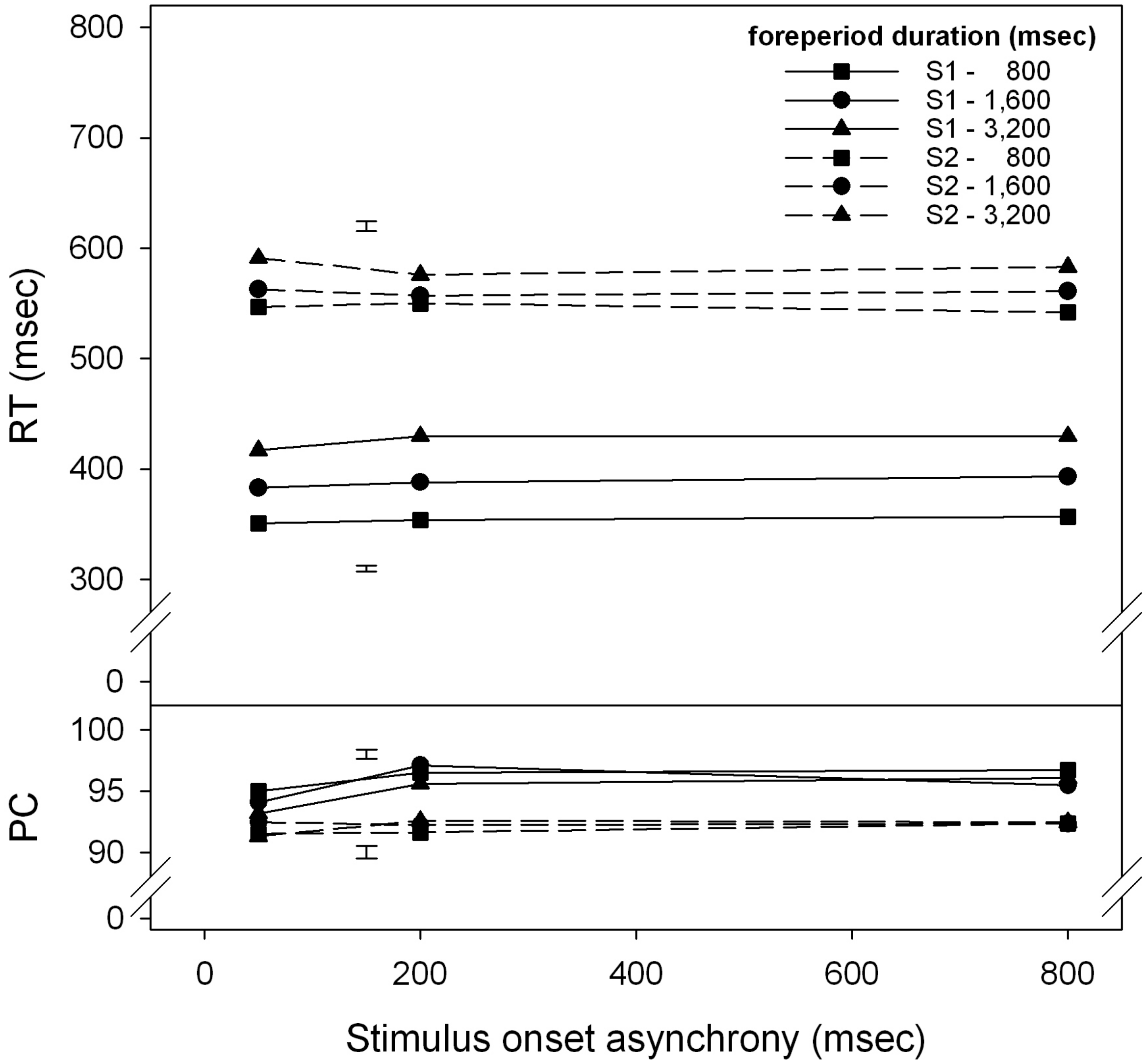

Figure 2.4. Results of the single-task conditions of Experiment 1. *Upper panel:* Mean RT for the S1 and S2 single-task condition as a function of foreperiod duration and SOA. *Lower panel:* Percentage of correct responses (PC) for the S1 and S2 single-task condition as a function of foreperiod duration and SOA (legend as in upper panel). The error bar in each panel provides the standard error of the mean. This standard error was computed from the pooled error-terms of the corresponding ANOVA according to a suggestion made by Loftus (2002).

Dual-task condition

Figure 2.5 summarizes the results for the dual-task condition. The upper panel represents mean RT for each task and the lower panel PC. There was no effect on PC, *p*s > .144. All trials with grouped responses, which can undermine the interpretation of PRP data, were eliminated from RT analyses.[11] Specifically, all trials with interresponse intervals less than 100 msec were defined as grouped responses.

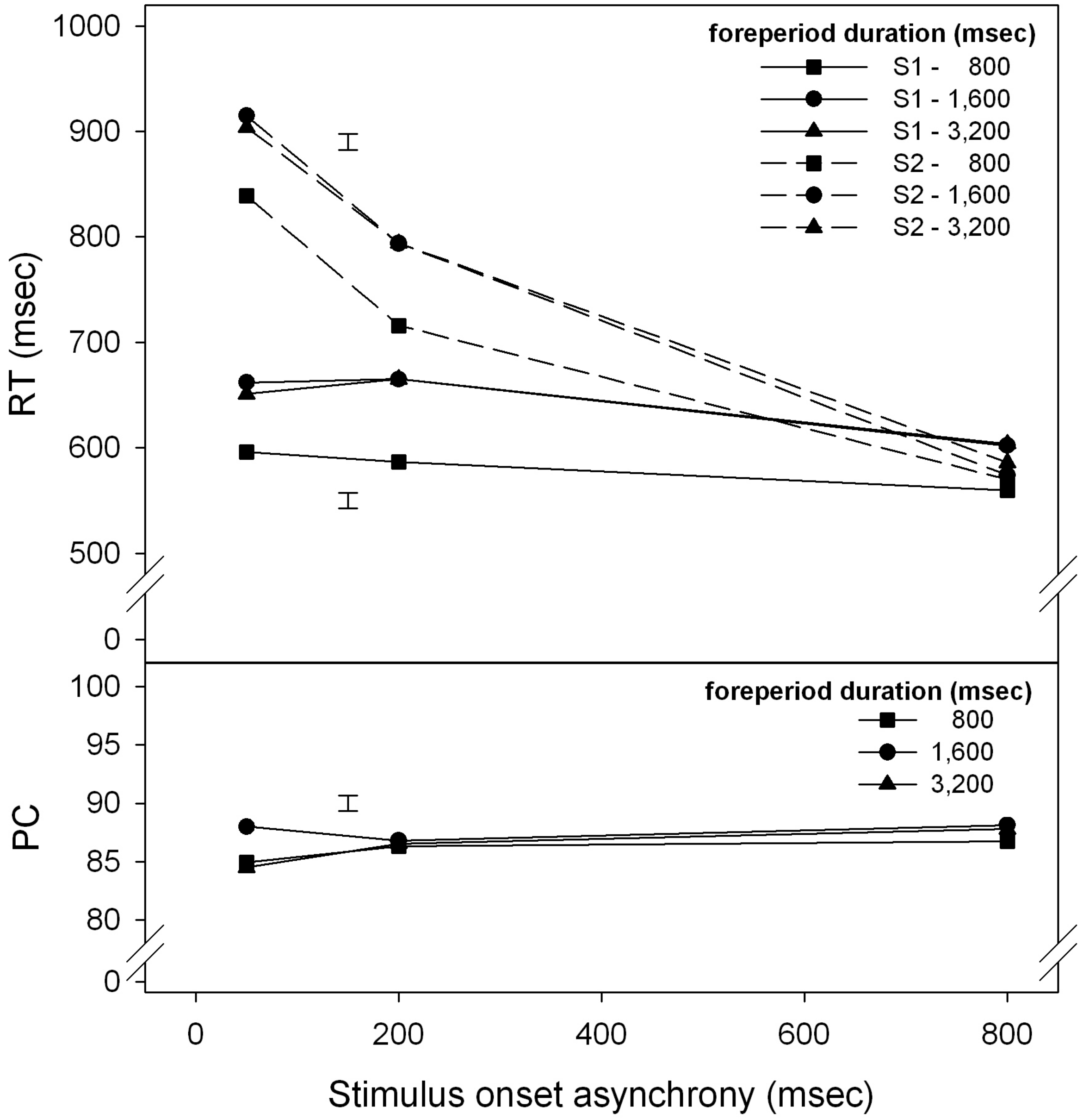

Figure 2.5. Results of the dual-task condition of Experiment 1. *Upper panel:* Mean RT to S1 and S2 in the dual-task condition as a function of foreperiod duration and SOA. *Lower panel:* Percentage of correct responses (PC) as a function of foreperiod duration and SOA.

An ANOVA on RT1 revealed again a strong effect of foreperiod duration, $F(2,34) = 8.2$, $p = .001$, confirming that the single-task foreperiod effect generalizes to the dual-task situation. In contrast to the S1 single-task condition, however, the effect saturated faster in the

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[11] Whether or not these trials were discarded had virtually no effect on the results of the RT1 and RT2 analyses.

dual-task condition. Most likely, this was due to increased task difficulty. It is known that estimating time intervals is resource demanding (Brown, 1997), as is maintaining response readiness (Gottsdanker, 1975). Assuming that these processes are more difficult for longer foreperiods (Niemi & Näätänen, 1981; Requin et al., 1991), dual-task interference might be expected to yield an earlier asymptote for foreperiod effects. Also, RT1 decreased with increasing SOA, $F(2,34) = 14.9$, $p < .001$. This is presumably because processing of Task 1 was interrupted by Task 2 during some trials with short SOAs. The interaction of foreperiod and SOA was not significant for RT1, $F(4,68) = 1.1$, $p = .367$.

In the analogous ANOVA on RT2, the usual PRP effect was obtained, that is, RT2 increased substantially as SOA decreased, $F(2,34) = 203.3$, $p < .001$. Theoretically more important, however, was the finding that RT2 increased with foreperiod duration, $F(2,34) = 7.4$, $p = .003$. In addition, and as predicted by the effect-propagation account, this effect decreased virtually to zero as SOA increased, $F(4,68) = 5.6$, $p = .003$; in fact, a post-hoc analysis revealed no effect at the longest SOA, $p = .662$. At the two shortest SOAs, the size of foreperiod effect on RT1 was fully propagated to RT2. This was confirmed statistically by computing the difference between the long (3,200 msec) and short (800 msec) foreperiods separately for RT1 and RT2 and then comparing these two differences. In the 50 msec SOA condition the foreperiod effect was 55 msec for RT1 and 64 msec for RT2, which did not differ statistically, $p = .479$. In the 200 msec SOA condition, the corresponding values were virtually identical (77 vs. 78 msec).

As noted earlier, the S2 single-task control condition showed that any direct effect of foreperiod duration on RT2 was negligible because S1 constituted presumably a more useful warning signal for S2 than the asterisk. To provide further evidence that foreperiod effects on RT2 in the dual-task condition were primarily due to effect propagation, the size of the foreperiod effect on RT2 between the S2 single-task and the dual-task condition was compared. Under the effect propagation hypothesis, foreperiod effects should be larger in the dual-task than in the single-task condition when SOA is short. This prediction was confirmed by a significant Foreperiod×SOA×Task interaction, $F(4,136) = 5.52$, $p < .001$.

2.1.1.3. Discussion

This study was conducted to localize the effect of temporal preparation in the processing chain from input to response. Specifically, it addressed the question whether temporal preparation enhances the speed of motor or premotor processes. The effect-propagation property of bottleneck models was used as an inferential tool to answer this question. The present results are clear-cut. First, and as expected, a sizeable foreperiod effect on RT1 was observed in the visual single-task condition. Second, essentially the same effect on RT1 was obtained in the dual-task condition at all SOAs. Third, and crucially, this foreperiod effect on RT1 carried over in full size to RT2 at short SOAs, and yet was virtually nil at the longest SOA. As explained above, this pattern of results supports the assumption that temporal preparation exerts its effect prior to the completion of response selection.

The finding that the foreperiod effect on RT2 disappears at long SOA is also important for ruling out an alternative interpretation of the present results. According to this alternative view, foreperiod effects for RT2 do not reflect effect propagation from Task 1 but direct effects of the warning signal on Task 2. This view emphasizes that the asterisk did not just improve temporal preparation for the onset of S1 but also for the onset of S2. It does appear likely that the asterisk helped the dual-task participants to prepare Task 2, given the significant (albeit small) foreperiod effect in the S2 single-task condition. If this was the basis for foreperiod effects on the dual-task RT2, however, there would be no reason to expect the foreperiod effect to be larger in the dual-task condition or to disappear at the longest SOA. Such a pattern is predicted under the effect propagation hypothesis and this is, indeed, what was observed.

Thus, this study provides evidence for the notion that temporal preparation enhances the speed of premotor processes, but does not change the speed of motor processes. This conclusion completely agrees with the results from recent chronophysiological studies in which temporal preparation was manipulated using short foreperiods (Hackley & Valle-Inclán, 1998, 1999), short, medium, and long foreperiods (Müller-Gethmann et al., 2003), and variable versus fixed intertrial intervals (Smulders, 1993). In these studies, the onset of the LRP was used as a landmark to partition RT into two segments, one including perceptual, decision, and early motor stages, and the other, only late motoric processes. These studies tested the hypothesis that temporal preparation influences the speed of late motoric processes, which had been proposed by Sanders (1980) based on behavioural data generated within an additive factors framework. Interestingly, and contrary to the prediction of this hypothesis, the duration of the LRP-R interval, which indexes the duration of late motoric processes, was not systematically influenced by foreperiod duration in neither of these studies. By contrast, variations in the duration of the S-LRP interval resembled almost perfectly the foreperiod effect on RT. Based on these rather unexpected results, it was concluded that the LRP findings disagree with the prevailing view, according to which temporal preparation affects late motor stages.

It is important to note that the present conclusion of an early effect does not deny the possibility that temporal preparation affects various aspects of response preparation and execution other than speed. For example, it has been demonstrated that the force of a response is sensitive to a manipulation of temporal preparation (Mattes & Ulrich, 1997). Participants produce more force when they are temporally less prepared and this finding suggests that temporal preparation operates at a motor level. Nevertheless, it has been repeatedly reported that RT and dynamics of the response are uncorrelated (e.g., Mordkoff, Miller, & Roch, 1996). This lack of a correlation is inconsistent with the idea that changes in response force are accompanied by changes in the duration of motor or premotor processes. Thus, motor adjustments that accompany temporal preparation may serve a different purpose than speeding up responses. Analogous arguments may be applied to other physiological markers of motor preparation such as modulation of probe reflex amplitudes and MEPs.

One may argue that the logic of this effect-propagation approach, and therefore the present conclusion, depends greatly on the validity of bottleneck models. The basic premise of this model class is the existence of a central processor that can only operate at one task at a time. In contrast, capacity models reject such a structural bottleneck but instead assume that both tasks need to share limited resources (Tombu & Jolicœur, 2003). Because this alternative model class implies the same effect-propagation property as structural bottleneck models (Navon & Miller, 2002), the present conclusions may be robust with respect to violation of this key assumption.

2.1.2. Conclusion

In conclusion, this experiment employed the PRP paradigm to identify the processing stages which are affected by temporal preparation. In contrast to the prevailing notion that temporal preparation operates exclusively on late motor processes, the present study provided evidence for an earlier locus of temporal preparation. Specifically, and in accordance with findings obtained in studies employing the LRP to bisect RT in two subsequent components, the present results suggest that temporal preparation exclusively influences the speed of perceptual and decision-related processing.

2.2. Temporal preparation enhances the temporal resolution of the visual system: Evidence from temporal order judgments[12]

Based on the results obtained in Experiment 1, one might ask whether the facilitating influence of temporal preparation on premotor processing also generalizes to behavioural measures other than RT. As has been outlined in the Introduction, some recent studies tackled this question by investigating the influence of temporal preparation on performance in perceptually demanding stimulus discrimination tasks (Correa et al., 2005; Rolke & Hofmann, 2007). These studies demonstrated a facilitation of spatial discrimination for low-level spatial stimulus features (i.e., spatial gap discrimination, see Rolke & Hofmann, 2007) as well as higher-level discriminations that required the integration of several spatial stimulus features (i.e., letter discrimination, see Correa et al., 2005; Rolke, 2008). The experiments reported below were designed to investigate whether this facilitation is restricted to the processing of spatial stimulus properties, or whether other aspects of perception also might benefit from temporal preparation.

This question seems especially interesting in the light of studies which demonstrated that attentional influences on certain aspects of perception are not necessarily beneficial. For example, it has been shown that spatial attention enhances spatial resolution, but can impair processing of temporal stimulus properties (e.g., Hein, Rolke, & Ulrich, 2006; Yeshurun & Levy, 2003). Therefore, in the present study, the question was addressed whether temporal preparation within a constant foreperiod paradigm enhances the temporal resolution of the visual system. Specifically, it was investigated whether temporal preparation enhances discrimination performance in a temporal order judgment task (TOJ). In this task, participants have to judge the temporal order of two target stimuli, which are presented with a varying SOA. For example, in Experiment 2a, two dots were presented, and participants had to indicate which of the two dots (the one presented to the left or the one presented to the right of a fixation cross) was presented first.

Performance in TOJ can be described by two parameters, (a) the point of subjective simultaneity (PSS), which may indicate a bias in temporal stimulus processing, and (b) the just noticeable difference (JND, also called difference limen or DL) as an index of the accuracy of temporal processing, and thus, temporal resolution (e.g., Sternberg & Knoll, 1973). These two measures are illustrated in Figure 2.6, which depicts an exemplary

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[12] The data reported below have been published in: Bausenhart, K. M., Rolke, B., & Ulrich, R. (2008). Temporal preparation improves temporal resolution: Evidence from constant foreperiods. *Perception & Psychophysics, 70*, 1504-1514.

psychometric function relating SOA duration to the percentage of "right dot presented first" responses.

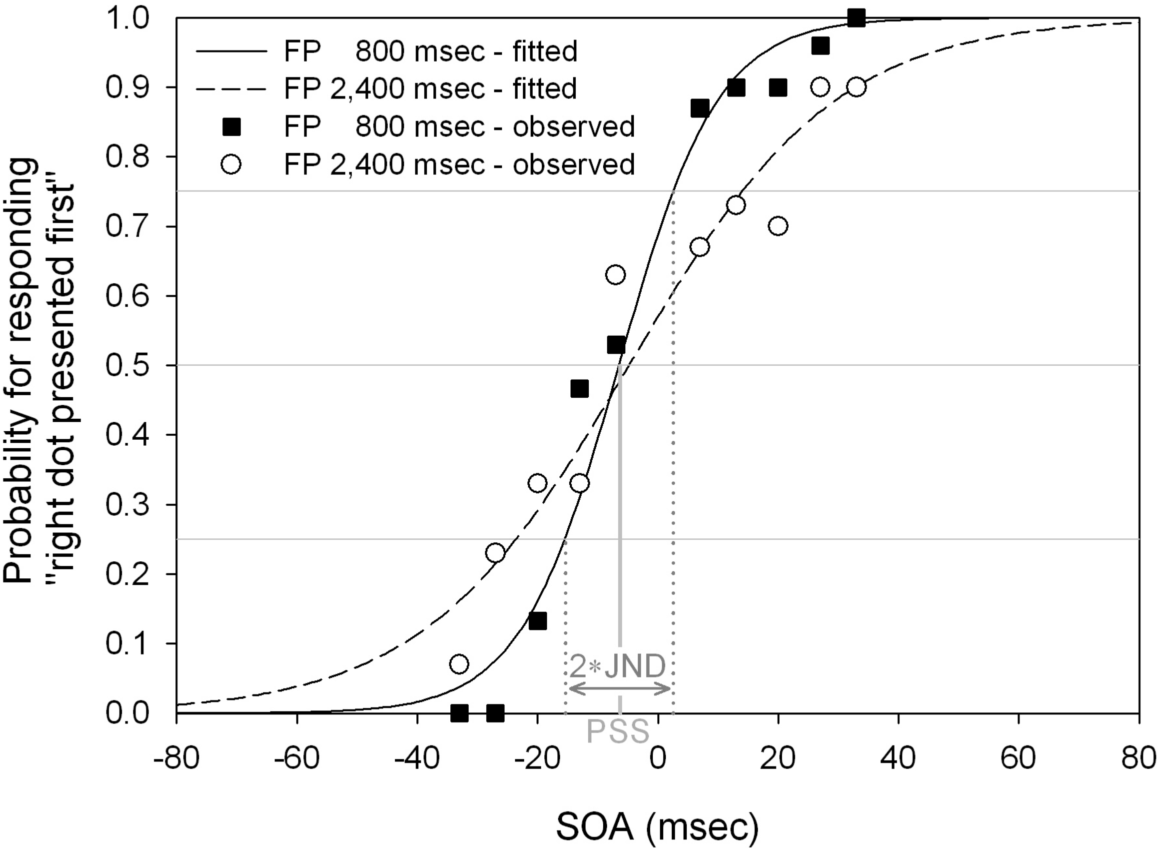

Figure 2.6. Observed probability for a "right dot presented first" response at different stimulus onset asynchronies (SOAs) and the corresponding fitted psychometric functions for two foreperiod (FP) durations. Negative SOAs indicate that the left dot was presented first, positive SOAs indicate that the right dot was presented first. From the psychometric functions, the point of subjective simultaneity (PSS) can be derived as the SOA duration which corresponds to 50% "right dot first" responses. The just noticeable difference (JND) reflects the minimum SOA duration needed to judge the temporal order of the stimuli correctly (half the interquartile range of the psychometric function). For clarity, PSS and JND are depicted only for the 800 msec foreperiod condition. The data shown in this figure are the results of one participant of Experiment 2a.

Specifically, the PSS corresponds to the SOA duration at which both target stimuli are equally often reported as having been presented first (e.g., 50% "right stimulus presented first" responses). Thus, it marks the SOA at which both target stimuli subjectively appear simultaneously. For example, a PSS of 0 msec indicates that simultaneity is correctly perceived, because with a SOA of 0 msec, both target stimuli actually occur simultaneously. In contrast, a shift of the PSS away from 0 msec indicates a bias in perception, namely that one of the target stimuli is processed faster than the other, and accordingly has to be presented later than the other in order to be perceived as simultaneous. Such shifts of the PSS have been repeatedly demonstrated, for example as a result of directing spatial attention to one of the stimuli and away from the other stimulus (Hikosaka, Miyauchi, & Shimojo, 1993; Schneider & Bavelier, 2003; Shore, Spence, & Klein, 2001; Stelmach & Herdman, 1991). The JND, in contrast, reflects the smallest SOA between the two target stimuli that allows correct discrimination of temporal order. This time interval is located around the PSS, and is usually defined as half the interquartile range of the psychometric function (e.g., Sternberg & Knoll, 1973). The steeper the psychometric function, the smaller is JND. Accordingly, high discrimination performance, and therefore, high temporal resolution, is associated with small values of JND.

Relevant evidence for the notion that temporal preparation influences temporal resolution was recently provided in a TOJ experiment conducted by Correa, Sanabria, Spence, Tudela, and Lupiáñez (2006) within a temporal orienting paradigm. The results of this study were clear-cut: when the explicit cue indicated the presentation time of the target stimuli validly, participants judged the order of the target stimuli more accurately than in invalid trials. In addition, when the foreperiod was short, JND was smaller for valid compared to invalid trials. These results suggest that temporal orienting enhances the temporal resolution of visual perception. Independent of cue validity, the authors report that more correct responses were made after the long than after the short foreperiod. This result indicates that temporal resolution increases with foreperiod duration when foreperiod varies from trial to trial. Unfortunately, JND analyses for these conditions were not reported.

Given these results of a beneficial effect of temporal preparation in a temporal cueing context, one might expect a similar benefit of temporal preparation within a constant foreperiod design. There is some evidence, however, that constant foreperiods might be less effective in influencing performance in temporal tasks than variable foreperiods. For example, within a variable foreperiod context, the duration of a stimulus is perceived as being longer following long than following short foreperiods, and at least under certain conditions, duration judgements are also more accurate (Bendixen, Grimm, & Schröger, 2006; Grondin & Rammsayer, 2003; Mo & George, 1977). In contrast, no such effects were found when constant foreperiods were employed (Grondin & Rammsayer, 2003; Mo & George, 1977). Thus, these studies indicate that constant foreperiods might be less effective in influencing performance in temporal tasks than variable foreperiods. As has been outlined in the Introduction, different sources of uncertainty contribute to constant and variable foreperiod effects, and one might assume that these sources influence temporal perception differentially. Accordingly, it might be premature to generalize the beneficial effect of temporal orienting on temporal resolution obtained within the explicit cueing paradigm (Correa, Sanabria et al., 2006) to constant foreperiod manipulations, in which only time uncertainty, but not expectancy, influences the preparatory process. Since still relatively little is known about the specific processes underlying temporal preparation, it seems especially important to investigate this issue empirically.

2.2.1. Experiment 2a

To examine the influence of temporal preparation on temporal resolution within the constant foreperiod paradigm, a TOJ experiment was conducted. Thus, the two target stimuli for which the temporal order judgment had to be performed, were either presented after a short (800 msec) or after a long (2,400 msec) foreperiod. In case of a short foreperiod, participants should be able to temporally prepare for the occurrence of the targets, whereas in case of a long foreperiod, due to increased time uncertainty, temporal preparation for the targets should be worse. Therefore, if temporal preparation increases temporal resolution, TOJ performance should be better in the short foreperiod condition, and as a consequence, smaller JNDs should be obtained. Unlike in spatial attention studies, however, where attention usually is directed to one of the target stimuli and away from the other (Hikosaka et al., 1993; Schneider & Bavelier, 2003; Shore et al., 2001; Stelmach & Herdman, 1991, but see Hein et al., 2006), in the present experiment both target stimuli are presented within a short time interval after a given foreperiod duration. Thus, within each foreperiod condition, participants should be equally temporally prepared for both target stimuli. Accordingly, none of the two target stimuli should be perceived earlier than the other, and thus, no influence of foreperiod duration on PSS is expected.

2.2.1.1. Method

Participants

14 participants were recruited (6 male, mean age = 28.1 years). They received either course credit or payment for their participation. All had normal or corrected-to-normal vision.

Stimuli and apparatus

All stimuli were presented in white (90 cd/m²) on a black background (< 1 cd/m²). Stimulus presentation was controlled via Matlab, using the Psychophysics Toolbox extension

(Brainard, 1997; Pelli, 1997). Participants were seated in a dimly lit room at a viewing distance of approximately 50 cm from the computer screen. The stimuli consisted of a fixation point (0.1° visual angle), a square frame (5.9°), the target dots (0.5°), a square mask consisting of a random black and white check pattern (5.3°), and a question mark (0.6° × 1.1°). Responses were collected via the ‘y’ and ‘-‘ key of a standard German keyboard.

Procedure and design

The time course of a single experimental trial is depicted in Figure 2.7. At the beginning of each trial, the screen remained empty for a variable interval of a random duration that followed an exponential distribution with a mean of 2,000 msec. This random duration is assumed to increase the functional significance of the warning signal (Müller-Gethmann et al., 2003). Then a fixation dot appeared at the centre of the screen. It remained on the screen for 2,400 msec in short foreperiod trials or for 800 msec in long foreperiod trials.[13] Subsequently, the warning signal, a white frame, was added to the screen and stayed visible until the end of the trial. After a foreperiod duration of 800 or 2,400 msec, the fixation point disappeared, and one of the target dots appeared equally likely on the left or on the right side of the centre of the screen. The distance between the centre and the dot position was 0.9°. After a variable SOA of 7, 13, 20, 27, or 33 msec, the second dot appeared on the opposite side of the screen centre. The two dots remained on the screen for 100 msec and were then replaced by the random check pattern mask, which filled the warning signal frame. This mask was present for 500 msec. After the offset of the mask, a question mark appeared as a response signal in the centre of the frame until there was a response or for a maximum duration of 2,000 msec. This temporally delayed response signal was introduced to discourage participants from speeded responding, and thus, to further minimize possible influences of motor processing on TOJ performance (for example through speed-accuracy tradeoffs, see Wickelgren, 1977). Participants had to indicate whether the left or the right dot had appeared first with the index finger of their left and right hand, respectively. They were asked to respond as correctly as possible after the appearance of the question mark and were informed that response speed did not matter.

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[13] This interval was introduced to keep overall trial duration constant regardless of whether the foreperiod of the present trial was short (800 msec) or long (2,400 msec). Otherwise, trial duration and foreperiod duration would be confounded, and one might argue that observed foreperiod effects might be better explained by differences in trial duration (cf., Bausenhart, Rolke, & Ulrich, 2007). For example, within a given amount of time, the targets would be presented more often in the short foreperiod condition than in the long foreperiod condition, and therefore, memory representations of the target stimuli might be especially strong, or participants might be more alert because they have to respond more often.

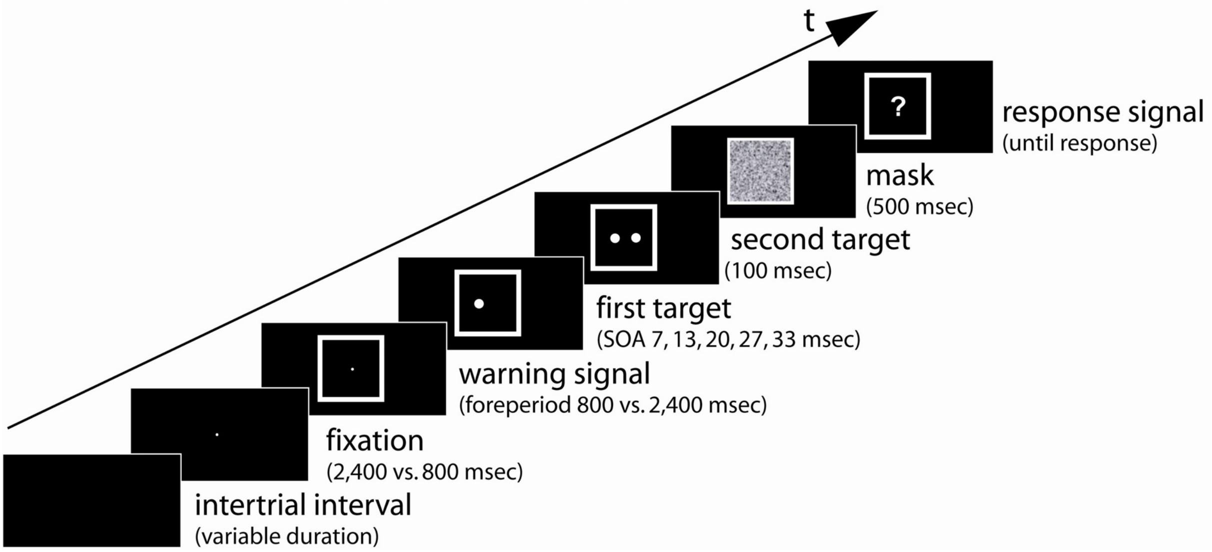

Figure 2.7. Time course of an experimental trial in Experiment 2a.

One experimental session consisted of 32 blocks with 20 trials each. After each block, participants received feedback about their percentage of correct responses. While SOA (7, 13, 20, 27, or 33 msec) varied randomly between trials, each foreperiod duration (800 vs. 2,400 msec) was kept constant across the trials of 16 consecutive blocks. The order of the two foreperiod conditions was balanced across participants. The first block of each foreperiod condition was considered practice and therefore discarded from data analysis. Trials in which no response key had been pressed after 2,000 msec of the appearance of the question mark were discarded from data analysis (1.6 %).

2.2.1.2. Results

The data of three participants with performance close to chance level were discarded from data analysis, because for these participants, the fitted psychometric functions revealed estimations of JND values clearly above 100 msec, a value far beyond the range of the actually presented SOAs.

Percent correct

A repeated measures ANOVA with factors SOA and foreperiod duration was conducted on mean percentage of correct responses (PC). P-values were, when appropriate, adjusted for violations of the sphericity assumption using the Greenhouse-Geisser correction. This analysis revealed a main effect of SOA, $F(4,40) = 60.33$, $p < .001$, indicating more correct responses as the interval between the two target dots increased. Crucially, the manipulation of temporal preparation also influenced PC, with shorter foreperiods yielding more correct responses, $F(1,10) = 10.13$, $p < .01$. This effect was not significantly influenced by SOA, $F(4,40) = 0.67$, $p = .599$ (see Figure 2.8).

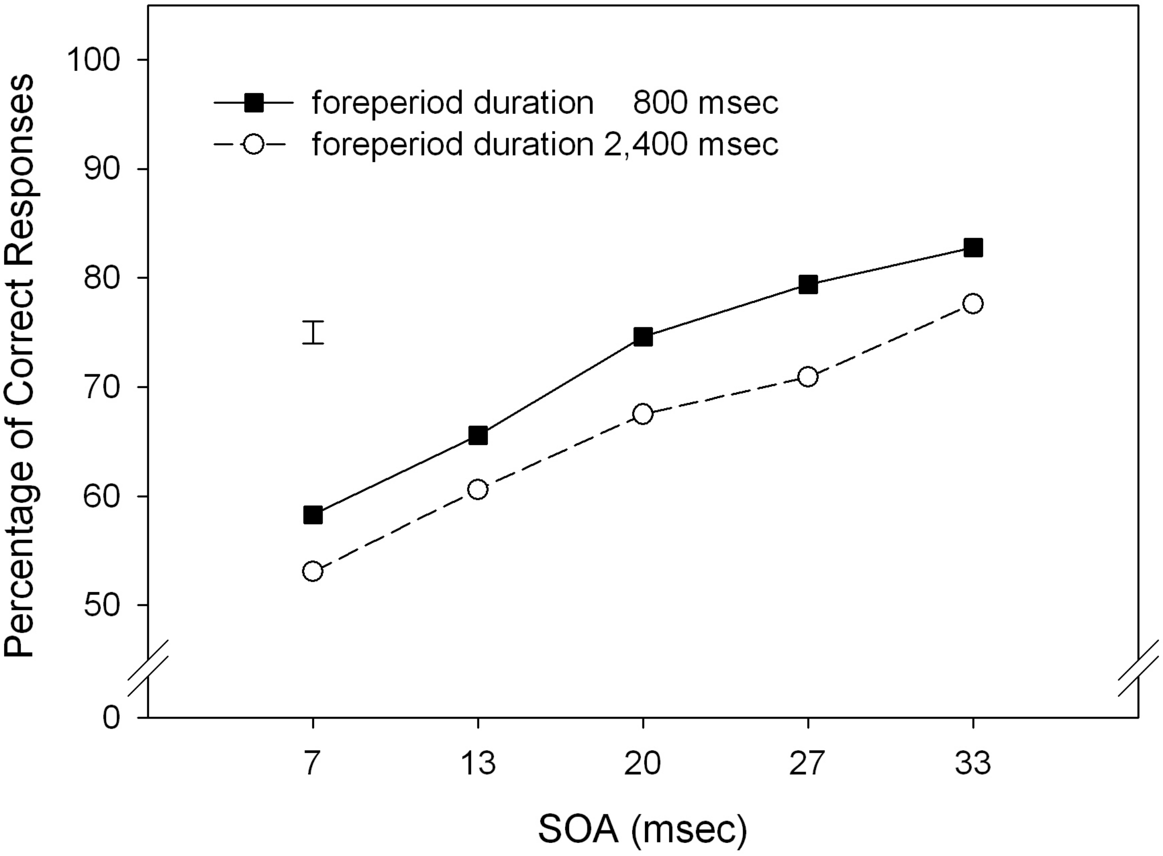

Figure 2.8. Mean percentage of correct responses in Experiment 2a depicted as a function of stimulus onset asynchrony (SOA) and foreperiod duration. The error bar provides the standard error of the mean, which was computed from the pooled error terms of the corresponding ANOVA according to a suggestion made by Loftus (2002).

JND & PSS

To estimate JND and PSS for each participant and foreperiod duration, the proportion of "right dot presented first" responses was computed at each SOA level, whereas SOA levels now were defined as ranging from -33 msec (left dot preceded right dot) to +33 msec (right dot preceded left dot). Then, a maximum likelihood procedure was employed to estimate the PSS and the JND, which maximized the likelihood for the following logistic psychometric function (Bush, 1963),

$$P(\text{"}right\ dot\ first\text{"} \mid SOA) = \frac{1}{1 + e^{-(SOA-PSS)/(0.91 \cdot JND)}} \qquad (1)$$

A paired samples *t*-test on the JND-estimations revealed better performance for short compared to long foreperiods, $t(10) = 2.58$, $p < .05$ (JND = 20.1 vs. 32.0 msec, respectively). Thus, participants in the short foreperiod condition needed a shorter SOA duration to obtain a 75 % correct level of temporal order discrimination. As expected, PSS in the short foreperiod condition (2.1 msec) did not differ significantly from PSS in the long foreperiod condition (4.4 msec), $t(10) = 0.95$, $p = .366$.

2.2.1.3. Discussion

The higher percentage of correct responses as well as the smaller JND associated with short foreperiods indicate improved TOJ when participants were able to predict the moment of stimulus occurrence accurately. This effect suggests that temporal preparation within a constant foreperiod paradigm improves the temporal resolution of visual perception.

These results are consistent with those of Correa, Sanabria et al. (2006), who found evidence for improved temporal resolution within an explicit temporal cueing paradigm. Thus, there is no evidence for a dissociation between temporal preparation within the constant foreperiod and within the temporal orienting paradigm. Despite the possibility that different sources of uncertainty, namely time uncertainty and expectancy, contribute to the effects of constant foreperiods and temporal orienting, a similar preparatory mechanism might underlie those effects.

The present experiment assessed TOJ performance in a task that required processing of the stimulus location to enable judgments about stimulus order. This might constrain the interpretation of the results as being solely due to enhanced temporal resolution. In particular, and as outlined in Chapter 1.4.2.6 of the Introduction, it has been shown that temporal preparation can also enhance processing of spatial stimulus location (Doherty et al., 2005). Specifically, these authors found some evidence for a synergistic effect of spatial and temporal expectations. While temporal expectations alone had no effect on the amplitude of the P1 ERP component, combined spatial and temporal expectations yielded a higher P1 amplitude than spatial expectations alone. Accordingly, enabling temporal expectations about a stimulus might enhance the efficiency of building up expectations about the spatial location of this stimulus, or it might facilitate directing visual attention to the expected stimulus location.

Against the background of this study, the present results might be interpreted in a different way. Accordingly, rather than mirroring enhanced temporal resolution in the good temporal preparation condition, the results might be partly due to an enhanced effect of temporal preparation on the processing of spatial stimulus location. In other words, temporal preparation might have merely facilitated localization of the target stimuli and thus improved judgments of the location of the stimulus presented first. Accordingly, improved TOJ performance associated with good temporal preparation might not be the result of enhanced temporal resolution per se but might reflect improved location processing. Experiment 2b was designed to overcome this alternative explanation.

2.2.2. Experiment 2b

This experiment aimed at decoupling the effect of temporal preparation on temporal resolution from potential effects of temporal preparation on location processing (Doherty et al., 2005). Thus, in contrast to Experiment 2a, which required participants to indicate the temporal order of the presented stimuli by identifying the *location* of the stimulus presented first, in Experiment 2b participants were asked about the *identity* of the stimulus presented first. Both target stimuli were now presented spatially overlapping at the centre of the screen. Thus, because the location of both target stimuli was identical, this stimulus arrangement ensured that location processing was irrelevant for performing the TOJ task.

2.2.2.1. Method

Participants

Fourteen participants were recruited (2 male, mean age = 25.2 years). They participated for course credit or payment. All had normal or corrected-to-normal vision.

Stimuli and apparatus

Again, all stimuli were presented in white (90 cd/m²) on a black background (< 1 cd/m²) and participants were seated in a dimly lit room in a viewing distance of approximately 50 cm from the computer screen. A plus-sign and a multiplication-sign (both 1.3° visual angle) served as target stimuli. Thus, the two different target stimuli were identical except for their spatial orientation (specifically, the multiplication-sign was the plus-sign tilted by 45°). All other stimuli were identical to those employed in Experiment 2a. Responses were collected via the right and left ‘Shift‘ keys of a standard German keyboard.

Procedure and design

The course of a single trial is depicted in Figure 2.9. It was identical to Experiment 2a, except for the following changes. First, following the foreperiod, one of the two target stimuli was presented at the centre of the screen. After a variable SOA, this stimulus was superimposed by the second target stimulus, thus forming the image of a star which remained on the screen for 100 msec before being masked. Second, SOA durations were prolonged to 27, 33, 40, 47, and 53 msec, because pretesting indicated that TOJ for this stimulus arrangement was more difficult than in Experiment 2a. Third, for the same reason, maximum response time was increased to 3,000 msec. Participants had to indicate whether the plus- or the multiplication-sign had appeared first with the index finger of their left and right hand, respectively. As in Experiment 2a, trials in which no response key had been pressed were discarded from data analysis (0.9 %).

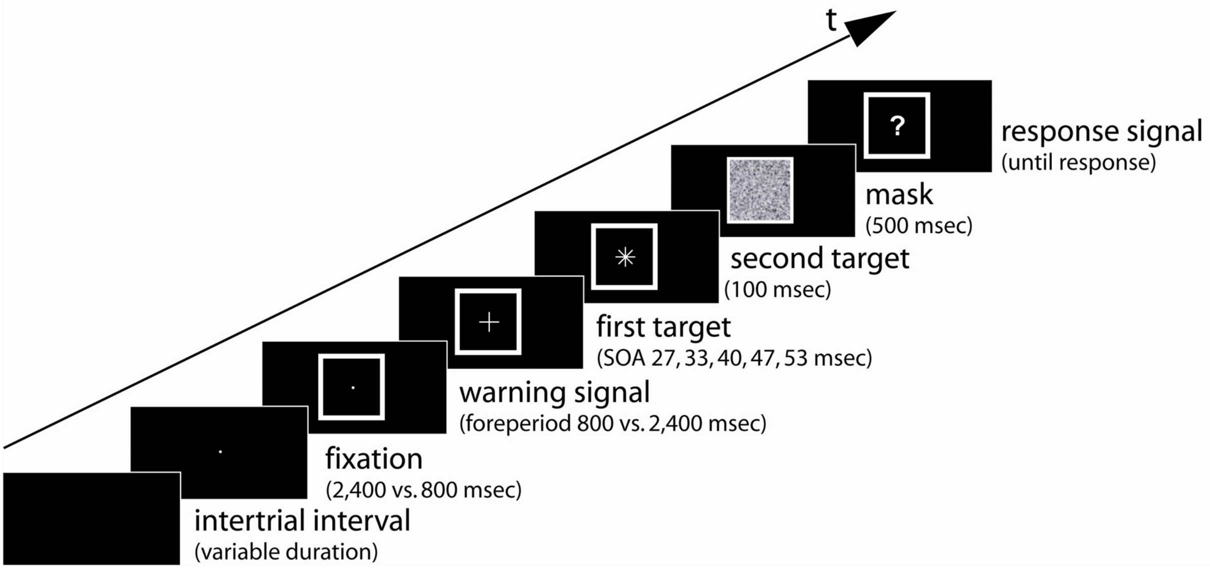

Figure 2.9. Time course of an experimental trial in Experiment 2b.

2.2.2.2. Results

Percent correct

An ANOVA on PC revealed a main effect of SOA, $F(4,52) = 48.32, p < .001$, indicating more correct responses as the interval between the two target stimuli increased. The manipulation of temporal preparation also influenced PC, with shorter foreperiods yielding more correct responses, $F(1,13) = 17.98$, $p = .001$. This effect was not significantly influenced by SOA, $F(4,52) = 0.64, p = .578$ (see Figure 2.10).

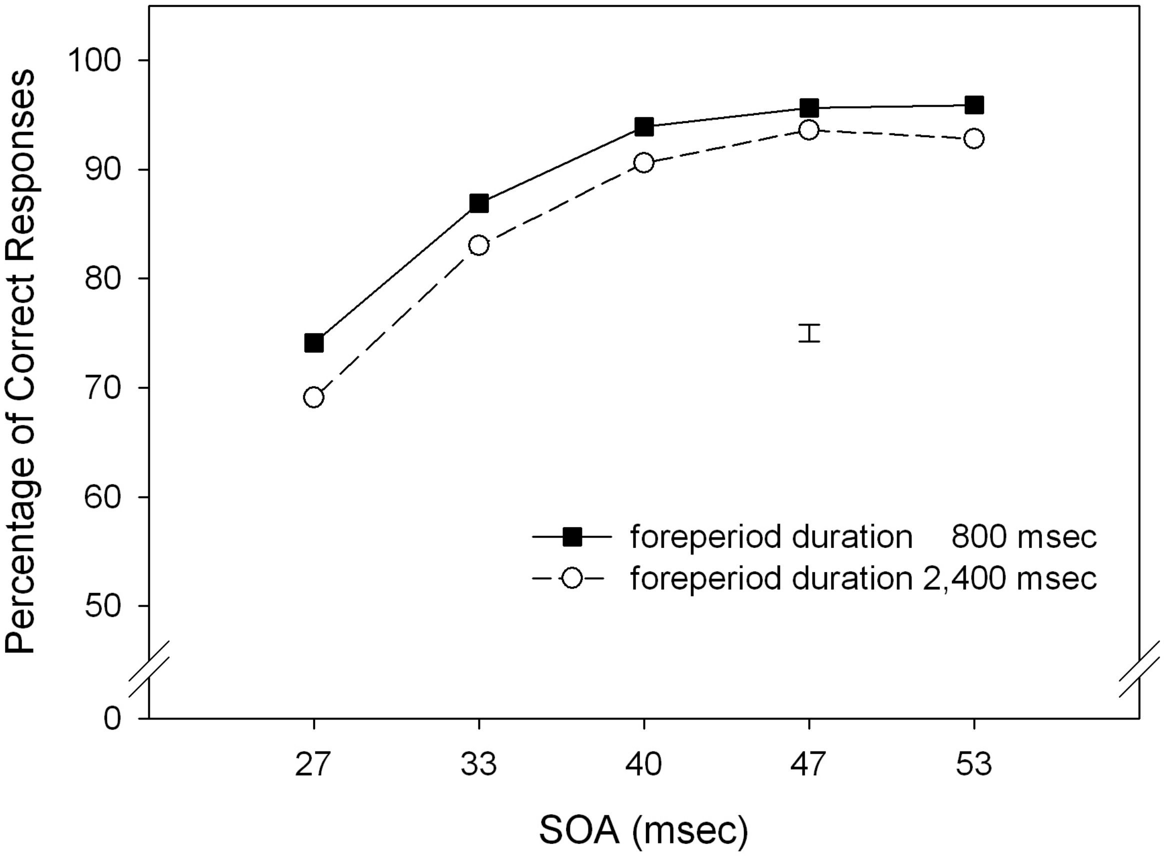

Figure 2.10. Mean percentage of correct responses in Experiment 2b, depicted as a function of SOA (stimulus onset asynchrony) and foreperiod duration. The error bar provides the standard error of the mean, which was computed from the pooled error terms of the corresponding ANOVA according to a suggestion made by Loftus (2002).

JND & PSS

JND and PSS for each participant and foreperiod duration were computed as in Experiment 2a. First, the proportion of "multiplication-sign presented first" responses at each SOA level was collected, now defined as ranging from -53 msec (plus-sign preceded multiplication-sign) to +53 msec (multiplication-sign preceded plus-sign). Again, a maximum likelihood procedure was employed to estimate PSS and JND. A paired samples *t*-test for JND showed better performance for short foreperiods compared to long foreperiods, $t(13) = 4.11$, $p = .001$ (JND = 17.8 vs. 22.4 msec, respectively). Again, PSS did not differ significantly between the short and the long foreperiod condition, $t(13) = 1.29$, $p = .219$, (PSS = -2.0 vs. 1.4 msec, respectively).

2.2.2.3. Discussion

These results argue strongly for a higher temporal resolution of visual perception when participants can precisely prepare for the moment of target presentation within a constant foreperiod design. This result replicates the results obtained in Experiment 2a and also those found by Correa, Sanabria, et al. (2006) within a temporal orienting paradigm. Most important, however, the present results show that the improvement of temporal resolution seems not to be due to a facilitation of location processing by temporal preparation (Doherty et al., 2005), since in Experiment 2b the spatial location of both target stimuli was identical and irrelevant for the selection of the correct response.

2.2.3. Experiment 2c

The results of Experiment 2a and 2b in combination with the results of Correa, Sanabria, et al. (2006) provide converging evidence for an enhancement of temporal processing when participants can temporally prepare for target presentation. The present experiments, and also the study of Correa, Sanabria, et al. (2006), however, employed only two different foreperiod durations. In order to investigate the time course of temporal preparation, Experiment 2c aimed at generalizing these results to a wide range of foreperiod durations. To this end, Experiment 2c basically replicated Experiment 2a, but employed six different foreperiod durations ranging from 150 to 4,800 msec. As outlined in the Introduction (cf. Chapter 1.1.2), RT usually increases with increasing foreperiod duration in a constant foreperiod design, reflecting the increasing time uncertainty about the moment of target occurrence. This pattern can be found over a rather broad range of foreperiods, with the exception of very short foreperiods. Specifically, at short foreperiods up to approximately 200-400 msec, RT usually decreases with increasing foreperiod duration, and when a wide range of foreperiods is employed, RTs follow an U-shaped function (e.g., Bertelson & Tisseyre, 1969; Müller-Gethmann et al., 2003). This time course has been interpreted as evidence that the build-up of temporal preparation takes time, and it has been suggested that foreperiod effects of very short foreperiods might be rather due to the arousing properties of the warning signal (e.g., Hackley & Valle-Inclán, 2003; Ulrich & Mattes, 1996). Importantly, Müller-Gethmann et al. (2003) found this U-shaped pattern of foreperiod effects not only for RT but also for the duration of the S-LRP interval, a component that is thought to index the duration of premotor processes. It is unclear, however, whether this characteristic time course of temporal preparation generalizes to accuracy measures, such as the JND in a TOJ task.

2.2.3.1. Method

To investigate the time course of temporal preparation, TOJ performance was assessed in six constant foreperiod conditions ranging from 150 msec to 4,800 msec. In order to compensate for the increased time requirements associated with testing such a wide range of foreperiod durations, the employed SOA durations were no longer predefined values as in the method of constant stimuli employed in Experiments 2a and 2b. Rather, SOA duration was adjusted adaptively from trial to trial according to participants' performance in the previous trial following an adaptive weighted rule (Kaernbach, 1991). Specifically, this rule aims at centering SOA durations, and hence, participants' performance around the values used for estimating JND, that is, the SOA durations that correspond approximately to the 25th and 75th percentile of the underlying psychometric function. This procedure has proved to enable robust and, most important, efficient threshold estimations based on a comparably small number of experimental trials. Finally, the thresholds obtained with this adaptive method are comparable to those obtained with the method of constant stimuli (e.g., Lapid, Ulrich, & Rammsayer, 2008).

Participants

Thirty participants were recruited (8 male, mean age = 26.07 years). All had normal or corrected-to-normal vision.

Stimuli and apparatus

All stimuli were identical to those employed in Experiment 2a.

Procedure and design

The course of each trial was similar to Experiment 2a, with the following exceptions. First, 6 different foreperiod durations (150, 300, 600, 1,200, 2,400, and 4,800 msec) were employed. Second, following the intertrial interval, the fixation dot was presented for 4,950 msec minus the foreperiod duration of the current block. Thus, again overall trial duration was kept constant irrespective of the foreperiod duration of the current block. Third, the method of constant stimuli was replaced by an adaptive weighted up-down procedure (Kaernbach, 1991). In more detail, within each foreperiod block, two randomly interleaved runs with 60 trials each were presented to estimate the 25th (lower run) and the 75th percentile (upper run) of the psychometric function (see also Lapid et al., 2008). In the first trial of the lower run, the left target dot was presented 40 msec before the right dot (SOA = -40 msec), and in the first trial of the upper run, the right target dot was presented 40 msec before the left dot (SOA = +40 msec). In the following trials, this SOA value was changed according to an adaptive rule. After a "right dot presented first" response, SOA duration for the next trial of the respective run was decreased by either 20 msec (lower run) or by 6.6 msec (upper run). After a "left dot presented first" response, SOA duration was increased by 6.6 msec (lower run) or by 20 msec (upper run). If no key was pressed within the maximum response time of 2,000 msec, the trial was excluded from later data analysis, and the present SOA duration was repeated in the next trial of the respective run.

Each participant completed 120 trials within each of the six foreperiod conditions. The order of these foreperiod blocks was balanced across participants according to an even Latin square. No performance feedback was provided, but after each 30 trials a break allowed participants to rest. The first 30 trials in each foreperiod block were considered practice and discarded from further analysis.

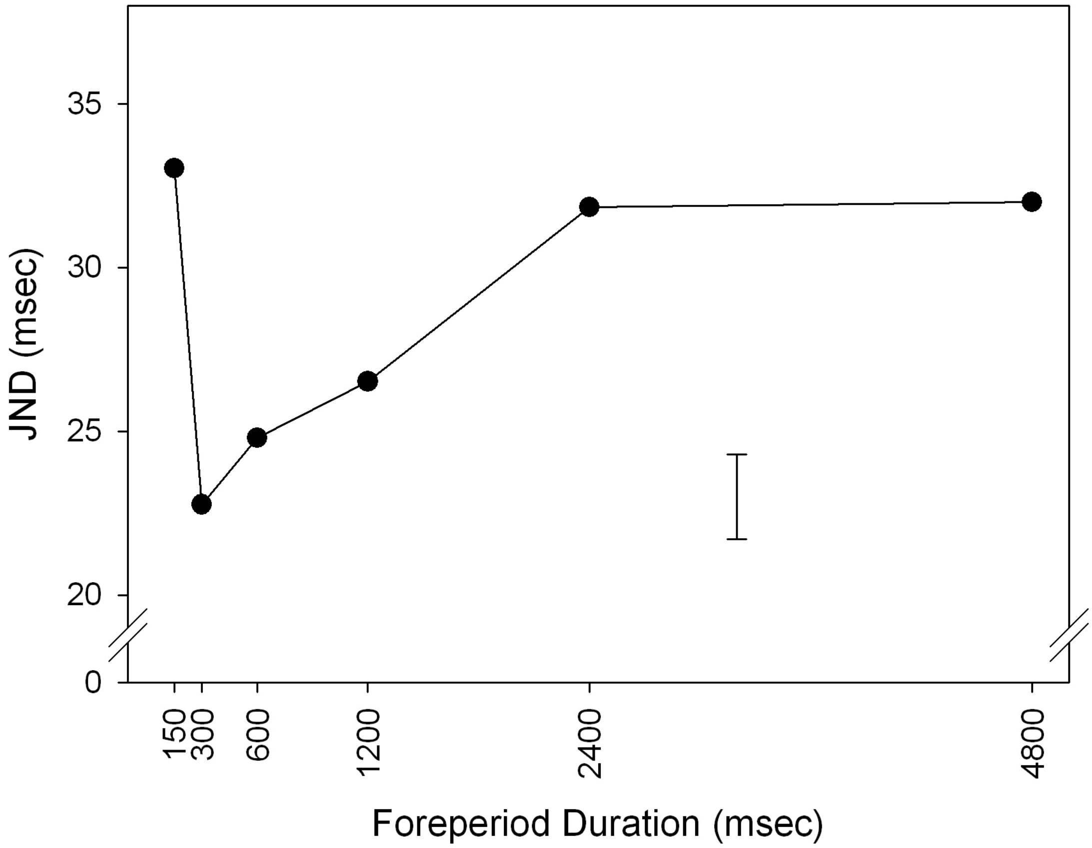

Figure 2.11. Mean estimated just noticeable differences (JND) in Experiment 2c, depicted as a function of foreperiod duration. The error bar provides the standard error of the mean, which was computed from the pooled error terms of the corresponding ANOVA according to a suggestion made by Loftus (2002).

2.2.3.2. Results

The adaptive weighted up-down procedure employed here tracks the SOA durations down to the 25th and 75th percentile of each participants underlying psychometric function. Accordingly, independent of individual differences and experimental conditions, performance always approximately corresponds to 75 percent correct responses. Therefore, in the following, only the results for JND and PSS are reported. These two variables were computed for each participant and foreperiod duration as in Experiment 2a. A repeated measures ANOVA with the factor foreperiod duration was conducted on JND and PSS.

The ANOVA on JND revealed a small but significant main effect of foreperiod duration, $F(5,145) = 2.90$, $p < .05$. As can be seen in Figure 2.11, JND values show a similar U-shaped dependency on foreperiod duration as can be typically observed for RT data. In contrast to JND, PSS did not depend on foreperiod duration, $F(5, 145) = 0.87$, $p = .451$.

2.2.3.3. Discussion

These results replicate the beneficial effect of temporal preparation on temporal resolution within a constant foreperiod paradigm found in the previous experiments, and extend it to a wider range of foreperiod durations. The observed pattern of results is highly consistent with those previously found for RT (Bertelson & Tisseyre, 1969) and for S-LRP data (Müller-Gethmann et al., 2003). To our knowledge, this is the first demonstration of this typical U-shaped pattern for an accuracy measure in a perceptual task. The pattern indicates that temporal preparation in a constant foreperiod paradigm needs some time to develop fully. Specifically, the optimal state of preparation in our experiment seems to be reached after 300 msec of preparatory processing. This remarkable similarity between the effects of constant foreperiods on RT and JND points to a common preparatory mechanism that applies to both latency and accuracy measures of performance.

2.2.4. General Discussion

The present experiments were designed to investigate the influence of temporal preparation within a constant foreperiod paradigm on the temporal resolution of visual perception. To this end, three experiments measuring TOJ performance were conducted. In Experiments 2a and 2b, two different foreperiod durations were employed. Both experiments showed improved performance when foreperiod was short and participants thus were able to prepare for the exact time of target presentation. Specifically, more correct responses and lower JND were observed in the short than in the long foreperiod condition. Experiment 2c employed a wide range of foreperiod durations, and an adaptive procedure for threshold estimation. Interestingly enough, the pattern of results that was found for JND resembles the one that is usually observed for latency measures such as RT. For short foreperiods (< 300 msec), performance increases as the foreperiod duration increases. For longer foreperiods, however, performance becomes worse as the foreperiod duration is lengthened. This U-shaped pattern indicates that building up temporal preparation is time-consuming. Since TOJ performance depends mainly on perceptual processing and not on motor processes, our results argue strongly for a perceptual locus of temporal preparation. The results therefore corroborate the facilitating influence of temporal preparation on perceptual processing found in previous studies employing either constant foreperiod designs (Rolke, 2008; Rolke & Hofmann, 2007) or temporal orienting studies (Correa et al., 2005).

Moreover, the present results show that within a constant foreperiod design, TOJ is enhanced by temporal preparation. This result is consistent with a similar effect obtained by Correa, Sanabria, et al. (2006) within an explicit temporal cueing paradigm. The results of Experiment 2a and also those obtained by Correa, Sanabria, et al., however, might rather be due to improved location processing than to enhanced temporal resolution. Therefore, Experiment 2b was conducted, in which the judgment of temporal order did not require location processing, but depended solely on the processing of stimulus identity. Since this second experiment replicated the beneficial effect of temporal preparation, the alternative interpretation according to which processing of stimulus location is enhanced when participants are temporally prepared, seems less plausible.

Given this enhancement in temporal resolution, one might ask why no effects of constant foreperiods on another indicator of temporal processing, say, duration judgments, were found in previous studies (Grondin & Rammsayer, 2003; Mo & George, 1977). For example, according to counter models of time perception (Creelman, 1962; Treisman, 1963) one might expect that enhanced temporal resolution is the result of a higher neural pulse rate, and thus, comes along with longer duration judgments (e.g., Rammsayer & Ulrich, 2001). The fact that no such effects were reported, however, might be well explained by methodological characteristics of the single stimulus presentation procedure employed to investigate duration judgments. For example, Mo and George (1977) presented in each trial a visual stimulus of either 500 msec or 550 msec duration, and participants then had to decide if the long or the short stimulus had been presented. In the constant foreperiod condition, this procedure might have masked a potential foreperiod effect on perceived duration. Specifically, as a result of good temporal preparation, the stimuli in the short foreperiod block might have been perceived longer than in the long foreperiod block. Within each of the foreperiod blocks, however, the 550 msec stimulus still would be perceived longer than the 500 msec stimulus. Accordingly, the required "shorter/longer" decision would be unaffected by foreperiod duration. In the experiments of Grondin and Rammsayer (2003), several modifications might have made this explanation less valid. First, participants had to memorize a given standard duration at the beginning of the experiment. Then, in each trial one of several different comparison stimulus durations was presented, and participants had to judge whether the comparison was longer or shorter than the memorized standard duration. Even this procedure might be problematic, however, since it has been recently proposed that internalized standard durations might also be influenced by the duration of the stimuli presented in previous trials (Lapid et al., 2008). Thus, if a short foreperiod causes the comparison stimuli to be perceived as longer, this might also prolong the internal representation of the standard duration. As a consequence, the "longer/shorter than standard" judgments would also remain relatively unchanged by foreperiod duration. In addition, foreperiod duration was manipulated as a between-subjects variable, and the range of employed foreperiods was rather small (300-600 msec). In the present Experiment 2c, this range of foreperiods produced only a small increase in observed JND as well. In sum, possible influences of constant foreperiods on perceived duration and on the accuracy of duration discrimination might have been rather underestimated by previous studies.

The present study shows that temporal preparation enhances the temporal resolution of visual perception. This result strengthens the assumption that temporal preparation exerts its influence at a perceptual processing level. The question about the specific mechanism that underlies this perceptual effect, however, remains open. As outlined in Chapter 1.3.2 of the Introduction, Rolke and Hofmann (2007) proposed the early onset model of temporal preparation that explicitly refers to the preparation-based modulation of perceptual processing. Rolke (2008) suggested that this model may also account for the beneficial effects of temporal preparation on temporal resolution observed in the present experiments. Specifically, the first TOJ stimulus in the present experiments was always presented at the end of a given foreperiod duration, whereas the second stimulus was presented following the first stimulus with an unpredictably changing SOA. Therefore, participants presumably were better prepared for the first TOJ stimulus than the second one. According to the early onset model, this would lead to an especially early detection of the first stimulus, and thereby might have improved participants' judgments about temporal order. As a consequence, temporal resolution would be enhanced by temporal preparation.

Another possible mechanism which could account for the facilitating effect of temporal preparation on TOJ, however, might be based on the rate of perceptual information sampling. Specifically, one might assume that temporal preparation increases this rate of information sampling, and thereby improves temporal resolution (see also Correa, Sanabria et al., 2006). Since more information samples would be collected during perceptual analysis of stimuli for which one is temporally prepared, this enhanced sampling rate would also accelerate the accumulation of stimulus information within the perceptual system, thereby leading to similar predictions as the early onset hypothesis proposed by Rolke and Hofmann (2007). So far, research on temporal preparation does not provide any direct evidence concerning the question whether early onset or increased rate of information sampling contribute to the effects of temporal preparation. This unsolved issue will be taken up in Experiment 4, which aims at disentangling those distinct but not mutually exclusive mechanisms and at uncovering their respective contributions to the effect of temporal preparation on perceptual processing.

2.2.5. Conclusion

To summarize, the present experiments show that temporal preparation within the constant foreperiod paradigm enhances TOJ for visual stimuli. Importantly, this demonstrates that temporal preparation effects on early stimulus processing are not restricted to tasks that require high spatial resolution but generalize to tasks that require high temporal resolution. Moreover, the beneficial influence of temporal preparation on temporal resolution seems to be independent of specific task requirements, since it was observed when decisions about the temporal order of two successively appearing stimuli had to be based either on stimulus location or stimulus identity. In addition, the time course of preparation in this perceptual task closely follows the typically U-shaped function previously observed for latency measures. These facilitating effects of temporal preparation might be due to an early onset of information processing or to a higher rate of information sampling in the perceptual system associated with temporal preparation.

2.3. Temporal preparation enhances pitch discrimination: Evidence from discrimination thresholds[14]

Summarizing the results of the experiments reported above and the accuracy studies cited in the Introduction (Chapter 1.4.1.3), it can be concluded that temporal preparation improves perceptual processing in the visual modality. Specifically, temporal preparation seems to shorten the premotor portion of RT (Hackley & Valle-Inclán, 2003; Müller-Gethmann et al., 2003, see also the present Experiment 1), and enhances the spatial (Correa et al., 2005; Rolke, 2008; Rolke & Hofmann, 2007) as well as the temporal resolution (Experiments 2a to 2c) of the visual system. This perceptual facilitation by temporal preparation questions the unspecific motor character of the temporal preparation effect that has been proposed by Sanders (1980) and been backed up by a variety of studies that demonstrated an influence of temporal preparation on various correlates of motor processing (e.g., Brunia et al., 1982; Hasbroucq et al., 1997; Loveless & Sanford, 1975; Mattes & Ulrich, 1997). Contrasting to this motor view of temporal preparation, many researchers tend more and more to conceive temporal preparation as an attentional phenomenon. This conception is reflected, for example, in definitions of the preparatory process as "orienting attention to time" (e.g., Lange & Röder, 2006).

Relating the mechanisms underlying temporal preparation to attention seems to be a viable account, because similar effects on the accuracy of visual processing have been obtained for other attentional manipulations. For example, it has been shown that spatial orienting of attention facilitates spatial resolution (e.g., Carrasco, Penpeci-Talgar, & Eckstein, 2000; Cheal, Lyon, & Hubbard, 1991; Henderson, 1991; Yeshurun & Carrasco, 1999), and also – at least when attention is directed voluntarily by means of predictive spatial cues – temporal resolution (Hein et al., 2006) within the visual system. The beneficial effect of spatial attention, however, is not restricted to the visual modality. Specifically, spatial orienting also improves auditory processing (e.g., Mondor & Zatorre, 1995; Spence & Driver, 1994). Spence and Driver (1994), for example, found improved target localization and pitch discrimination when attention was directed to the side of target presentation by means of a predictive auditory cue. Such facilitating effects of spatial attention orienting can also be observed across different modalities as vision, audition, and touch (Spence & Driver, 1997;

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[14] The data reported below have been published in: Bausenhart, K. M., Rolke, B., & Ulrich, R. (2007). Knowing when to hear aids what to hear. *Quarterly Journal of Experimental Psychology, 60*, 1610-1615.

Spence, Nicholls, Gillespie, & Driver, 1998). According to these results, attentional selection can be described as a general, modality-independent process.

Accordingly, if temporal preparation exerts its effects by enabling an orientation of attention to time, it should, like spatial attention, not only facilitate visual perceptual processing, but also enhance perceptual processing within other sensory modalities. As outlined in the Introduction, electrophysiological evidence resulting from the investigation of auditory perception-related post-stimulus ERPs seems to support this notion. Specifically, these studies demonstrated within the framework of temporal orienting that the amplitudes of early auditory ERPs are enhanced by temporal preparation (Lange et al., 2006; Lange et al., 2003; Sanders & Astheimer, 2008). It remains unclear, however, if these effects on ERP amplitudes go along with corresponding improvements in accuracy measures. Even though some studies found that temporal preparation improves auditory stimulus detection (e.g., Howarth & Treisman, 1958, 1961; Treisman & Howarth, 1959; Wright & Fitzgerald, 2004), it seems rather unclear whether these results reflect a genuine improvement of perceptual processing, or whether preparation-related shifts in decision criteria might have contributed to these results (cf. Chapter 1.4.1.3 of the Introduction). More convincing evidence for an influence of temporal preparation on perceptual processing within the auditory modality therefore might be derived by employing discrimination tasks. Accordingly, two experiments were conducted to investigate the influence of temporal preparation on auditory discrimination thresholds.

2.3.1 Experiment 3a

This experiment investigated the influence of temporal preparation on auditory perceptual processing. To this end, participants were required to perform a pitch discrimination task within a single stimulus presentation procedure. Specifically, in each trial, one of two differently pitched target stimuli was presented and participants had to decide whether they just had heard the high- or the low-pitched tone. The duration of the target tone was changed adaptively from trial to trial according to participants' performance in order to estimate the tone duration associated with approximately 75 % correct responses. Temporal preparation for the target tones was manipulated by means of a constant foreperiod paradigm.

2.3.1.1. Method

Participants

14 subjects (mean age 26.9 years), among them nine women, participated in this experiment. According to self-report, all but one were right-handed and none of them reported hearing problems.

Stimuli and apparatus

Stimulus presentation was controlled via Matlab, using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997). The target stimulus was a pure sinusoidal tone of 800 or 816 Hz (70 db SPL). This target was preceded by a warning signal and followed by a mask, both of which consisted of white Gaussian noise (average power 80 db SPL, maximum frequency 11,128 Hz). All auditory stimuli were presented binaurally over headphones. Responses were collected via the left and right 'Shift' keys of a standard German keyboard.

Procedure and design

Each trial (see Figure 2.12) started with the presentation of a silent interval of variable duration, randomly selected from an exponential distribution with a mean of 2,000 msec. Then, the warning signal was presented for 200 msec and followed by another silent interval of 600 or 2,200 msec, yielding foreperiod durations of 800 or 2,400 msec, respectively. At the end of the foreperiod, one of the two target stimuli was presented and immediately followed by the mask for 300 msec. To discourage speeded responding, a silent interval of 500 msec followed the mask. Then, a visual signal appeared on the screen indicating that a decision was required within 2,000 msec. Specifically, the German words "Tiefer Ton" (low pitch) and "Hoher Ton" (high pitch) were presented at the lower left and right side of the computer screen, and participants were required to press the left or right 'Shift' key to indicate whether they had perceived the low- or the high-pitched tone, respectively. The trial ended 800 msec after participants completed this two-alternative forced-choice task.

Each of the two foreperiod durations was presented for 230 successive trials, and the order of foreperiod conditions was balanced across participants. Within each of these foreperiod conditions, targets were high-pitched in 50 percent of the trials, and low-pitched in the remaining 50 percent of the trials. The two target pitches were presented in random order. In the first 30 trials of each foreperiod condition, target duration was kept constant at 50 msec to familiarize participants with the two pitches. These trials were discarded from data analysis.

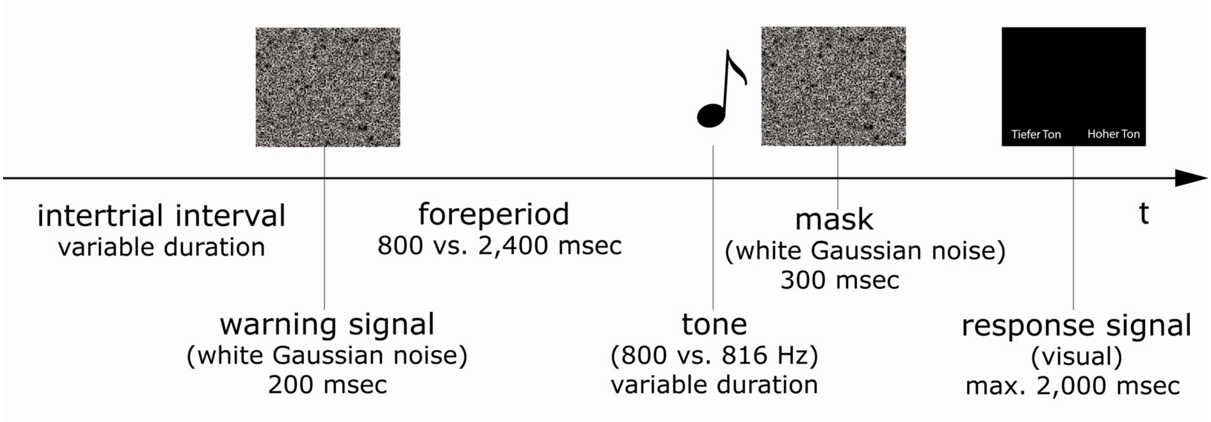

Figure 2.12. Time course of an experimental trial in Experiment 3a.

For the following trials, the duration of the target was changed adaptively according to the weighted up-and-down procedure by Kaernbach (1991) in order to estimate the target duration associated with 75% correct responses for each foreperiod duration and participant (threshold duration). Specifically, after each correct response, target duration was decreased by 2 msec, while after each incorrect response, target duration was increased by 6 msec. Since it is known that pitch discrimination deteriorates with decreasing target duration (e.g., Moore, 1973), smaller threshold durations indicate better performance.

2.3.1.2. Results

To estimate threshold duration, the proportion of correct responses for each presented target tone duration was computed separately for each participant and foreperiod duration. Then, a maximum likelihood procedure was employed that maximized the likelihood of a psychometric function ranging from 50 to 100 percent of correct responses. Specifically, a two-alternative forced-choice logistic function (Equation 2) was fitted to the observed data points (Ulrich & Miller, 2004) in order to estimate the parameters *threshold duration* and *b*.

$$P(correct \mid x) = 0.5 + \frac{0.5}{1 + e^{-(x - threshold\,duration)/b}} \qquad (2)$$

In this function, P represents the probability of a correct response at a target duration of x, *threshold duration* is the target duration corresponding to a value of 75 percent of correct responses, and b is a scale parameter. This was done for each participant and foreperiod duration separately, and a t-test was conducted on the resulting estimated threshold durations. This t-test revealed better performance for short foreperiods (threshold duration = 21.5 msec) than for long foreperiods (threshold duration = 27.8 msec), $t(13) = 2.82, p < .05$.

2.3.1.3. Discussion

The shorter threshold durations obtained for short compared to long foreperiod durations indicate that temporal preparation facilitates pitch discrimination. Therefore, this result strongly suggests a perceptual locus of temporal preparation that is not restricted to the visual modality, but extends to the auditory modality as well. The present results, however, are subject to an alternative interpretation. According to this interpretation, not only temporal preparation but also short term memory processes might have been influenced by the employment of different foreperiods. Specifically, within the single stimulus presentation procedure employed here, participants have to form a memory representation of each of the two target tones (or of a single subjective “standard tone” with a pitch between the two target tones) to enable decisions about target pitch. Given that short foreperiod trials have a shorter overall duration than long foreperiod trials, the increased rate of target presentation within the short foreperiod condition might have especially strengthened the short term memory representations of the targets in this condition. As a consequence, a more stable representation of the target tones would have been built in the short foreperiod condition, thereby improving pitch discrimination in this condition. Thus, Experiment 3b was designed to overcome potential short term memory effects within the single stimulus presentation procedure employed here.

2.3.2. Experiment 3b

Experiment 3b was conducted to rule out this alternative interpretation of Experiment 3a and to strengthen the notion that temporal preparation facilitates early auditory processing. To this end, trial duration in both foreperiod conditions of Experiment 3b was kept constant in order to minimize possible influences on the stability of short term memory representations. Thus, if temporal preparation exerts its influence via a facilitation of perceptual processing, again, improved pitch discrimination associated with short compared to long foreperiods is expected. If, however, the positive influence of temporal preparation on pitch discrimination observed in Experiment 3a was solely due to short term memory processes, Experiment 3b should not reveal such a pattern.

2.3.2.1. Method

Participants

A fresh sample of 18 participants (mean age: 27.7 years, 12 female) was recruited. According to self-report, all but two were right-handed and none of them reported hearing problems.

Stimuli and apparatus

All stimuli were identical to those employed in Experiment 3a.

Procedure and design

The procedure was identical to Experiment 3a, except of the following change. In case of the short foreperiod duration, an additional time interval of 1,600 msec was introduced between the variable intertrial interval and the presentation of the warning signal. This interval, combined with the duration of the short foreperiod (800 msec), added up to 2,400 msec. Consequently, the duration of short foreperiod trials exactly mirrored the duration of long foreperiod (2,400 msec) trials. Thus, an equal rate of target stimulus presentation was provided for both conditions of temporal preparation.

2.3.2.2. Results

The procedure to obtain estimations of threshold duration for each participant and foreperiod duration was identical to the one employed in Experiment 3a. As in Experiment 3a, a *t*-test on the obtained estimations of threshold duration revealed better pitch discrimination performance for short foreperiods (threshold duration = 16.9 msec) than for long foreperiods (threshold duration = 20.1 msec), $t(17) = 2.12$, $p < .05$.

2.3.2.3. Discussion

Since the effect of foreperiod duration on threshold duration in the present experiment in absolute terms is smaller than the one observed in Experiment 3a, short term memory processes indeed might have contributed to the effect found in Experiment 3a. This possibility, however, has been ruled out in the present experiment. Therefore, the remaining effect of temporal preparation on pitch discrimination performance observed here cannot be attributed to a beneficial influence of temporal preparation on the formation or stabilization of short term memory representations of the target stimuli. Accordingly, this effect further strengthens the idea that temporal preparation improves perceptual processing within the auditory modality.

2.3.3. General Discussion

The present results show that temporal preparation enhances pitch discrimination performance. Specifically, shorter target durations were necessary to identify pitch correctly in 75% of all trials in the short foreperiod condition than in the long foreperiod condition. Because the discrimination task employed here depends primarily on perceptual processing, an exclusive motor locus of temporal preparation effects has to be rejected on basis of the present results. In addition, the results of Experiment 3b ruled out an alternative explanation according to which the facilitating effect obtained in Experiment 3a is due to an especially stable internal representation of the target stimuli in the short foreperiod condition.

These results further extend the findings of previous studies which indicate an influence of temporal preparation on auditory stimulus detection (e.g., Howarth & Treisman, 1958, 1961; Treisman & Howarth, 1959; Wright & Fitzgerald, 2004). Specifically, improved performance in a discrimination task is unlikely to result from a pure change in decisional criteria. Therefore, the present results argue strongly for a genuine improvement of perceptual processes within the auditory modality. Moreover, these findings also are consistent with an independent line of evidence showing an influence of temporal preparation on auditory perceptual processing. This evidence stems from temporal orienting studies which demonstrated a modulation of the amplitude of perception-related auditory ERP components (Lange et al., 2006; Lange et al., 2003; Sanders & Astheimer, 2008). Therefore, it seems plausible to assume that similar mechanisms underlie the beneficial effects of temporal preparation on auditory perception within the constant foreperiod paradigm and temporal orienting studies.

Taking together the present results and those of previously conducted studies, it seems likely that these mechanisms are not bound to a specific modality. More precisely, the observed beneficial effect of temporal preparation on auditory perception is closely in line with the influence of constant foreperiods on spatial and temporal resolution observed within the visual modality (Rolke, 2008; Rolke & Hofmann, 2007, see also Experiments 2a to 2c of the present work). Furthermore, the present results also agree with other studies that demonstrated effects of temporal preparation on correlates of visual and tactile perception within temporal orienting paradigms (e.g., Correa et al., 2005; Correa, Sanabria et al., 2006; Lange & Röder, 2006). Therefore, and presumably comparable to spatial orienting processes, the mechanism by which temporal preparation aids perceptual processing can be characterized as a modality-unspecific attentional orienting mechanism.

The specific performance measure employed in the present study also enables some speculations on how such a mechanism might improve perceptual discrimination. Specifically, threshold duration indicates how much time is needed to extract sufficient information from a physical stimulus presentation to enable correct decisions about target pitch in 75 percent of all trials. Hence, when temporal preparation was impaired in the long foreperiod condition, a longer physical stimulus presentation, and therefore more time to extract information about the stimulus was needed to achieve the same level of performance as in the short foreperiod condition. Therefore, one might assume that the dynamics of information processing may be altered by temporal preparation. For example, and consistent to the early onset hypothesis proposed by Rolke and Hofmann (2007), temporal preparation might enable an earlier onset of information accumulation following target stimulus onset. Alternatively, a higher rate of information accumulation (Correa, Sanabria et al., 2006) might also account for the observed effects, because this implies that more information could be extracted from a physical stimulus during a given amount of time. Although the present results may be suggestive, however, they do not enable a conclusion on whether one or both of these mechanisms actually contribute to temporal preparation effects. Therefore, Experiment 4 of the present work was designed to test these assumptions more directly.

Finally, it should be noted that the present results also have important implications for theorizing about the role of attention in audition. Specifically, it has been well demonstrated that attention can be directed to specific frequency regions, thereby improving perceptual accuracy for stimuli within these regions (Hübner & Hafter, 1995; Ward, 1997). Likewise, orienting attention to a spatial direction can also facilitate discrimination of auditory stimuli from that direction (Spence & Driver, 1994). Based on these findings, Mondor, Zatorre, and Terrio (1998) proposed that selection of auditory information depends on an attentional template defined by both frequency and location. In contrast, we used a warning signal that was uninformative about inherent properties of the target, as its frequency or its spatial location. Nonetheless, this unspecific warning signal did improve pitch discrimination. This perceptual facilitation might reflect that the time of occurrence per se serves as a target feature which can be used for attentional selection. Alternatively, temporal preparation might have raised the effectiveness with which attention to nontemporal stimulus features, such as frequency or location, was focused on the target (see Doherty et al., 2005 for a similar account in the visual modality). In either case, the present result highlights the importance of the temporal dynamics in orienting of attention. Therefore, considering the role of temporal preparation seems to be necessary for any complete account of attention in the auditory domain.

2.3.4. Conclusion

Taken together, the present experiments demonstrated that the time needed to identify the pitch of an auditory target stimulus decreases with decreasing foreperiod duration. Therefore, temporal preparation in a constant foreperiod paradigm improves perceptual processing within the auditory modality. Hence, these results provide strong evidence for a perceptual locus of temporal preparation and suggest that temporal preparation exerts its influence through a modality-unspecific attentional facilitation of perceptual stimulus processing. Again, these results might be explained by changes in the dynamics of information processing. For example, temporal preparation might lead to an early onset of information processing or to a higher rate of information sampling in the perceptual system.

2.4. Temporal preparation affects the dynamics of the response: Evidence from speed-accuracy trade-off functions

In the previous experiments, it was demonstrated that temporal preparation shortens processing time from stimulus to response (Experiment 1), and improves perceptual processing in the visual (Experiment 2a-2c) as well as in the auditory modality (Experiment 3a & 3b). These results confirm and extend previous studies that raised the possibility of a premotor locus of temporal preparation effects (e.g., Correa et al., 2005; Rolke & Hofmann, 2007, cf. Chapter 1.4.1.3). Further support for this notion stems from converging electrophysiological evidence which shows that temporal preparation shortens the S-LRP interval (e.g., Hackley & Valle-Inclán, 2003; Müller-Gethmann et al., 2003, cf. Chapter 1.4.2.5), and affects the amplitudes of perception-related ERPs (e.g., Correa, Lupiáñez, Madrid et al., 2006; Lange et al., 2006; Lange et al., 2003, cf. Chapter 1.4.2.6). Taking these results together, it seems reasonable to assume that temporal preparation unfolds its effects – at least partly – in premotor or even perceptual processing stages.

Despite this growing body of evidence for a premotor locus of temporal preparation effects, so far, relatively little progress has been achieved in shedding light on the mechanisms underlying these effects. As has been described previously, however, temporal preparation effects might be explained by the assumption that temporal preparation changes the dynamics of information processing. For example, temporal preparation might lead to an earlier onset of the accumulation of perceptual information about a target stimulus (Rolke & Hofmann, 2007; cf. Chapter 1.3.2). More specifically, this early onset account assumes that during stimulus processing, external stimulus information is translated into internal activation and accumulated over time. When the amount of accumulated information reaches a criterion level, a decision is made and a response is initiated (cf. Grice, 1968). If the accumulation of perceptual evidence can begin earlier when temporal preparation is high, this model implies that a higher level of accumulated activation would be reached when stimulus processing becomes interrupted, for example, by a masking stimulus (Kahneman, 1968; Sperling, 1963). This account therefore predicts that temporal preparation improves the accuracy of stimulus detection and discrimination, because post-perceptual decision processes are supplied with more relevant stimulus information under high levels of temporal preparation. In addition, shorter RT should be observed when participants are temporally well-prepared, as the criterion level would be reached earlier and thus, response selection and execution could start – and accordingly would be finished – earlier. Hence, this model can account for the results of various studies which have demonstrated that temporal preparation improves perceptual discrimination and shortens RT as well as the duration of premotor processing (Experiments 1-3; see also Correa et al., 2005; Klein & Kerr, 1974; Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981).

There is, however, an alternative account to this early onset model. According to this alternative, information accumulation would not start earlier when one is temporally well prepared, but the uptake of information about the stimulus would be faster, thus resulting in a higher rate of information accumulation. Similar to the early onset hypothesis, this account suggests that the criterion on which one bases his reactions would be reached sooner under conditions that enable good temporal preparation. This idea is strongly related to the finding that temporal preparation improves the temporal resolution of the visual system (cf. Experiment 2; see also Correa, Sanabria et al., 2006). This finer temporal resolution might be the result of a mechanism that increases the speed of perceptual information sampling when participants are temporally well prepared. Such a higher speed of information sampling, in turn, might result in a higher rate of information accumulation and thereby improve discrimination performance.

The two accounts outlined above (i.e., early onset and higher rate of information accumulation) assume that temporal preparation changes the dynamics of information processing. However, enhanced perceptual discriminability might also be explained by signal enhancement or a more effective suppression of external background noise. Such effects have already been well documented within the domain of spatial orienting. Specifically, it has repeatedly been shown that covert spatial attention increases spatial resolution by reducing the influence of interfering external noise (Morgan, Ward, & Castet, 1998; Shiu & Pashler, 1995), and by enhancing contrast sensitivity of the perceptual system (Cameron, Tai, & Carrasco, 2002; Carrasco et al., 2000; Carrasco, Williams, & Yeshurun, 2002; Reynolds, Pasternak, & Desimone, 2000). Such changes might as well be induced by temporal preparation, and they would improve the quality of the stimulus representations without necessarily changing the dynamics of stimulus processing.

The speed-accuracy trade-off function

So far, experimental research does not yield conclusive results about which of these proposed mechanisms (earlier start of information accumulation, higher rate of information accumulation, or enhanced discriminability) contribute to the perceptual effects of temporal preparation. Clearly, such a distinction can not be accomplished on the basis of conventional

RT experiments. However, important insights in these mechanisms might be gained by investigating the speed-accuracy trade-off (SAT) functions underlying performance. A SAT function reflects the relationship between processing time and accuracy and therefore incorporates measures of the dynamics of processing as well as discrimination performance (e.g., Carrasco & McElree, 2001; Dosher, 1976, 1981; Reed, 1973; Wickelgren, 1977).

Specifically, in a typical SAT experiment the time available for stimulus processing is manipulated, and the response accuracies corresponding to different processing times are registered. This can be accomplished, for example, with the response signal method (e.g., Carrasco, Giordano, & McElree, 2006; Miller, Sproesser, & Ulrich, 2008; Wickelgren, 1977). In this method, and similar to conventional RT experiments, a target stimulus is presented to which participants have to make a two-alternative forced-choice decision. Unlike in RT experiments, however, participants are instructed to withhold their response until a response signal is presented. Importantly, the stimulus onset asynchrony (SOA) between the target stimulus and the response signal is varied from trial to trial. This procedure reveals a characteristic relationship between SOA and the obtained level of accuracy. For very short SOAs, participants' performance is close to chance level. The more time is available for target processing (i.e., the longer the SOA), the more accurate participants' responses will be. Clearly, if SOA is increased beyond a critical duration, no further gains in accuracy will be observed, as participants have already reached maximum accuracy for the requested decision (Figure 2.13).

This relationship between processing time (t) and accuracy of performance can be described mathematically by an exponential approach to an asymptotic performance level:

$$Accuracy(t) = \upsilon + (\lambda - \upsilon)(1 - e^{-\beta(t-\delta)}) \quad \text{for } t > \delta \text{, else 0,} \quad (3)$$

where υ corresponds to the chance level of performance (e.g., in the present experiment, υ equals 50 % of correct responses, because a two-alternative forced-choice task was employed). λ corresponds to the *asymptote* of the function, that is, the maximum level of performance that can be reached when ample processing time is available for stimulus processing. This parameter thus indicates discriminability. δ denotes the *intercept* of the SAT function, that is, the processing time at which a participant's responses depart from chance level. Finally, β is the *rate* parameter, which describes how fast processing accuracy rises from chance to asymptote. Accordingly, δ and β are indicative of processing speed, that is, the dynamics of information processing. More specifically, the rate parameter describes the speed of information accumulation, whereas the intercept denotes the onset of information accumulation.

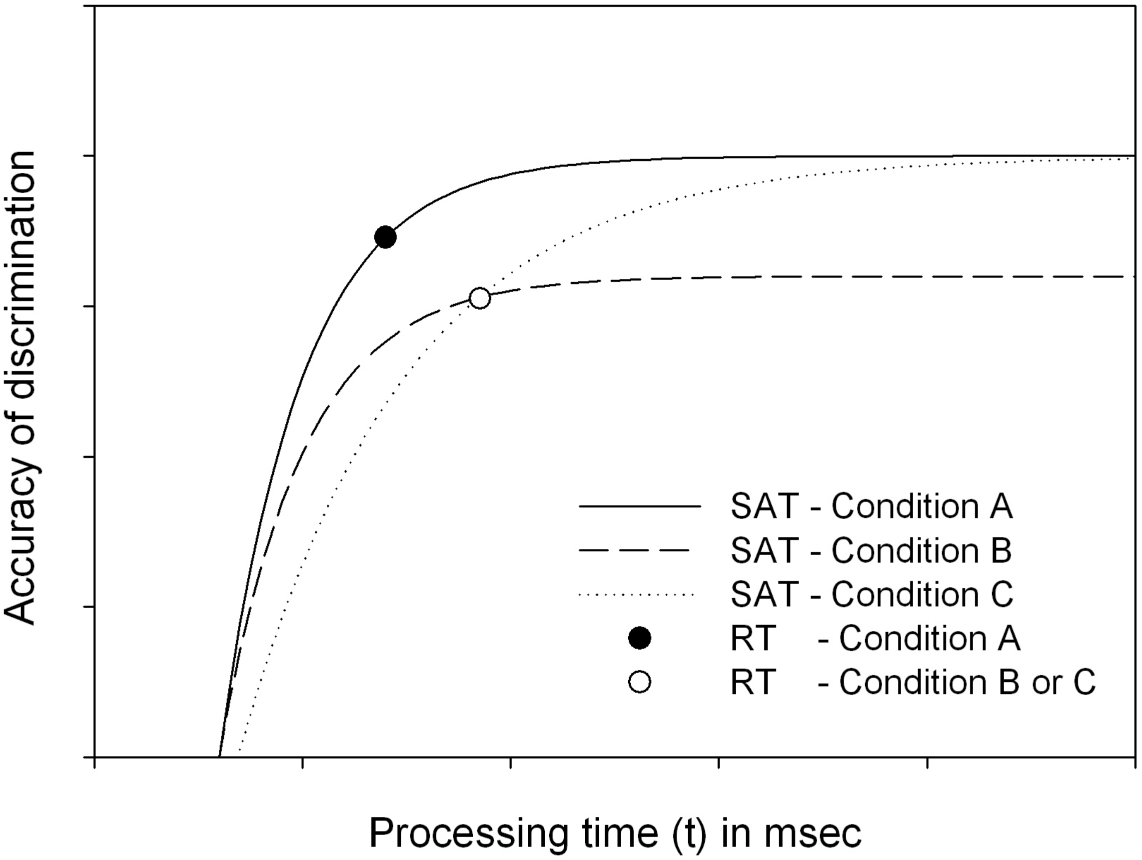

Figure 2.13. Hypothetical SAT functions relating processing time to accuracy corresponding to three different experimental conditions (A, B, and C). Condition A differs from Condition B only in asymptote, but not in rate or intercept. In contrast, Condition C has the same asymptote as Condition A, but a different rate and intercept. Note that even though RT data obtained within a simple RT experiment (circles) can reveal differences between experimental conditions (compare A, filled circle, with B/C, open circle), this is not necessarily the case: Identical RT results might be obtained even though the SAT functions underlying performance differ drastically (see Conditions B and C).

The three parameters λ, β, and δ can be estimated depending on participants' performance in various experimental conditions. Differences in these estimated parameters between conditions can then be attributed to differential effects exerted by the experimental manipulation on discriminability, the speed of information accumulation, or the onset of information accumulation. For example, in Figure 2.13, hypothetical SAT functions corresponding to three different experimental conditions (A, B, and C) are depicted. It can be seen that Conditions A and B differ in their asymptote, but not in rate or intercept. Thus, one can conclude that the experimental manipulation that distinguishes Condition A from B affects only discriminability. In contrast, Condition C shares the same asymptote with Condition A, but has a later intercept, and a smaller rate. Thus, in Condition C, information accumulation starts later, and information is aggregated more slowly than in Condition A. However, if there is sufficient time available for stimulus processing, it can be seen that discriminability does not differ between those conditions.

Importantly, these insights cannot be gained by means of a regular RT experiment. This is illustrated by the circles in Figure 2.13, which depict hypothetical results of such an RT experiment. Even if it can safely be concluded that Condition A (filled circle) is somewhat easier to perform than Conditions B and C (open circle), because responses are more accurate and faster in Condition A, one cannot decide whether this effect results from differences in discriminability or in the dynamics of information processing. Finally, even though the SAT functions underlying performance in Conditions B and C differ clearly from each other in processing dynamics and in discriminability, an RT experiment might fail to reveal any difference between those conditions at all (open circle). Hence, SAT experiments are an especially useful tool for investigating differences in the dynamics of information processing.

SAT methodology has been repeatedly employed to gain insights into processing dynamics (Carrasco, Giordano, & McElree, 2004; Carrasco et al., 2006; Carrasco & McElree, 2001; Carrasco, McElree, Denisova, & Giordano, 2003; Dosher, 1976, 1981; McElree & Carrasco, 1999; McElree, Murphy, & Ochoa, 2006). For example, Carrasco and McElree (2001) used exogenous cues in a visual search task to direct covert spatial attention to the target location. By employing the response signal method to manipulate SAT, they found increased asymptotes as well as a higher rate of information accumulation in the cued condition compared to a condition with neutral cues. Thus, covert spatial attention does not only improve discriminability, but also increases the speed of information accumulation. In a similar way, SAT procedures have been successfully employed to investigate the theoretical mechanisms underlying, for example, visual search (Carrasco et al., 2006; McElree & Carrasco, 1999), memory retrieval processes (Boldini, Russo, Punia, & Avons, 2007; Dosher, 1981; Hintzman & Caulton, 1997; Mulligan & Hirshman, 1995; Wickelgren, Corbett, & Dosher, 1980), and the processing of semantic information (McElree, Murphy et al., 2006; McElree, Pylkkänen, Pickering, & Traxler, 2006).

2.4.1. Experiment 4

In the present experiment, a SAT procedure was employed to investigate the influence of temporal preparation on the dynamics of stimulus processing. To this end, a response signal SAT procedure was combined with a spatial discrimination task (Miller et al., 2008; Wickelgren, 1977) and with a constant foreperiod paradigm. Given Rolke and Hofmanns' (2007) notion of early onset as described above, one would expect that good temporal preparation results in a earlier start of information accumulation. Accordingly, the intercept of the SAT function estimated in an experimental condition with good temporal preparation should be shorter than the intercept of a condition with worse temporal preparation. The idea that temporal preparation is associated with faster information accumulation brought forward by studies investigating performance in TOJ (cf. Experiments 2a-c; see also Correa, Sanabria et al., 2006), however, might be reflected in a variation of the rate parameter of the SAT function. Finally, if temporal preparation exerts its effects on stimulus processing merely by improving discriminability, this should result in differences in asymptotic performance.

2.4.1.1. Method

Participants

16 participants were tested. The data of one participant had to be replaced because Equation 3 provided poor fits for these data, that is, the model fits showed uniformly small adjusted R^2 values, all below 0.5.[15] The final sample consisted of 14 woman and 2 men with a mean age of 26.1 years (SD = 4.8). They received either course credit or payment for their participation. According to self-report, all but one were right-handed, and all had normal or corrected-to-normal vision.

Stimuli and apparatus

All visual stimuli were presented in white (90 cd/m²) on a black background (< 1 cd/m²). Stimulus presentation was controlled via Matlab, using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997). Participants were seated in a dimly lit room at a viewing distance of approximately 50 cm from the computer screen. The visual stimuli consisted of a horizontal (3.9° × 0.1° visual angle) bar and two vertical bars of slightly different lengths (3.8° and 4.0°, width 0.1° visual angle). White Gaussian noise (80 dB, 200 msec) served as

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[15] However, including the data of this participant in the analyses did not change any of the reported effects.

warning signal, and a pure sinusoidal tone of 800 Hz (76 dB, 50 msec) served as the response signal. Responses were collected via the left and right ‘Arrow’ keys of a standard keyboard.

Procedure and design

The time course of a single experimental trial is depicted in Figure 2.14. Throughout each trial, a horizontal line was presented at the centre of the screen. First, this horizontal line was presented alone for a variable time interval (200 msec + X, with the random variable X following an exponential distribution with a mean of 2,000 msec). This random duration is assumed to increase the functional significance of the warning signal (Müller-Gethmann et al., 2003). At the end of this interval the warning signal was presented for 200 msec binaurally via headphones. After a foreperiod of either 800 or 2,400 msec following warning signal onset, the target stimulus (a vertical line) was superimposed on the horizontal line, so that both lines formed a cross. The vertical line remained on the screen for 50 msec and was positioned in such a way that it bisected the horizontal line, and its lower part had exactly the same length as the right and left part of the horizontal line, but the upper part of the vertical line was either 2 pixels shorter or longer than the other three parts of the cross. After a variable SOA of 50, 100, 150, 200, 300, 500, 1,000 or 2,000 msec following target stimulus onset, the response signal was presented binaurally over headphones for 50 msec. Within 300 msec after response signal onset, participants had to indicate with a key press whether the upper line was longer or shorter than the other parts.

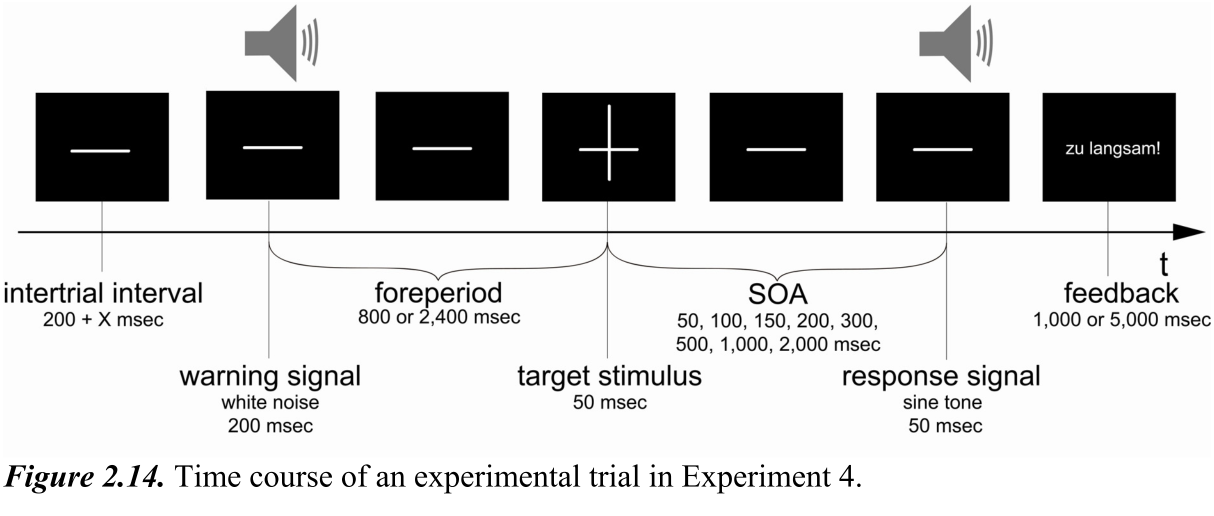

Figure 2.14. Time course of an experimental trial in Experiment 4.

For a “shorter” response, half of the participants pressed the left ‘Arrow’ key with their left index finger. For a “longer” response, they pressed the right ‘Arrow’ key with their right index finger. For the other half of participants, this assignment was reversed. Visual error feedback was provided after registration of the key press or after 1,000 msec in case no key was pressed. The feedback was presented 2.8° of visual angle below the screen centre in case of a wrong, anticipated (RT < 0 msec) or too slow response (RT > 300 msec). After a wrong answer, the German word “Fehler” (“error”) remained on the screen for 1,000 msec. After an anticipation or a too slow response the German phrases “zu früh reagiert” (“too early”) or “zu langsam” (“too slow”) were presented for 5,000 msec, respectively. This long presentation time was chosen to motivate participants to respond within the required RT window of 300 msec.

Each participant took part in four experimental sessions conducted on separate days. Each session consisted of 12 blocks with 48 trials each. Foreperiod duration (800 vs. 2,400 msec) was kept constant within each block of trials, but alternated between blocks of trials. Half of the participants began with a 800 msec foreperiod block, and the other half began with a 2,400 msec block. The SOA was varied from trial to trial, and each of the eight SOA durations was presented with equal likelihood and thus 6 times within each block. The first complete session was considered practice and therefore discarded from data analysis.

2.4.1.2. Results

First, all trials with RTs that fell outside the required time window of 300 msec were discarded from further analysis (11.92 %). For the remaining trials, mean response latency (i.e., SOA + RT) and mean percentage of correct responses were calculated separately for each participant, SOA and foreperiod duration. The SAT function described above (see Equation 3) was then fitted to these data by means of a least-squares minimization (cf. McElree & Carrasco, 1999), based on the simplex search method by Nelder and Mead (1965). Accordingly, this procedure estimated parameters for discriminability (λ) as well as processing speed (β and δ) that minimized the root mean squared deviations of the predicted values from the observed data for each participant and foreperiod duration. In addition, we fitted the SAT function to the data averaged across all participants.

As outlined above, temporal preparation might exert its influences either by improving stimulus discriminability, by shortening the time until onset of information accumulation, by increasing the rate of information accumulation, or also by any combination of these mechanisms. To test for all these possibilities, we adopted a nested model testing scheme (see also McElree & Carrasco, 1999, for a description of this approach). According to this scheme eight models were fitted to the data of each participant and also to the averaged data. The eight models differed from each other with respect to how many parameters of the SAT function were allowed to vary according to foreperiod condition. The most conservative of these models allowed only one common asymptote as well as one common rate and one common intercept for both foreperiod conditions. Accordingly, this model assumes no influence of temporal preparation on any of the parameters of the SAT-function. In the following, this model will be termed *1λ-1β-1δ*. In contrast, the least restrictive model (termed *2λ-2β-2δ*) fitted different asymptotes, rates and intercepts for each of the two foreperiod conditions. All other possible models between those two extremes were fitted as well. The quality of the fits was then determined by an adjusted R^2 statistic (Reed, 1976),

$$R^2{}_{adj} = 1 - \frac{\sum_{i=1}^{n} (d_i - \hat{d}_i)^2 / (n-k)}{\sum_{i=1}^{n} (d_i - \bar{d})^2 / (n-1)} \qquad (4)$$

in which d_i are the observed data values, $\hat{d}_i$ are the predicted data values, n is the number of observed data points, and $\bar{d}$ is the mean of data values. Importantly, the accounted variance is adjusted by the number of free parameters (k) of the respective model. Thus, $R^2{}_{adj}$ imposes a penalty for models which allocate more parameters to the different conditions, and as a result, more parsimonious models are preferred over less restrictive ones.

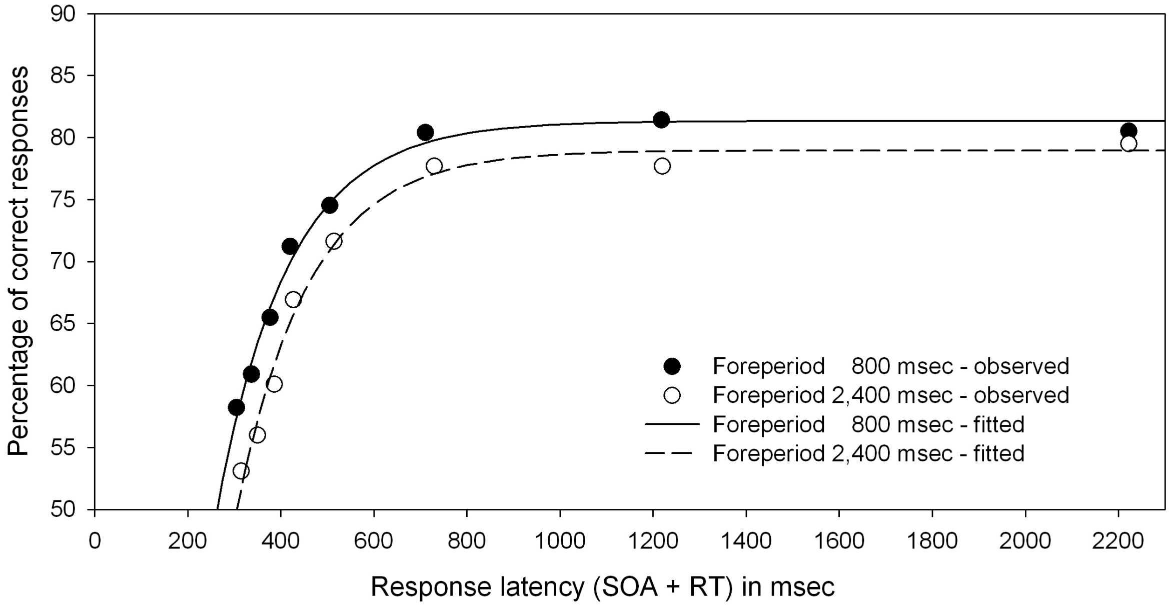

Figure 2.15. Symbols represent the average response accuracy in percent correct as a function of response latency and foreperiod duration (800 vs. 2,400 msec) in Experiment 4. Curves show the best-fitting SAT functions for these average data. The parameters of these functions are listed in Table 2.1.

For the data averaged across all participants, the highest value of adjusted R^2, and thus, the best fit was yielded by the *2λ-1β-2δ* model, that is, the model that assumed one common rate parameter, but separate parameters for asymptote and intercept for each foreperiod condition (see Figure 2.15). Short foreperiods resulted in a higher asymptotic performance as well as an earlier intercept (see Table 2.1 for the respective parameter estimates). Adjusted R^2 for this model was 0.985, which constitutes an improvement as compared to, for example, the adjusted R^2 of 0.914 for the conservative *1λ-1β-1δ* model, or 0.945 for the *2λ-1β-1δ* model, which allocates different asymptotes, but an identical rate and intercept to the different foreperiod conditions.

Importantly, the differences in dynamics between the two foreperiod conditions could not be better captured in the rate parameter, as an adjusted R^2 of 0.968 for the *2λ-2β-1δ* model clearly indicates. This value shows, however, that modelling foreperiod differences in rate and asymptote represents the data better than modelling differences in asymptote alone. Despite that this might indicate some possible influence of foreperiod on the rate parameter, the fully saturated *2λ-2β-2δ* model which allocates separate values for each foreperiod condition to each of the three parameters produced an adjusted R^2 of 0.984, and thus did not further improve the fit of the *2λ-1β-2δ* model.

Table 2.1
Parameters of the Best Fitting Model (2λ-1β-2δ) for the SAT Function Fitted to the Data of Experiment 4 Averaged Across All Participants

	Foreperiod 800 msec	Foreperiod 2,400 msec
Asymptote*(λ)*	81.33	78.96
Rate (1/*β)*	155.1	155.1
Intercept (*δ*)	263.1	305.6

Note. Asymptote is given in percent, intercept in msec. For convenience, rate is expressed as its inverse 1/*β*, which is also measured in msec units.

These results were further corroborated when participant-specific fits were regarded. Although there was considerable variability regarding the individual best fitting models, the sum of adjusted R^2 values across participants for the *2λ-1β-2δ* model was higher than for all other models. The parameters of this model, individually fitted for each participant, and the corresponding means of these values are depicted in Table 2.2. One-tailed paired-sample *t*-tests confirmed that the short foreperiod condition was associated with shorter intercepts, $t(15) = 3.18$, $p < .01$, and higher asymptotes, $t(15) = 2.48$, $p < .05$, than the long foreperiod condition.

Table 2.2
Parameters of the Overall Best Fitting Model (2λ-1β-2δ) for the SAT Functions Individually Fitted for Each Participant

	Asymptote (λ)		**Rate ($1/\beta$)**	**Intercept (δ)**		R^2_{adj}
Participant	FP 800 msec	FP 2,400 msec		FP 800 msec	FP 2,400 msec	
1	79.84	76.55	146.7	215.0	229.6	0.568
2	76.13	68.33	129.4	315.3	321.9	0.703
3	85.98	81.78	62.9	290.6	314.8	0.949
4	85.36	82.31	181.9	231.8	221.0	0.744
5	82.52	78.81	127.5	330.1	342.6	0.947
6	80.29	77.77	145.2	304.6	335.1	0.911
7	88.53	84.90	138.0	286.7	334.2	0.892
8	78.00	82.71	154.2	218.9	282.1	0.727
9	81.71	85.52	193.7	294.4	313.7	0.681
10	84.14	78.17	205.3	227.0	241.8	0.760
11	86.27	77.79	171.3	261.2	326.9	0.816
12	83.58	82.42	200.4	250.1	295.2	0.782
13	77.86	81.93	157.2	275.5	318.2	0.766
14	60.61	58.06	315.8	243.5	509.9	0.653
15	81.51	78.65	171.8	264.8	333.5	0.819
16	89.07	87.69	106.3	152.5	300.8	0.970
Mean	81.34	78.96	163.0	260.1	313.8	0.793
(*SE*)	(1.67)	(1.79)	(13.7)	(11.3)	(16.2)	(0.03)

Note. Asymptote is given in percent, intercept in msec. For convenience, rate is expressed as its inverse $1/\beta$, which is also measured in msec units. FP = foreperiod.

To consider a possible influence of individual differences carefully, we also determined the best-fitting model for each participant individually and then submitted the respective estimated parameters for asymptote, rate, and intercept to one-tailed paired-sample *t*-tests. These analyses provided further evidence for the idea that temporal preparation influences asymptote and intercept, but not the rate of information processing. Specifically, asymptotes corresponding to the short foreperiod duration were higher than for the long foreperiod duration, $t(15) = 2.43$, $p < .05$, and the intercept in the short foreperiod condition was earlier than in the long foreperiod condition, $t(15) = 2.36$, $p < .05$. Rate was not significantly influenced by foreperiod, $t(15) = 1.19$, $p = .13$. Similar effects were also obtained when the individual parameter estimates for the least restrictive model (2-2-2) were submitted to *t*-tests.[16]

2.4.1.3. Discussion

The present experiment investigated the influence of temporal preparation on the time course of information processing. Specifically, temporal preparation was manipulated in a constant foreperiod design and participants were required to perform a spatial discrimination task. The time available for stimulus processing was varied by employing the response signal SAT method, in order to obtain measures of response accuracy for a wide range of response latencies. SAT functions were fitted to these data to investigate which aspects of stimulus processing are influenced by temporal preparation. The results suggest that temporal preparation alters the dynamics of information processing and improves stimulus discriminability.

More specifically, the overall best-fitting model allocated separate intercepts and asymptotes to the two foreperiod durations. Theoretically most important, the quality of the model fit was substantially reduced when only one common intercept parameter was allowed for both foreperiod durations. Statistical comparisons of models fitted to the data of individual participants showed that intercepts were shorter for the short compared to the long foreperiod duration. Because the intercept of the SAT function denotes the point in time at which discrimination performance first departs from chance level, these results indicate that

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[16] An alternative way to take individual differences into account is to fit nonlinear mixed effects models (NLME) to the data (Pinheiro & Bates, 2000). This method of nonlinear multi-level regression allows estimating fixed and random effects simultaneously. Specifically, fixed effects correspond to the effects of experimental conditions on the sample mean (in our case, foreperiod effects on rate, asymptote and intercept), whereas random effects reflect interindividual differences in these effects, that is, the variability across participants that is associated with the fixed effects. Accordingly, one model is fitted to the data of all participants simultaneously (for an elaborate description of this approach, see Oberauer & Kliegl, 2006). We ran this alternative data analysis procedure using the nlme package for R (Pinheiro, Bates, DebRoy, & Sarkar, 2005) for all model versions from 1λ-1β-1δ to 2λ-2β-2δ. This procedure yielded virtually identical results to those described in the result section. The best fit was provided by a model that incorporated separate asymptotes (81.12 % and 78.76 %) and intercepts (271.2 msec and 311.1 msec) for the short and the long foreperiod condition, respectively, and one common rate parameter ($1/\beta = 144.9$ msec) as fixed effects. Systematic analyses revealed that interindividual variability in the data could be captured best with two additional random effects, one associated with asymptote and one associated with intercept. Thus, mixed effects models can readily account for the data observed in our experiment, and – as can be seen when comparing to Table 2.1 – the parametrization of the best-fitting model is fairly consistent with the results of the analysis described previously.

information about stimulus identity gets available earlier when participants are temporally well prepared. These results are closely in line with the early onset hypothesis (Rolke, 2008; Rolke & Hofmann, 2007), which suggests that temporal preparation enables an earlier onset of accumulation of stimulus information.

This evidence for an earlier onset of information accumulation corresponds well to the results of a number of studies which demonstrated that temporal preparation shortens the duration of premotor processing stages. Specifically, these studies employed latency measures such as the LRP (Hackley & Valle-Inclán, 1998, 1999; Müller-Gethmann et al., 2003) and RT in the PRP paradigm (cf. Experiment 1 of the present work) to bisect RT in a premotor and a motor processing phase. For example, Müller-Gethmann et al. (2003) investigated the influence of constant foreperiods on the duration of the S-LRP interval. This interval indexes the time from the presentation of a stimulus until the selection of an appropriate response to this stimulus, and therefore, the duration of premotor stimulus processing. The authors found that the S-LRP interval duration decreased with decreasing foreperiod duration. This shortening of the S-LRP interval might be the result of an earlier start of information accumulation: if the accumulation of information starts sooner after target stimulus presentation, stimulus identification and response selection will also be finished earlier, and this in turn will result in a shorter S-LRP interval.

In addition, recent results of a study by Seifried, Ulrich, Bausenhart, Rolke, and Osman (submitted) also are closely in line with the assumption of an earlier start of information accumulation. These authors conducted a series of foreperiod experiments employing the classical paradigm of the complication experiment to measure perceptual latency (e.g., Haggard, Clark, & Kalogeras, 2002; Sanford, 1971). In this paradigm, participants watch a clock hand constantly rotating in front of a numbered clock face, and simultaneously have to detect the onset of a target tone. Then, they report the position of the clock hand at the moment at which they detected the target tone. Subsequently, perceptual latency can be calculated as the time difference between the reported position and the actual position of the clock hand at the moment of target presentation. Thus, perceptual latency denotes the time that elapses between the physical occurrence of a signal and its detection, that is, the moment in which the signal is perceived and can be reported. To investigate the influence of temporal preparation on perceptual latency, Seifried et al. presented additional noise bursts that served as warning signals for the presentation of the target tone. These warning signals preceded the target tones by constant foreperiods of either 600 or 2,000 msec. When foreperiod was short and participants were therefore temporally well prepared, perceptual latency was shorter than in the long foreperiod condition. This finding indicates an earlier detection of the target tones associated with good temporal preparation. Importantly, because an earlier start of information accumulation should be reflected in earlier detection of a target stimulus, and thus, shorter perceptual latency, this finding is closely in line with the present results.

However, the studies outlined above (Experiment 1 of the present work; Hackley & Valle-Inclán, 1998, 1999; Müller-Gethmann et al., 2003; Seifried et al., submitted) can not differentiate between such an earlier start of information accumulation and an alternative explanation of the observed temporal preparation effects. According to this alternative, the preparation-related speeding of premotor processing and stimulus detection might also be due to an increased rate of information sampling within the perceptual system (cf. Experiments 2a-2c of the present work; Correa, Sanabria et al., 2006). Consequently, information accumulation would not start earlier, but proceed faster when participants are temporally well prepared. Unlike previous experiments, the present study provides a means to distinguish between these alternatives, because onset and speed of information accumulation are reflected by separate parameters (i.e., intercept and rate) of the SAT function.

Importantly, and in contrast to the intercept, temporal preparation seems to leave the rate parameter unaffected. Specifically, the model that provided the best fit to the averaged data did not allocate separate rate parameters to the two foreperiod durations. The quality of this fit was not improved when rate (in addition to intercept and asymptote) was allowed to vary according to foreperiod duration, and importantly, was reduced when differences in processing dynamics were forced into rate instead of intercept. These results were corroborated when separate models were fitted to the data of individual participants: no significant differences in rate were obtained between foreperiod conditions, neither for the individual best fitting models, nor for the least restrictive model.

Therefore, the present results imply that the speed of information accumulation is not influenced by temporal preparation. As outlined above, such an influence might have been expected based on the results of Experiment 2a-2c (see also Correa, Sanabria et al., 2006). Apparently this finer temporal resolution associated with temporal preparation is not reflected in the rate parameter of the SAT functions estimated by the present study. Rather, enhanced temporal resolution might also be explained by an earlier start of information accumulation about the first target stimulus in a TOJ task (cf. Rolke, 2008).

Interestingly, this lack of an effect of temporal preparation on the rate of the SAT function underlying performance contrasts with results observed within the domain of spatial orienting (Carrasco et al., 2006; Carrasco & McElree, 2001). In these studies, SAT parameters were compared between a condition in which a spatial precue validly indicated the position of a visual target stimulus and a neutral cue condition. The best-fitting models for these conditions included differences in the rate parameter, in such a way that higher rates were found for the validly cued condition. These results, however, were obtained within a search task that required participants to scan a stimulus display for a tilted, nonfoveally presented gabor stimulus and to identify its orientation. A direct comparison of these results with those of the present task, which required spatial discrimination of a single, shortly presented target stimulus at fixation, therefore may not be particularly eligible. However, given that several recent studies comparing the effects of spatial and temporal orienting (Coull & Nobre, 1998; Doherty et al., 2005; Griffin et al., 2002; MacKay & Juola, 2007) provided somewhat inconsistent conclusions about whether both phenomena are based on different or related mechanisms, SAT methodology might prove as a useful tool for future investigations of this issue.

Finally, temporal preparation affected asymptotic performance. Specifically, the best fitting model for the average data allocated different asymptote parameters to both foreperiod conditions, with a higher asymptote corresponding to the short foreperiod condition. This result was confirmed statistically by comparing asymptote parameters fitted to the data of individual participants, regardless of whether the overall best-fitting model, the least restrictive model, or the individually best-fitting models were compared. Accordingly, when there is ample time for stimulus processing, short foreperiods enable higher discrimination performance. Therefore, stimulus discriminability is enhanced by temporal preparation.

As hypothesized above, this influence of temporal preparation on discriminability might be mediated by either improved suppression of external noise or by enhanced contrast sensitivity (cf., Cameron et al., 2002; Carrasco et al., 2000; Carrasco et al., 2002; Morgan et al., 1998; Reynolds et al., 2000; Shiu & Pashler, 1995, for similar mechanisms in covert spatial attention). Recent results of Rolke (2008) provide some support for a potential influence of these mechanisms. Specifically, she demonstrated in a series of experiments that temporal preparation improved the accuracy of letter identification, but importantly, this temporal preparation effect diminished as target contrast was enhanced, or as the SOA between a target letter and the presentation of a subsequent mask was prolonged. Accordingly, temporal preparation proved to be especially useful when identification of the target stimulus is rendered difficult either by interfering external noise (i.e., the mask) or by low stimulus contrast. Consequently, one might assume that temporal preparation facilitates perception, at least partly, by reducing such external noise and by improving contrast sensibility of the perceptual system. Such mechanisms might also be responsible for the improved asymptotic performance in spatial discrimination in the short foreperiod condition obtained in the present study.

It should be considered, however, that the observed temporal preparation effect on asymptote alternatively might also have emerged as a consequence of the shorter intercept associated with temporal preparation. Given that the target stimulus in the present experiment was only presented for 50 msec, its internal visual short term memory representation might have been subject to rapid decay once the target physically had been removed from the display. Accordingly, if temporal preparation enables an earlier start of the accumulation of target information, more information might be retrieved from the decaying internal representation during the limited time for which it is accessible. However, the target stimulus in the present study was not masked, and spatial attention could easily be focused on the target because target location was identical throughout the experiment. Therefore, we tend to assume that such rapid decay should have had a rather small effect on participants performance, because these conditions are known to enable stimulus consolidation into a more stable representation (cf. Sperling, 1960). Most important, however, is that even though the present experiment may not be decisive about whether the observed temporal preparation effect on discriminability stems from a genuine improvement of perceptual processes or rather from rapid decay of stimulus representations, this does not hamper the main conclusion of the present experiment that temporal preparation influences the dynamics of information processing.

2.4.2. Conclusion

In conclusion, the present experiment employed SAT methodology to investigate whether temporal preparation within a constant foreperiod paradigm influences the dynamics of stimulus processing. Such an influence indeed could be confirmed. Specifically, the earlier intercept of the SAT functions associated with good temporal preparation indicates that temporal preparation leads to an earlier onset of information accumulation. The rate of information accumulation, in contrast, seems to be unaffected by temporal preparation. Finally, temporal preparation also has a beneficial influence on stimulus discriminability, even when there is ample time for stimulus processing.

3. SUMMARY AND GENERAL CONCLUSION

Over several decades of psychological research, it has been assumed that temporal preparation effects emerge predominantly in motor processing stages (e.g., Loveless & Sanford, 1975; Mattes & Ulrich, 1997; Sanders, 1980; Spijkers & Walter, 1985). This motor view, however, has been challenged by more recent behavioral and electrophysiological results indicating a potential influence of temporal preparation on earlier processing stages (e.g., Correa et al., 2005; Müller-Gethmann et al., 2003; Rolke & Hofmann, 2007). The present experiments were conducted in order to investigate such potential influences of temporal preparation on premotor and especially perceptual processing. Indeed, such influences could be demonstrated within various experimental paradigms. Detailed discussions of these results were already provided in the respective chapters of the experimental section of the present work. Therefore, in the following, only a short overview over the experiments and their most important results is given.

The first experiment aimed at determining the locus of temporal preparation effects on RT. To this end, a dual-task experiment was conducted. According to the standard account of dual-task performance, i.e., the central bottleneck model (e.g., Pashler, 1984; Pashler & Johnston, 1989), the effect of an experimental manipulation of the first task should only propagate to the second task when the experimental manipulation affects processing stages prior to or at the processing bottleneck. No such propagation should be observed when an experimental manipulation merely affects post-bottleneck processing of the first task. Because the bottleneck process itself has been associated with central processing of the target stimulus (McCann & Johnston, 1992; Pashler & Johnston, 1989), the effect-propagation account enables a bisection of RT in two phases of processing: a first phase associated with perceptual processing and more central decision-related processes as response selection, and a second phase in which the motor response is initiated and executed. Accordingly, the dual-task paradigm can be employed to determine whether an experimental manipulation unfolds its effects in either premotor or motor processing stages. Hence, in the first experiment of the present work, temporal preparation for the first task was varied by means of a constant foreperiod paradigm. This manipulation strongly affected processing of the first task: short foreperiods, which typically yield better temporal preparation, led to shorter RT than long foreperiods. This effect propagated in full size to the second task. Two experimental control conditions were run to rule out possible alternative explanations for the observed temporal preparation effect on RT to the second task. The results obtained within these conditions strengthen the conclusion that the observed RT pattern of the second task was indeed due to effect propagation from the first task. Therefore, the results of Experiment 1 can be interpreted in terms of a premotor locus of temporal preparation effects. More specifically, temporal preparation seems to shorten the duration of perceptual and / or central stimulus processing.

To further refine this inferred locus of temporal preparation effects, a series of experiments was subsequently conducted to investigate temporal preparation effects on perceptual stimulus processing. To this end, psychophysical methods were employed to assess the influence of temporal preparation on perceptual thresholds in the visual and in the auditory modality. In the first series of experiments, participants had to judge the temporal order of two stimuli appearing in rapid succession. The onset asynchrony between both stimuli was varied in order to determine how long both stimuli had to be separated in order to enable a 75 percent level of correct temporal order identification. This threshold value, JND, can be used as an index of the temporal resolution of the visual system (e.g., Hein et al., 2006; Sternberg & Knoll, 1973). Importantly, combining the temporal order judgment task with a constant foreperiod manipulation in Experiment 2a revealed that JND decreased when foreperiod was short. Therefore, temporal resolution improved in case of a good temporal preparation. This result was confirmed in a second experiment in which both target stimuli were presented spatially overlapping rather than to the left and right to the center of the screen. Thereby, it could be ruled out that the observed temporal preparation effects were due to or at least mediated by concurrent spatial uncertainty and the need to process target stimulus location (Doherty et al., 2005). Finally, a third experiment employed a wide range of different foreperiod durations to investigate the time course of temporal preparation. Again, temporal preparation affected temporal resolution thresholds. More specifically, and consistent with previous results obtained with measures of processing latency (Bertelson & Tisseyre, 1969; Müller-Gethmann et al., 2003), thresholds varied with foreperiod duration in a characteristic U-shaped pattern, revealing the lowest thresholds, and therefore, the highest temporal resolution with foreperiods of intermediate duration. This pattern of results indicates that even for a purely perceptual task, temporal preparation is demanding and time-consuming, that is, it needs time to develop fully and to reach an optimal state. This optimal state, once reached, can not be simply maintained over time, but rather, temporal preparation seems to be adjusted to the current temporal expectations about the moment of target stimulus delivery, with these expectations getting more and more imprecise as foreperiod lengthens.

The finding that temporal preparation improves temporal resolution in the visual modality corresponds well to recent research demonstrating that temporal preparation improves also the spatial resolution of the visual system (Correa et al., 2005; Rolke & Hofmann, 2007). Given these effects of temporal preparation on visual perceptual processing, one might assume that perceptual processing in other modalities might similarly benefit from temporal preparation. Therefore, two experiments were conducted to investigate the influence of a constant foreperiod manipulation on auditory pitch discrimination. In these experiments, participants had to discriminate between a high and a low pitched sine tone, and the duration of the tone was varied in order to identify the specific duration needed to identify tone pitch correctly in 75 % of all trials. In Experiment 3a, this threshold duration was affected by temporal preparation within a constant foreperiod paradigm. Specifically, when foreperiod was short, shorter threshold durations were obtained than when foreperiod was long. This result was replicated in the second experiment of this series, in which an alternative explanation of preparation effects was tested. According to this alternative, the effects of foreperiod duration would have emerged as a consequence of the overall shorter trial duration in short compared to long foreperiod trials. This confound of foreperiod duration and trial duration might have led to better performance in the short foreperiod condition rather as a result of a higher rate of stimulation and improved memory representations of the target stimuli than as a result of differences in temporal preparation per se. By keeping trial duration in short and long foreperiod trials constant, this alternative explanation could successfully be ruled out. Together, these results show that temporal preparation within a constant foreperiod paradigm improves pitch discrimination. This generalization of temporal preparation effects from the visual to the auditory modality bears implications for the nature of temporal preparation, as it can be described as a nonspecific, modality-independent process that is capable of improving perceptual processing.

Having consistently demonstrated temporal preparation effects on discrimination thresholds, and therefore, the quality of perceptual processing, the question emerged what mechanisms might underlie those effects. Recent theoretical accounts of temporal preparation proposed that these effects might emerge as a consequence of changes in the dynamics of information processing. For example, temporal preparation might lead to an earlier onset of accumulation of information about the target stimulus (cf. Rolke, 2008; Rolke & Hofmann, 2007), or might enhance the rate of this accumulation process (Correa, Sanabria et al., 2006; Experiments 2a-2c). Each of these changes of processing dynamics might lead to faster responses and also to improved target stimulus perception, especially when target identification is perceptually demanding, targets are presented shortly and masking hinders further perceptual processing. The dynamics of information processing can be investigated empirically by examining the relationship between speed and accuracy of responding (e.g., Carrasco & McElree, 2001; Reed, 1973; Wickelgren, 1977). Therefore, the final experiment of the present work employed a SAT procedure in which the time available for stimulus processing is varied over a large range (cf. Miller et al., 2008; Wickelgren, 1977), and the respective obtained levels of accuracy associated with the different processing times can be described by an exponential approach to an asymptotic performance level. Parameters of this mathematical relationship, i.e., intercept, rate, and asymptote, reflect the onset of information accumulation, the speed of information accumulation, and stimulus discriminability, respectively. By varying temporal preparation for the target stimulus in a constant foreperiod paradigm, it could be investigated which parameters of the SAT function, and therefore, which aspects of information processing are affected by temporal preparation. Hierarchical modeling of these parameters showed that short foreperiods, and therefore high temporal preparation, was associated with shorter intercepts and a higher asymptotic performance level. Accordingly, these results can be interpreted in favor of the notion of an early onset of information accumulation.

Taking together, the present experiments showed that temporal preparation shortens the duration of premotor processing, improves the quality of perceptual processing, and presumably does so by enabling an earlier onset of accumulation of information about the target stimulus. This early locus of temporal preparation effects contrasts sharply with the results of various former studies, which led to the widespread assumption that temporal preparation affects predominantly motor processes (e.g., Loveless & Sanford, 1975; Mattes & Ulrich, 1997; Sanders, 1980; Spijkers & Walter, 1985). How can these conflicting views be reconciled? For one thing, it seems important to note that many of the electrophysiological studies assessing temporal preparation effects on different amplitude measures reflecting activity of the motor system (e.g., Brunia et al., 1982; Loveless & Sanford, 1974; cf. Chapters 1.4.2.2-1.4.2.4) used simple task or tasks in which the response hand was known in advance. These conditions enable, either fully or partly, motor preprogramming of the appropriate response even when the target stimulus has not yet been presented. Consequently, most of these studies focused on analyzing preparatory processing during the foreperiod. Indeed, these studies were able to demonstrate preparatory adjustments of activity in various components of the motor system. Regarding these results, however, it often remains unclear whether the observed effects reflect temporal preparation processes per se, or if they rather mirror the time course of event preparation, that is, preparation for a specific target stimulus and the appropriate motor response. Moreover, there often seems to be no strong relationship between such amplitude measures reflecting preparatory adjustments during the foreperiod and latency measures indexing the duration of subsequent stimulus processing (e.g., Requin et al., 1977; Semjen et al., 1973).

This criticism does not hold true, however, for evidence for a motor locus of temporal preparation obtained within the framework of the AFM (e.g., Sanders, 1980; cf. Chapter 1.4.1.1). At a first glance, these results seem to be especially inconsistent with the present results which argue for a shortening of premotor processing stages, given that both lines of evidence employ the same latency measure, namely RT. Importantly, the results of the first experiment of the present work do not only suggest that temporal preparation affects the duration of premotor processing, but, based on the finding that the preparation effect on RT of the first task propagated in full size to the second task, that it does so exclusively. Accordingly, no effects of temporal preparation in motor processing stages should have been observed in AFM studies. Such effects, however, have been found repeatedly (Sanders, 1980; Spijkers, 1990; Spijkers & Walter, 1985). One possible way to bring these conflicting results together might be found in Correa et al.'s notion that "temporal preparation […] can flexibly enhance processing at different stages, according to the most relevant demands of the task at hand" (Correa et al., 2005, p. 334). Actually, the AFM-based evidence for a motor locus of temporal preparation was obtained with rather complex manual tasks as reaching movements or line drawing, whereas the first experiment of the present work, which found no evidence for a motor locus, required relatively simple button presses. On the other hand, whereas many AFM studies could not provide clear evidence for a perceptual locus of temporal preparation effects (Bernstein et al., 1973; Frowein & Sanders, 1978), the present Experiments 2a-2c and 3a-3b consistently demonstrated such influences with perceptually demanding, near-threshold stimulation (see also Rolke, 2008). Therefore, one is left with the impression that temporal preparation may have widespread consequences for various levels of processing, and that its influence on a given processing stage might be most pronounced when processing demands in this stage are high.

On basis of these thoughts, there remains an important issue that has not been tackled by the present work. Given that perceptual as well as motor processing can benefit from temporal preparation, may central processes as, for example, response selection, be facilitated by temporal preparation as well? Because the results of the first experiment of the present study may have partly or even fully emerged from a shortening of central processing stages, this possibility remains viable. However, the present experiments can not provide decisive evidence for this question, and they were not designed to do so, either. Direct empirical evidence relevant for this topic is surprisingly scarce: only few studies employing the AFM were conducted to investigate this issue, and, as has been described in Chapter 1.4.1.1 of the Introduction, they are partly prone to alternative explanations and led to rather inconsistent results regarding a potential central locus of temporal preparation (e.g., Broadbent & Gregory, 1965; Frowein & Sanders, 1978; Simon & Slaviero, 1975). Another study concerned with this issue was reported in Chapter 1.4.2.6 (Hackley et al., 2007). Based on electrophysiological results, these authors argued that the greatest portion of the temporal preparation effect on RT emerges in central processing stages, and that the respective contributions of early perceptual and motor facilitation to the overall RT effect are rather small. These results clearly stress the need for a further empirical investigation of potential influences of temporal preparation on central processing.

The present experiments, however, were designed to explore the effects of temporal preparation on another aspect of stimulus processing, namely, perception. Consistent beneficial influences of temporal preparation on perception within the visual as well as in the auditory modality could be demonstrated in these experiments. These findings thus point to a view of temporal preparation as a general, modality-independent attentional phenomenon. Furthermore, temporal preparation effects do not seem to be restricted to specific task demands, because such effects have been observed for various tasks requiring spatial resolution (Rolke & Hofmann, 2007; Experiment 4 of the present work), integration of complex spatial features (Rolke, 2008), temporal resolution (Correa, Sanabria et al., 2006; Experiments 2a-2c of the present work), and analysis of tone pitch (Experiments 3a & 3b of the present work). Thus, temporal preparation effects seemingly can be generalized to different aspects of processing, modalities and task demands.

Regarding generalization of the present results, however, another issue remains unsettled so far. That is, it is not clear if the present results, which were all obtained within a constant foreperiod paradigm, generalize to other ways of manipulating temporal preparation. As outlined in the Introduction, another prominent way to examine temporal preparation is to vary foreperiod duration unpredictably from trial to trial. Thereby, participants' expectancy of the target stimulus is manipulated. Specifically, in the variable foreperiod paradigm, participants do not know in advance which foreperiod duration will be presented. Therefore, expectancy about whether or not a target stimulus will occur after each of the possible foreperiod durations determines temporal preparation for the target (Elithorn & Lawrence, 1955; Näätänen & Merisalo, 1977; Niemi & Näätänen, 1981). In contrast, for constant foreperiods, there should be no differential target expectancy between foreperiod durations. Rather, it is assumed that temporal preparation effects are merely due to participants' inability of estimating the exact duration of the upcoming foreperiod, and therefore, due to time uncertainty (Näätänen et al., 1974). Given that the sources of temporal preparation in these two paradigms might differ from each other (cf. Chapter 1.2.1)[17], one should be skeptical about assuming that the effects of temporal preparation on stimulus processing will be similar in both paradigms. Moreover, effects of explicit temporal cueing (Correa et al., 2005; Miniussi et al., 1999) or instructions (Lange et al., 2003; Sanders & Astheimer, 2008), as examined in temporal orienting paradigms, are also more probably due to differences in target expectancy than to mere time uncertainty.

Despite these possible differences in the sources of uncertainty, the effects of temporal preparation within the constant foreperiod paradigm and temporal orienting paradigms seem to converge quite well. For example, temporal preparation facilitates spatial discrimination and letter identification and enhances temporal resolution both in the constant foreperiod paradigm (Rolke, 2008; Rolke & Hofmann, 2007; present Experiment 2a-2c) and in temporal orienting studies (Correa et al., 2005; Correa, Sanabria et al., 2006). Moreover, even though to date there seem to be no temporal orienting studies examining auditory discrimination performance with behavioral measures (but see Wright & Fitzgerald, 2004, for a comparable approach), there have been consistent demonstrations of enhanced amplitudes of perception-related ERP components to auditory stimuli (Lange & Röder, 2006; Lange et al., 2003; Sanders & Astheimer, 2008). These studies supplement the results of the present Experiments 3a and 3b quite well. Therefore, even though there is a lack of systematic comparison of temporal preparation in the constant foreperiod paradigm, the variable foreperiod paradigm, and temporal orienting paradigms, the obtained effects within each of these paradigms often correspond well to each other. Some exceptions, as for example in the domain of duration judgments (Grondin & Rammsayer, 2003; Mo & George, 1977), however, should also be

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[17] It should be emphasized here that a current account of temporal preparation, i.e., the trace conditioning account proposed by Los and colleagues (Los et al., 2001; Los & Van Den Heuvel, 2001), does not assume different sources of temporal preparation in the constant and the variable foreperiod paradigm. This account suggests that in both cases, the temporal relation between warning signal and response signal is acquired according to the principles of trace conditioning. In any given trial, this conditioning process leads to the development of response-related activation during the foreperiod, and timing and strength of this activation vary according to the foreperiod duration of the previous trials. However, this account states the conditioned response consists of response-related, and therefore motor activation. Thus, the trace conditioning view can hardly explain how perception of a target stimulus might be facilitated by temporal preparation. Accordingly, trace conditioning seems not to be especially suited for describing the effects of temporal preparation on premotor processing obtained within the present experiments (see also Chapter 1.2.2).

acknowledged and underline the need for further investigation of the relationship between different experimental procedures.

One might argue that temporal preparation effects obtained within various paradigms are nonetheless sufficiently consistent, so that it might be assumed that effects found within one specific paradigm should indeed generalize to other ways of manipulating temporal preparation. Even if this assumption would hold true in further research, however, it should not be equated with assuming that the mechanisms underlying these effects in different temporal preparation paradigms are also similar. That is, similar effects of temporal preparation might actually emerge from different underlying mechanisms. Potentially relevant research on this issue might, for example, examine whether variable foreperiods and temporal orienting alter processing dynamics in a similar manner as constant foreperiods. Further important evidence might also be found in the neuroanatomical basis of temporal preparation, by investigating whether temporal preparation induced within different paradigms activates similar brain areas and networks. Unfortunately, to date there have been only few systematic approaches to investigate the comparability of the mechanisms underlying different manipulations of temporal preparation (but see Correa, Lupiáñez, & Tudela, 2006; Coull et al., 2000; Los & Van Den Heuvel, 2001). This question, however, seems to be crucial for a deeper understanding of the phenomenon of temporal preparation and the appealing prospect of eventually achieving a unified view of its different aspects.

4. ABSTRACT

Over several decades, the ability to predict upcoming events and to prepare for these events has been an important topic in psychological research. One fundamental aspect of such preparatory processes is preparing for the exact moment in time at which an event is expected to occur. A great number of experimental studies demonstrated that this so-called temporal preparation influences predominantly motor stages of processing. For example, temporal preparation affects various correlates of motor processing as reflex amplitudes, motor evoked potentials, response force and the contingent negative variation. More recent studies, however, cast doubt on this traditional 'motor view' of temporal preparation and suggest that processing in premotor stages might also be affected by temporal preparation. The aim of the present work was to test this assumption directly, especially with regard to a possible influence of temporal preparation on perceptual processing and the mechanisms underlying these effects. To this end, temporal preparation effects were examined within various well-established experimental paradigms of cognitive psychology, as the central bottleneck paradigm, the temporal order judgment task and the method of speed-accuracy trade-off.

First, the effect propagation property of the central bottleneck paradigm was used to localize the effect of temporal preparation in either premotor or motor stages of stimulus processing. The results of this experiment suggest that the shortening of reaction time, which is typically observed under conditions of good temporal preparation, emerges exclusively in premotor stages of information processing. On the basis of this paradigm, however, one can not decide whether this is due to a facilitation of perceptual or central processing stages. Therefore, further experiments were conducted to investigate the influence of temporal preparation on perceptual processing more directly. Specifically, these experiments assessed the influence of temporal preparation on discrimination thresholds for visual temporal order judgments and auditory pitch discrimination. In both modalities, lower discrimination thresholds were consistently observed under conditions of high temporal preparation. Accordingly, temporal preparation indeed seems to improve the quality of perceptual analysis.

These results can hardly be explained by traditional theoretical accounts of temporal preparation, which assume that temporal preparation affects stimulus processing by enhancing motor activation. A more recent account, however, states that temporal preparation might improve perceptual processing by changing the dynamics of information accumulation within the perceptual system. To test this assumption, speed-accuracy trade-off for a spatial discrimination task was manipulated in the final experiment of the present work. The observed relationship between processing speed and accuracy indicates that temporal preparation indeed leads to an earlier onset of information accumulation. This result does not only strengthen the notion that temporal preparation effects emerge in premotor processing stages, but also provides a promising basis for further research on the ubiquitous phenomenon of temporal preparation.

5. ZUSAMMENFASSUNG

Die Fähigkeit, Vorhersagen über zukünftige Ereignisse zu treffen und sich anhand dieser Vorhersagen auf die kommenden Ereignisse vorzubereiten, ist seit langer Zeit Gegenstand psychologischer Forschung. Ein wichtiger Aspekt solcher Vorbereitungsprozesse ist die Vorbereitung auf den Zeitpunkt, zu dem ein Ereignis eintreten wird. Diese zeitliche Vorbereitung wurde lange als Prozess angesehen, der seine Wirkung vorwiegend im motorischen System entfaltet. Beispielsweise konnte konsistent gezeigt werden, dass verschiedene Korrelate der Aktivität des motorischen Systems wie Reaktionskraft, Reflexamplituden, motorisch evozierte Potentiale, und die Kontingente Negative Variation mit dem Ausmaß an zeitlicher Vorbereitung variieren. Neuere Studien hingegen widersprechen dieser klassischen Sichtweise und legen eine Wirkung zeitlicher Vorbereitung auch auf vormotorische Reizverarbeitungsstufen nahe. Die vorliegende Arbeit überprüft diese Annahme, insbesondere auch im Hinblick auf eine mögliche Verbesserung der Reizwahrnehmung durch zeitliche Vorbereitung und die einem solchen Effekt zugrunde liegenden Mechanismen. Zu diesem Zweck wurde der Einfluss der zeitlichen Vorbereitung in verschiedenen etablierten Paradigmen der Kognitionspsychologie untersucht, wie beispielsweise dem Doppelaufgabenparadigma, dem zeitlichen Reihenfolgeurteil sowie der Methode des Geschwindigkeits-Genauigkeitsabgleiches.

Zunächst wurde die Effektübertragungseigenschaft des Doppelaufgabenparadigmas genutzt, um den Effekt der zeitlichen Vorbereitung auf die Reaktionszeit in entweder motorischen oder prämotorischen Reizverarbeitungsstufen zu lokalisieren. Die Ergebnisse dieser Studie sprechen dafür, dass die Reaktionszeitverkürzung, die typischerweise unter guter zeitlicher Vorbereitung auftritt, ausschließlich in vormotorischen Verarbeitungsstufen entsteht. Anhand dieses Paradigmas kann allerdings nicht entschieden werden, ob dies eher auf eine Beeinflussung von Wahrnehmungs- oder Entscheidungsprozessen zurückzuführen ist. Deshalb wurde in weiteren Experimenten der Einfluss zeitlicher Vorbereitung auf die Reizwahrnehmung in der visuellen und auditiven Modalität direkter untersucht, indem Diskriminationsschwellen für das zeitliche Reihenfolgeurteil und die Tonhöhendiskrimination erfasst wurden. Unter Bedingungen guter zeitlicher Vorbereitung zeigte sich sowohl eine feinere zeitliche Auflösung des visuellen Systems als auch eine verbesserte auditive Diskriminationsleistung. Diese Ergebnisse sprechen dafür, dass die Qualität der perzeptuellen Verarbeitung von zeitlicher Vorbereitung profitieren kann.

Traditionelle Modelle zur Wirkungsweise der zeitlichen Vorbereitung, die Veränderungen der motorischen Aktivierung durch zeitliche Vorbereitung postulieren, lassen sich mit einer solchen verbesserten perzeptuellen Reizverarbeitung nur schwer in Einklang bringen. Einen möglichen Erklärungsansatz bietet allerdings die Vorstellung, dass zeitliche Aufmerksamkeit die Dynamik der Informationsakkumulation im perzeptuellen System beeinflusst. In einem letzten Experiment wurde zur Untersuchung dieser Annahme der Geschwindigkeits-Genauigkeitsabgleich für eine visuelle räumliche Diskriminationsaufgabe manipuliert. Anhand der resultierenden Beziehung zwischen Bearbeitungszeit und Genauigkeit für diese Aufgabe konnte gezeigt werden, dass zeitliche Vorbereitung tatsächlich zu einem früheren Beginn der Akkumulation von Information über den Zielreiz führt. Dieses Ergebnis stützt nicht nur die Annahme, dass die Effekte zeitlicher Vorbereitung in vormotorischen Stufen der Verarbeitung zu verorten sind, sondern stellt auch einen möglichen Ausgangspunkt für weitergehende theoretische Entwicklungen und empirische Untersuchungen dar.

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