ON THE ORIGIN OF VISUAL TEMPORAL-ORDER PERCEPTION BY MEANS OF ATTENTIONAL SELECTION

by
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"I have a friend who's an artist and has sometimes taken a view which I don't agree with very well. He'll hold up a flower and say 'look how beautiful it is,' and I'll agree. Then he says 'I as an artist can see how beautiful this is but you as a scientist take this all apart and it becomes a dull thing,' and I think that he's kind of nutty. First of all, the beauty that he sees is available to other people and to me too, I believe. Although I may not be quite as refined aesthetically as he is, I can appreciate the beauty of a flower. At the same time, I see much more about the flower than he sees. I could imagine the cells in there, the complicated actions inside, which also have a beauty. I mean it's not just beauty at this dimension, at one centimeter; there's also beauty at smaller dimensions, the inner structure, also the processes. The fact that the colors in the flower evolved in order to attract insects to pollinate it is interesting; it means that insects can see the color. It adds a question: does this aesthetic sense also exist in the lower forms? Why is it aesthetic? All kinds of interesting questions which the science knowledge only adds to the excitement, the mystery and the awe of a flower. It only adds. I don't understand how it subtracts." – Feynman (1981)

This synopsis turned out substantially longer than I had intended. This is quite fortunate because a substantially long list of acknowledgments will not look out of place. Such a long list is in order here because the individuals for whose support I'm thankful are real people with various valuable contributions, not an imaginary deity that could be thanked with a one-liner.

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Finally, I want to express my immense gratitude and admiration for my fiancée, friend, and fellow scientist Maike Amen. I'm grateful for all her support and understanding and amazed and inspired by her unparalleled diligence, determination, and creativity. Thank you.

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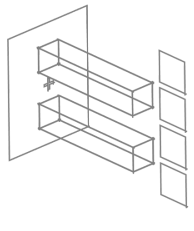
SYNOPSIS



1

INTRODUCTION

The perception of temporal order is a topic of high interest. Although it has been investigated in experimental psychology for more than one and a half century, important questions are still open. This thesis answers some of them with novel psychophysical methods. Before looking at the topic from the perception psychologist's perspective, I will briefly highlight why—despite it's apparent simplicity—temporal order is a fascinating topic in general.

1.1 TEMPORAL ORDER: PHYSICAL, PSYCHOLOGICAL, PHILOSOPHICAL?

In his book *Our Mathematical Universe*, cosmologist Max Tegmark (2014) outlines three parallel views on reality: *external reality*, a potentially mathematical and ultimate physical world that exists independently from any observer; *consensus reality*, a description of the physical world on which all observers agree; and, *internal reality*, which is based on the subjective perception of external reality.

Tegmark (2014) and several of his colleagues in physics occupy themselves with deriving consensus reality from their theories about and measurements of external reality. For example, a physicist may describe a certain ray of light as having a wavelength of 600 nanometers. This is a formal description all observers capable of performing the measurement can agree on. Psychologically, the perception of this orange light may vary substantially in the internal realities of different observers.

According to Tegmark (2014), consensus reality decouples the external and internal realities, allowing independent advancement of physical and psychological theories. He writes "[...] what Douglas Adams called 'the ultimate question for life, the universe and everything' splits cleanly into two parts that can be tackled separately: the challenge for physics is deriving the consensus reality from the external reality, and the challenge for cognitive science is to derive the internal reality from the consensus reality" (p. 339).

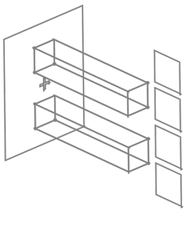
This thesis—joining others—takes up the second challenge for the domain of visual temporal-order perception, in particular, the order of two visual events. At first sight, the question in which order two visual events are perceived sounds inherently simple. There seem to be two possibilities for the order (or three, if one allows for the perception of simultaneity). Is not the perceived order of two events directly linked to the order in which they happened, which itself is unambiguously defined? In answering this question, there are certain parallels in the challenges for deriving consensus reality from external reality—the physicist's job—and deriving internal reality from consensus reality—the psychologist's and cognitive scientist's job.

In both cases, apparently, no challenge exists at all, at least at the level of our intuition and according to our everyday experiences. Usually, observers are certain about which of two events happened first. There is no doubt that every individual can perceive the true order of events. If the interval between the events shrinks until the order can no longer be distinguished—for example, if two runners cross the finish line almost simultaneously—it appears sufficient to view a slow-motion recording to resolve the order.

However, this simple view on temporal order disappears if we consider extreme cases. In the physical domain, this is the case, for example, if observers move at relativistic speeds. Where ordinary observers agree on an unambiguous order of events, observers moving at substantial fractions of the speed of light obtain apparently contradictory measurements. They report the same two events happening in different orders. To achieve a consensus reality, Einstein's special theory of relativity must be applied. With it, the contradiction can be resolved.

Similarly, in the psychological domain, the influence of selective visual attention on the distribution of processing resources must be taken into account to bring consensus and internal reality into agreement. If attention is biased toward one stimulus, prior entry may arise, that is, it is perceived earlier than a competing identical but unattended stimulus. Under the right circumstances, a stimulus shown later can also be perceived as the earlier one of a pair. Hence, the perceived temporal order can be in conflict both with the physical order and with the order in which an identical pair of stimuli is perceived under different attention conditions. Because much of the relevant factors are subject to substantial individual differences, it can also be in conflict with the order perceived by a different person in the same presentation. If theories of attention are applied, these conflicts can be resolved by accounting for the factors that lead to them.

Unfortunately, many theories of attention that have been applied to the problem are rather vague. They predict a general pattern, but they do not go a long way in quantitatively describing the exact mechanisms and the consequences. Consequently, important questions could not be addressed so far. For example, is attention speeding up the processing of the attended stimulus? Or is it slowing down the processing of the unattended stimulus or both to a varying degree? The goal of this thesis is to improve on this. A novel model of attention-altered order-perception is described with which such fundamental questions are in reach, and some of them are answered here.



Above, it was argued that advancing theory resolves conflicts in the description of how events unfold. Certainly, this does not mean that having a good theory leads to all observers under all conditions perceiving the same order per se; just as relativistic observers remain to witness conflicting orders, applying a good theory only helps them understand why. With a good theory, the *description* can be free of contradictions, and at least in principle, it is possible to correct for the effects. Advances in relativistic physics, many of which were achieved at the beginning of the last century, seemed to be of purely theoretical relevance first. However, in the second half of the century, they became enormously important for many practical applications. One example is the global positioning system (GPS), a system which would be impossible without taking special and general relativity into account for correcting signal latencies. Similarly, one can imagine that a good understanding of the mechanisms of visual attention and temporal-order perception becomes practically relevant, even though they work in the milliseconds domain. Possibly, a future driver assistance system might time and position visual warning signs just right to provide the critical information in a way that is helpful and not distracting.

1.2 TEMPORAL-ORDER PERCEPTION: A RESULT OF ATTENTIONAL SELECTION?

Before outlining the research questions this thesis addresses, I want to briefly discuss its title, *On the Origin of Visual Temporal-order Perception by Means of Attentional Selection*. It is a play on words with the title of Charles Darwin's important book, but is there more to it? I am not suggesting that mechanisms similar to natural selection play a role in modeling attentional selection at some relevant level of abstraction. Neither would I dare to claim that similar mechanisms are not important at some level. Instead, I want to focus on a different aspect of the title: the implicit claim that visual temporal-order perception *generally* originates from attentional selection. Obviously, for many everyday events, such as the perceived arrival order of buses, attention is no important influence. Furthermore, even on the below-one-second scale there are time intervals that are so large that attentional influences are highly unlikely to change temporal-order perception. A stimulus presented 400 ms before another stimulus will undoubtedly be perceived as appearing first by a normal human observer, irrespective of the distribution of visual attention. Still, in a sense the claim that temporal-order perception generally originates from attentional selection enjoys some support in this thesis.

The model of temporal-order perception derived in this thesis is based on a mathematical theory of visual attention, which describes individual stimulus encoding processes. In this model, attention is not a homunculus-controlled spotlight that alters other processes involved in temporal-order perception. The effects we usually attribute to selective visual attention rather emerge from more basic processes such as resource distributions and biased competition. In this sense, the model also covers cases in which resources are equally distributed; it is valid for stimulus sequences with targets separated by very long intervals. Neither of these cases leads to the observation of the typical attention effects. Hence, the underlying "attention" model is a very general model of stimulus encoding and selection. The situations mentioned above, which are free of attentional effects, are just special cases of the general model. Therefore, if we conceive attention as the potentially—but not necessarily—biased competition of visual stimuli for internal representation, visual temporal-order perception more or less generally originates from attentional selection.

The following sections present a set of unanswered questions about temporal-order perception. These questions and their importance need a brief explanation because they justify why a further and more in-depth investigation is required in a domain which has been subject to experimental assessment for over a century.

1.3 PRIOR ENTRY AND UNASKED QUESTIONS

1.3.1 *Visual Prior Entry*

The term "prior entry" was introduced by Titchener (1908) after a long tradition of experimental work, for example in Wundt's laboratory and even older considerations in astronomy (Hoffmann, 2007). It labels the idea that if attention speeds up the processing of stimuli, they may be perceived earlier than unattended ones. The origins of this idea are audiovisual complication experiments (Section 2.6). Typically, visual stimuli have to lead in presentation time to be seen as simultaneous with auditory ones. The amount of lead time is reduced when attention is directed to the visual stimuli (e.g., see Zampini, Shore, & Spence, 2005).

The same happens in the visual domain, where two simultaneously presented stimuli are perceived as simultaneous only if attention is distributed equally between them. Directing attention to one stimulus leads to its earlier perception (e.g., see Shore, Spence, & Klein, 2001). This visual form of prior entry is the effect which is of central interest in this thesis because it drives the misperception of the temporal order of visual events separated by short delays.[1] Prior entry is typically investigated with temporal-order judgment (TOJ) or simultaneity judgment (SJ) tasks. With data from these tasks, the pre-

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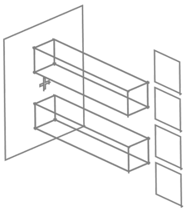
[1] The flip-book animation in the lower left corner of the odd pages visualizes the effect. In the animation, attention is directed to the lower targets, which are processed faster and encoded in reversed order.



sentation delay can be estimated with which the stimuli would be perceived as simultaneous, the point of subjective simultaneity (PSS; see Section 4.2).

The shift of the PSS under the influence of attention manipulations compared to the PSS in an attentionally neutral state is typically used as a measure of attention-induced prior entry. The usual interpretation of the PSS is that it represents the beneficial effect of attention on stimulus processing speed. As it will become apparent in the following sections, this interpretation is only an assumption that receives less support from PSS-based analysis of TOJ data than commonly assumed.

1.3.2 *TOJ Relativity*

Prior entry is frequently investigated with TOJ tasks.[2] This section briefly describes why the PSS method with which prior entry is typically inferred from TOJs has inherent limitations despite its popularity. These limitations go so far that the claim that attention speeds up processing in TOJs is not justified. The TOJ experimental paradigm is described in detail in Section 4.1. The usual method for analyzing the data is discussed in Section 4.2. Here, I will explain the essence of the fundamental limitations with a simple metaphor. To understand it, it is sufficient to know that in the TOJ task participants judge the order of two asynchronously presented stimuli. The PSS as a measure of prior entry is then calculated from these judgments.

The metaphor goes as follows. Suppose at a car race a sports reporter is positioned at one part of the track. He has a stopwatch, which he uses to stop the time between the leading car and the runner-up in every lap. Now suppose he reports that the leader is one second ahead three laps before the end of the race. In the subsequent lap, he reports that the runner-up—the audience's favorite—has caught up to the tenth of a second, undoubtedly taking the lead just before the checkered flag. Cheerfully he announces that, as usual, our hero can step up his game when it matters most. But is his inference correct?

Not necessarily. Because of the relative time the stopwatch records, a variety of scenarios are possible. Possibly, the race leader's performance decreased. She might have had a technical problem, going much more slowly now. Or, there was an unplanned pit stop, and her still being in the lead—though only slightly—reflects an increase in her performance combined with a drop in the runner-up's performance.

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[2] Sometimes SJ tasks are preferred, see Zampini et al. (2005). This thesis focuses on simple binary TOJs. However, the argument outlined in this section applies to SJs as well, or any other method that determines the PSS as the sole measure of attentional acceleration.

Without knowing the absolute lap times, the reporter cannot know whether or not the audience favorite is about to strike as usual. If he knew a lot about things that influence the speed of the cars, such as how much fuel was used up or how the tires degraded—monitoring such factors over many laps—he might be able to give a conclusive report. Of course, in his shoes, the most reasonable solution would be to time the absolute lap times for each car.

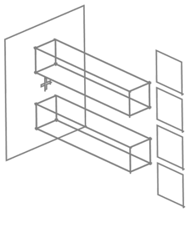
With data from TOJ experiments, it is not possible to estimate the absolute time a single stimulus took until it became conscious. TOJs are usually unspeeded. Even if reaction times were measured, they could not be expected to reflect the processing duration of stimuli until the judgment is made. They are contaminated with latencies of motor processes and other components or processes. (Reaction time and PSS-based measures even show dissociative behavior, see Jaśkowski, 1996, and J. Miller & Schwarz, 2006.) Therefore, a second stopwatch is required in the form of an independent task that allows measuring absolute processing time. This approach is followed in the Experiments 1 and 2 of this thesis. An approach analogous to obtaining knowledge about the factors that control the imaginary race cars' speeds is pursued in all other experiments of this thesis: A probabilistic model of the processes that encode the individual stimuli is considered to enhance TOJ data analysis, providing new insights outside the scope of the traditional method.

The point this section and the race car metaphor make is that the shift of the PSS is a relative measure. It is blind to the mechanisms that actually drive it. Similar to the idea that the audience favorite of the car race was assumed to show his usual boost in performance based on his previous displays, it is the attended stimulus which is typically believed to benefit in TOJs based on many observations of attentional benefits in other situations (see the introduction in Tünnermann, Petersen, & Scharlau, 2015). This claim can not be justified with the traditional TOJ analysis. Therefore, several important questions, such as "does attention speed up processing?", must be reassessed with methods powerful enough to support or reject such claims. The next sections isolate these fundamental questions which are then addressed in the remainder of this thesis.

1.3.3 *Questions to be Answered*

The Speed Question

One of the most fundamental questions, which was ignored until recently in prior-entry research, is whether attention speeds up the attended stimulus, slows down the unattended one, or acts in both ways to varying degrees (Weiß, Hilkenmeier, & Scharlau, 2013). This question already emerged in the discussion of TOJ relativity above. Besides the alternatives to pure attentional facilitation being poten-



tial explanations from a logical perspective, there is also theoretical and empirical support for them.

In human information processing, excitatory and inhibitory mechanisms are at work on various levels. On the lowest level, interconnected neurons can excite and inhibit their neighbors. In low-level visual processing, they are organized in receptive fields with excitatory and inhibitory areas. In recent years, the impact and importance of inhibitory processes have been recognized in sensory processing in general. Based on their measurement in the mouse visual cortex, Haider, Häusser, and Carandini (2013) write: "Having identified inhibition as a major determinant in the awake cortex, we suggest that behavioral factors such as attention and reward may also exert their influence by modulating inhibition" (p. 100). From such a perspective, an inhibition of unattended stimuli as a cause for prior entry can be entertained as a plausible alternative to a pure facilitation of attended stimuli.

Further support originates from a processing resource distribution perspective. Modern theories of visual attention assume capacity-limited processes (e.g., see Sections 2.5 and 3). In this view, if more resources are provided for the attended stimulus, it appears possible that these have to be deducted from those available for the unattended stimulus. Hence, if the overall available resources remain constant, inhibition of the unattended stimulus can be expected to the same degree as facilitation of the attended stimulus. If attention activated additional resources, pure acceleration would be present. Similarly, pure inhibition is possible if the attention manipulation reduces the overall available resources at the expense of the unattended stimulus.

As already mentioned, these alternatives have been largely ignored in prior-entry research. Studies that looked at this issue and evidence from similar phenomena are not conclusive so far (see introduction in Tünnermann et al., 2015). Therefore, the speed question is central to this thesis and is addressed in Manuscript A (Tünnermann et al., 2015, and Section 5.1) and Manuscript B (Tünnermann, Krüger, & Scharlau, in review, and Section 5.2).

The Peripheral Cue Question

Peripheral cues, which appear directly at the target location shortly before the target is presented, are highly effective in shifting the PSS in TOJs (see Shore et al., 2001). It has, however, been suspected that this advantage is not, or not purely, caused by selectively speeding up processing. Other factors could be the perceptual confusion of cue and target attributes (Pashler, 1998, p. 260; K. A. Schneider & Bavelier, 2003) or non-attentional sensory activation (K. A. Schneider & Bavelier, 2003; Wright & Ward, 2008, p. 25). Testing such alternatives is difficult with the common TOJ analysis methods, again, because no model of the individual stimulus encoding processes is considered. This question is addressed in Manuscript C (Tünnermann & Scharlau, in review, and Section 5.3) of this thesis.

Questioning TOJ Decision Rules

Further aspects of the prior-entry phenomenon can be investigated with the new techniques described in this thesis. For instance, it is believed that certain distortions of psychometric functions reflect that a non-deterministic decision function evaluates arrival times of independently processed stimuli. That is, if the arrival time difference does not exceed a certain threshold, the order percept may be uncertain and the report in binary TOJs random (see Section 4.3.1). Even though it is not possible to disprove this idea at this point, the model developed in this work provides an alternative explanation for the observed distortions with a deterministic decision function. This is explored in Experiments 8 and 9.

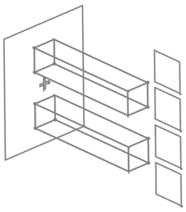
Can TOJs be Used to Measure Meaningful Attention Parameters?

Traditionally, TOJs are used to measure attention via the shift of the PSS. As was argued above, such shifts in the PSS have some difficulties, because they describe the relative performance and ignore the fundamental encoding processes that generate them. The method developed in this thesis uses a novel model based on Bundesen's (1990) Theory of Visual Attention (TVA), a mathematical approach which allows estimating meaningful parameters of the observer's visual attention system. These parameters are consulted to address the questions outlined in the previous sections.

However, it can also be asked whether using TOJs backed up with TVA constitutes a useful method to estimate these parameters for different purposes. Typically TVA parameters are estimated with whole-report (WR) or partial-report (PR) paradigms (see Section 3.0.2) which are limited to using letters and digits as stimuli. The TOJ task is appealing as an alternative that can work with almost arbitrary stimulus material. Hence, Manuscript *B* (Tünnermann et al., in review, and Section 5.2) presents this method as a tool for measuring TVA-based processing speed parameters. Because of the simplicity of the binary TOJ task, Section 6.4.2 discusses the method as a potential paradigm for measuring attention in animals. Similarly, it may be possible to use it to estimate attention parameters within dynamic environments such as computer games. This is discussed in Section 6.4.3.

1.4 STRUCTURE OF THIS THESIS

As mentioned above, up to now unanswered—and often unasked—questions about how attention influences the perception of temporal



order are addressed in this thesis. The remainder of Part I is organized as follows.

In Chapter 2, an account of research on attention is provided that covers early and modern theories of selection. Furthermore, it discusses the interactions between attention and memory systems, location cueing, and some considerations about the influence of attention on the perception of time.

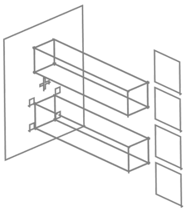
Chapter 3 explains Bundesen's (1990) TVA, as mentioned above, the mathematical model which provides the foundation for the models developed in this thesis. In addition to the basics, the chapter explains the neural interpretation of the theory and extensions toward the temporal domain.

Approaches to formally model the TOJ task and to analyze data obtained with it are presented in Chapter 4. This includes the traditional model-free analysis methods and the mechanistic interpretations of typical findings. Furthermore, the independent-channels model is presented, which is the basis for many TOJ frameworks. Stelmach and Herdman's (1991) Temporal Profile Model (TPM) is discussed as an early approach that tried to explicitly describe the processing within the channels. However, it can be shown that it leads to a dead end when used to derive a psychometric function of TOJs. More recent model-based approaches improve on this by assuming certain arrival time distributions in the channels. Finally, the TVA-based approach developed in this thesis is described. This includes a general recipe of how to derive concrete TVA-based TOJ models, and descriptions of the models used in this thesis.

The articles that belong to this cumulative thesis are summarized in Chapter 5. The experiments have been renumbered in the summaries to allow unambiguous references throughout the thesis. Experiments conducted in Manuscript *A* provide evidence that attention speeds up processing of the attended stimulus and slows down processing of the unattended one. Manuscript *B* further supports that attentional effects on the processing rates drive prior entry. However, in a salience experiment with a color pop-out, prior entry resulted from slowing down the non-singleton without increasing the processing speed of the singleton. Another experiment from this article provided further indications that the effect of peripheral cues cannot solely be explained by changes in stimulus processing rates. Motivated by this, the mechanisms behind peripheral cues are investigated in Manuscript *C*, which comes to the conclusion that a pattern of processing rate changes and perceptual cue–target confusions, which depend on the cueing interval, conjointly lead to the large shift observed in psychometric functions of cued TOJs. Furthermore, location-unspecific increases of available resources are also elicited by the cue depending on its lead time.

Chapter 6 contains a concluding discussion of these results within the theoretical context developed in this work. It also examines the assumptions which are introduced into the TOJ model by the use of TVA. Furthermore, this chapter discusses advantages of using the novel TVA-based TOJ analysis for the estimation of meaningful attention parameters.

The appendix of the synopsis in Part II consists of additional calculations and tables. Part III contains the original articles, Manuscripts *A* (Tünnermann et al., 2015), *B* (Tünnermann et al., in review), and *C* (Tünnermann & Scharlau, in review).



2

ATTENTION AND TEMPORAL-ORDER PERCEPTION

"With a little ingenuity, one could go on without limit, entertaining ever more baroque possibilities from one's armchair"
– Pashler (1998) (p. 27)

The experimental study of attention in the twentieth century was guided by a few highly influential questions, for instance, at which stage in processing attentional selection occurs. Very often, different researchers first endorsed rather extreme opposing views. With accumulating findings, many of these extreme views were qualified, declared special cases of greater schemes or found to depend on additional factors. Little was rejected with great confidence. Once in a while, researchers survey the ragged field of attention theories and empirical findings with the ambitious goal to compile a coherent theoretical framework. One of these surveys was undertaken by Pashler in 1998. His scheme provides the basis for the discussion in this chapter, and wherever required, the views and conclusion are updated.

The first sections outline some of the most important early views on attentional selection. The goal is not only to provide a compact historical account of modern-times attention research, but the chapter will also be a contrast to TVA which is the basis for the theoretical work of this thesis. TVA subsumes many of the former conflicting views in a coherent formal framework. This is a fact which can be appreciated best with the original controversies in mind. Starting points for the discussion—before any empirical evidence is consulted—are two popular frameworks that propose how attentional selection is carried out: early versus late selection.

2.1 THE LOCUS OF ATTENTIONAL SELECTION

"Worse, they'd put a waistcoat around its chest, with the paddles sticking out of the arm holes, and perched an oversize monocle by one of its prominent eyes. Near its snout was spread a tempting array of animals a crocodile might feed on: rabbits, frogs, fish. At least they had not managed to prize open the mouth and stuff prey into its craw"
– Chevalier (2009) (p. 120)

Early vs. Late Selection

The most influential *early selection* model, which nowadays is used as a prototype for this kind of theories, is Broadbent's (1958) filter model (Pashler, 1998, p. 14). In this model, a selective filter determines which stimuli undergo full processing and which do not. At early stages, the perceptual machinery determines stimulus features, such as location, color, or intensity for the visual domain. In the auditory domain, in which much of the early research was conducted, location, pitch, or loudness are analogous attributes that, according to the theory, can be accessed at early stages. Up to this level, processing is unselective and probably parallel. With these attributes available for all elements, the selective filter, controlled by attention, can then determine which stimuli are granted access to further processing. Hence, the filter introduces the selectivity and reduces the load for the later machinery that, according to the theory, can only process one element at a time. The post-filter processes ultimately lead to stimulus identification. Identified stimuli can be memorized or reported by observers. Importantly, this model implies that rejected stimuli, stimuli from which attention is drawn away, do not undergo processing any further than what is necessary for the selective filter to perform its filtering. Consequently, rejected stimuli are not identified.

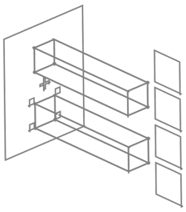
In *late selection* theories, as first proposed by Deutsch and Deutsch (1963) and Duncan (1980), there is no filter at an early stage. The selection in this type of model occurs at a stage late in processing. All stimuli are encoded in parallel to a level at which semantic representations are available. Only then a selection mechanism (controlled by attention) is applied, determining which representations reach the perceiver's awareness. The main consequence for this model is that all stimuli exposed to a perceiver are identified in a parallel process with apparently unlimited capacity.

Organizing Theories of Selection

Undoubtedly, early and late selection theories are two extreme cases concerning where selection takes place. A variety of intermediate theories can be considered.

Pashler (1998) suggested that alternatives do not lie in a continuous range between early and late selection (p. 22). Rather, a two-by-two matrix can be established which contains interesting theoretical alternatives. The two dimensions are the possibility of parallel processing ("possible if helpful", "not possible") and the question whether unattended stimuli are identified or not ("identified", "not identified"). The theory associated with the positive statement in both dimensions is late selection: Stimuli are processed in parallel and even rejected stimuli are identified. Both negative statements lead to early selection: Processing is serial and unattended stimuli are excluded from identification. Pashler describes an interesting alternative theory, controlled parallel processing (CPP), which occupies the matrix cell which allows for parallel processing but excludes rejected stimuli from identification.

According to CPP, the system first filters targets from distractors. If a stimulus is found to belong to the rejected ones, it is not further processed just as in the early selection theory. If multiple stimuli are potential targets, these can be processed in parallel, similar to the late selection theory. In this way, the controlled parallel theory features aspects of both, early and late, selection. The theory can be seen as the alternative that carries out the type of processing that is optimal depending on the situation (Pashler, 1998, p. 21). CPP is further discussed in Section 2.5.



The fourth cell of Pashler's (1998) two-by-two matrix represents serial processing and identifying even rejected stimuli. This rather odd theory would require that regardless of attention all stimuli are identified in a serial manner. Pashler mentions that such processing may occur in some situations, but the theory does not stand up well against empirical evidence in general. Hence, it is not further followed up.

Pashler (1998) notes that his two-by-two matrix only provides coarse theoretical categories (p. 23). Further interesting intermediate proposals have been made, which cannot be fully captured in the matrix. For instance, attenuation theory and graded capacity sharing are such cases.

Treisman's (1960) attenuation theory is based on attenuating unattended stimuli. Instead of completely rejecting them and denying them access to the identification machinery, processing of rejected stimuli is only attenuated. This is different to Broadbent's (1958) theory in which rejected stimuli are filtered out completely. Treisman's (1960) attenuation weakens the perceptual evidence to a level where the corresponding detectors will not identify the stimulus. However, if a detector is primed, its threshold is lowered, and an unattended stimulus may be detected. Priming can occur because of semantic reactivation or by detecting a similar stimulus. Via this mechanism, Treisman's (1960) framework can account for priming effects.

Another concept isolated by Pashler (1998) is graded capacity sharing (p. 24). Here, attention determines the share of limited processing resources available for each stimulus. This idea has some consequences for the processing speed. If there is only a single target, processing is carried out much quicker than if there are two or more targets that must share the resources. As will become clear in Chapter 3, graded capacity sharing is one the mechanisms TVA, the theoretical framework that was utilized in this thesis.

2.2 SELECTIVE ATTENTION

One important aspect present in all the theories described so far is the selective character of attention. Certain stimuli are "selected" by the attention system, whereas others are "rejected". Traditionally, attentional selection is considered important for processes of perception, for example, which elements are granted access to the visual short-term memory (VSTM). More recent views, however, point out that also "selection for action", the setup of motor programs toward attended objects is an important factor (e.g., see W. X. Schneider & Deubel, 2002).

2.2.1 *Auditory Selective Attention*

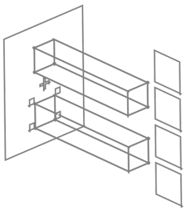
Much of the early research on selective attention was conducted in the auditory domain. Even though this thesis focuses on visual order perception and attention, I will briefly discuss the auditory roots of selective attention research. Furthermore, many attentional mechanisms are quite general—such as the selective character—and other may work at central stages which are independent of a particular modality.

In early attention research, the main paradigm used in the auditory domain was the shadowing task. When shadowing a message, subjects repeat the words presented in one channel and typically ignore other channels. The notion of a channel is important for the discussion. There is no direct relation in the sense that one ear represents one channel; however, the spatial separation that frequently emerges from binaural presentation often mimics such a relation (Pashler, 1998, p. 42).

Early shadowing experiments have been conducted by Cherry (1953). In these studies, different messages were presented to each ear, Cherry found that participants can easily ignore the message in the unattended channel and effortlessly shadow the message in the attended channel. Participants frequently fail to report any information presented in the unattended channel. They are also unaware of certain changes, for example, language switches or switching from normal to backwards playback. Certain other changes were however reported by the participants. The gender of the speaker, the pitch of the message, or when the spoken message was replaced with a tone of a constant frequency were noticed.

According to Cherry's (1953) interpretation, a change that can be detected based on simple statistics (e.g., pitch changes or switching to a tone) is noticed. By contrast, changes that require processing of words and semantics (e.g., language changes or backwards playback) go unnoticed. Follow-up studies showed that the report of words in the unattended channel cannot be improved by repeating them many times Moray (1959). This fact adds further support to the interpretation that the stimuli in the unattended channel are not processed further than required for selection, as postulated by early selection models.

In his review of early studies of selective attention in the auditory domain, Pashler (1998) addresses the question of task difficulty (pp. 53–55). Motivated by observing the ease of selective shadowing when sufficient cues are present to establish two spatially separate channels, researchers manipulated stimulus statistics to increase the task difficulty. Treisman and Riley (1969), for example, co-registered pairs of words in a dichotic presentation. That is, the start and end of each word in the attended channel was exactly matched with a



coinciding word in the unattended channel. This procedure removes sound arrival disparities as a cue for spatially distinctive sources. Under these conditions, which presumably do not allow the establishment of separate channels, subjects have difficulties selectively shadowing one message. Further findings show that adding information that allows distinguishing the sources (e.g., the gender of the speaker) leads to the establishment of channels that can be the target of successful selective attention (Treisman, 1964b; Underwood & Moray, 1971).

Up to here, the findings and interpretations are well in line with Broadbent's (1958) early selection model. However, as Pashler (1998) explains, researchers noticed that some information is processed in the unattended channel in certain situations (p. 45). For example, Treisman (1964a) reported that repetitions, when presented asynchronously in the two channels, were noticed when the unattended messages lead (at delays as large as 1500 ms). They could also be noticed when the message in the attended channel lead with a larger interval (at delays as large as 4500 ms).

For this to be possible, a lagging message in the unattended needs to be compared to an earlier message in the attended channel. This comparison is possible only if there is an echoic memory, a sensory memory that, as some researchers suggest, holds information briefly. Such a buffer could be used to perform the required comparisons. However, information used for this matching does not necessarily have to be semantic, because the matching may be carried out on low-level stimulus statistics. Hence, this finding does not contradict Broadbent's (1958) early selection theory (Pashler, 1998, p. 45).

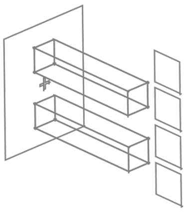
According to Pashler (1998), the fact that the presentation of one's name in unattended channels is typically recognized is sometimes considered support for late selection theories (p. 45). This was advocated for example by Deutsch and Deutsch (1963). Alternative explanations for this phenomenon, as well as an alternative explanation of how repetitions are noticed when the attended message leads, can be obtained from Treisman's (1960) attenuation theory. The mechanism is based on the idea that certain detectors are primed. The fact that there are substantial detections of these stimuli in the unattended channel is explained by the idea that the primed detectors are sufficiently sensitive because of the priming. They are then activated by the attenuated signal in the unattended channel.

Such findings that apparently favor late selection can often be reconciled with Broadbent's (1958) early selection theory by allowing for lapses. In the case of detecting one's name, for example, filtering may occasional lapse and select information from the other channel. Pashler's (1998) points out that this may happen even voluntarily when subjects become curious about the messages in the unattended channels (p. 48). Such possible lapses, unintended or voluntary, lead to difficulties in interpreting experimental results. When accidental selection occasionally leads to detection in the unattended channel, it remains unclear whether or to which degree information is processed in the unattended channel when it is actually unselected.

Pashler (1998) mentions a study by Corteen and Wood (1972), which revealed that subjects show conditioned galvanic skin responses for words in the unattended channel (pp. 49–51). This was initially interpreted as evidence in favor of the hypothesis that processing in this channel goes as far as semantic analysis. The results, however, were difficult to replicate (Wardlaw & Kroll, 1976) and of weaker magnitude for words in the unattended compared to the attended channel (von Wright, Andersson, & Stenman, 1975). The effect was almost entirely removed when trials in which subjects most likely lapsed (indicated, e.g., by shadowing errors) were removed from analyses Dawson and Schell (1982). These issues and similar unconvincing results led to the evidence for late selection not being conclusive. An early selection model that allows for occasional lapses may explain the data just as well (Pashler, 1998, p. 53).

MacKay (1973) found that disambiguating information in the unattended channel biases the interpretation of an ambiguous message in the shadowed channel. However, Newstead and Dennis (1979) found that this effect is removed if multiple instead of single words are presented in the unattended channel, as was the case in MacKay's study. Hence, the isolated word in the unattended channel may attract attention and disrupt the current selection state, leading to the influence. This, as Pashler (1998) puts it,"provides a final illustration of the tendency for breakthrough of the unattended effects in audition to become less convincing as the effects are investigated more carefully" (p. 52).

To sum up, a few things can be learned from these studies about the extent of processing unattended speech. The words in the unattended channel cannot be always and completely excluded from semantic processing of a certain degree. Conclusive evidence of this being the same degree as for the attended channel is lacking. Lapses or previously primed detectors may as well explain many findings in the frameworks of Broadbent and Treisman, respectively. An interesting observation was made by Pashler (1998): the more carefully the studies looked at the effects, the less evidence was found in favor of semantic processing of unattended stimuli (p. 53). More recent research has substantiated this view. In their article "Forty-five years after Broadbent (1958): still no identification without", Lachter, Forster, and Ruthruff (2004) found in experiments with visual stimuli that if one controls carefully for attention lapses toward the unattended ones, the evidence for identification of unattended information vanishes.



2.2.2 *Visual Selective Attention*

In the discussion of auditory selective attention, the question whether and when irrelevant stimuli are rejected proved helpful to test the different theories. Therefore, this discussion is continued for the visual domain.

Turning to the fate of rejected stimuli in visual perception, the first studies of interest are more or less visual versions of the early selective shadowing research. A study by Neisser (1976) showed that subjects had no problem reading prose when presented in every second line while every other line contained a different text presented in a different color. Only little is remembered from the unattended text. Whereas this study contains an additional disadvantage for the unattended text, the lower visual acuity, other studies used spatially overlapping presentations. Rock and Gutman (1981) used brief displays with overlapping line drawings of two motives, each in one color. When probed for recognition of the figures, participants were able to report the attended but not the unattended figure, even when the unattended figure was the outline of a known object (Pashler, 1998, p. 56).

Later variations of such experiments used two different video sequences that were superimposed in the same frame in the visual field. Subjects had no trouble attending to either of the videos and reporting events in the attended video. They had difficulties, however, monitoring both scenes simultaneously (Neisser & Becklen, 1975). Conspicuous events, such as removal or replacement of relevant elements in a scene, go unnoticed. This matches the results of Cherry's (1953) early shadowing studies in the auditory domain (Pashler, 1998, p. 57).

Semantic priming is a further branch of attention research which investigates the processing of rejected visual targets. One example is a task in which participants give a speeded response, judging whether a target is a word or a non-word letter string. If a semantically related prime word has been shown before, participants react faster. However, it is typically hard to argue that subjects really have the incentive to ignore the prime, because frequently it provides some helpful information, for example, regarding the target position. In cases where no such information is present, typically only beneficial effects are found when the words are related. No costs appear to be present when the words are unrelated. Therefore, it can be concluded that such studies provide little evidence for unselective word identification (Pashler, 1998, pp. 59–60).

Pashler (1998) suggests to assess indirect measures of identification (pp. 58–59). The Stroop effect (Stroop, 1935) illustrates the impact of unattended information. When participants go through a list of words and name the color each word is printed in, they are slower and make more errors when the word spells out an incompatible color (e.g., the word RED printed in green color). Hence, even though the color word is to be rejected, it influences the performance in the task.

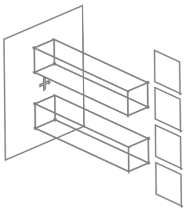
A similar influence is found in the flanker effect (C. W. Eriksen & Hoffman, 1973). In this task, participants had to react with different key presses to different identities of a centrally presented letters. Their reaction times were slowed down when adjacent letters—which were to be ignored—matched with the identity of a conflicting response.

However, as in the auditory domain the indications of unselective processing often can be explained by occasional lapses. Furthermore, explanations including unselective processing get less convincing with closer scrutinizing (Lachter et al., 2004; Pashler, 1998, p. 66). The line of argument to support this hypothesis is summarized in the following.

In a study by B. A. Eriksen, Eriksen, and Hoffman (1986), participants performed a task in which they had to decide whether a centrally presented probe belonged to a set of previously memorized letters. Flanker effects were observed depending on whether or not the typical adjacent (and to be ignored) flanker letters belong to the memory set. B. A. Eriksen et al. were interested in the distribution of reaction times. There are two alternative hypotheses of interest: First, the influence could be present in every trial. In that case, the cumulative distribution function would be shifted to the right by a constant offset with the magnitude of the net effect. Second, if the effect is caused by occasional lapses, only a portion of the trials would contain a slowdown. In this portion, the slowdown must be larger to produce the same net flanker effect (Pashler, 1998, p. 61–62).

B. A. Eriksen et al. (1986) found the first case, which is in favor of a true unselective processing in each trial. However, some doubts remain. In his book, Pashler (1998) hints at statistical difficulties (pp. 61–62). He further notes that in the majority of the literature, the explanation by lapses is not excluded, and the effects are typically only assumed to act in every trial.

A weakness that was further investigated is the problem that often rejected stimuli come from the same sets as the target stimuli and, therefore, carry some task relevance. Hence, the participant may be primed for those targets as assumed in Treisman's (1960) attenuation framework. To assess this, J. O. Miller (1987) performed experiments in the flanker paradigm. The flankers of interest were correlated with the target identities (specific flanker identities appear more often with specific target identities), but they did not belong to the instructed target set as in previous experiments. J. O. Miller interpreted their effect on the performance as evidence for automatic semantic processing. Pashler (1998) criticized that the information carried in the correlation is beneficial for the tasks, and subjects have no incentive



to ignore it (p. 63). He generalized this problem, as follows: "to the degree one finds effects of processing distractor items that are mostly beneficial, to performance, one cannot assume subjects are trying to exclude them" (Pashler, 1998, p. 63).

Pashler (1998) lists further experimental results which render the idea of an entirely unselective processing problematic (pp. 65–69). Among these, variations of the amount of rejected information are especially insightful. Kahneman and Chajczyk (1983) added additional rejected stimuli to the Stroop paradigm and Yantis and Johnston (1990) did so in a version of the flanker paradigm. The Stroop effect was reduced, which does not agree with the fully unselective processing that would leave the effect unchanged. The conflicting information should be processed and have the same impact no matter how many additional distractors are present. Similarly, for the flanker paradigm additional targets at unattended locations did not boost performance, as they do when some attention is present at their location.

To sum up, as outlined above, there is little evidence of completely unselective processing. Some amount of attention is required for a visual element to lead to effects in the typical tasks. According to (Pashler, 1998, Chapter 2), positive findings may result from occasional lapses, when attention briefly shifts to stimuli which were to be ignored.

2.3 VISUAL ATTENTION RESOURCES AND LIMITED MEMORY SYSTEMS

Outside of psychophysical laboratories, the perceptual system is mostly confronted with multiple items that potentially are to be processed in detail. The investigation of how multi-item displays are processed is important for understanding how processing resources are under the influence of attention . Extreme candidates are the fully serial and fully parallel processing discussed earlier in the context of early and late selection models. More elaborate models for multi-item processing originate from seminal studies by Sperling (1960) who introduced iconic memory and VSTM structures, which impose limits on the processing capacity (Pashler, 1998, p. 320). The VSTM has been revealed in whole-report experiments. In these, multiple items (more than five), for example letters, are briefly presented. For long presentation durations (e.g., 120 ms) the number of reportable letters converges to four to five elements Shibuya and Bundesen (1988). Additional time does not help observers to report more items. From this, it was concluded by Sperling and others that there is a limited short-term register in which the elements are stored before they are possibly forwarded to further memory structures for higher cognitive operations. The VSTM holds the elements over periods in the range of a few seconds; thus, it is a relatively durable register but has a limited capacity. Which elements are allowed to enter the VSTM is subject to attention. However, if the VSTM is filled up, no further elements can enter, even if they belong to the attended set. It has however been recognized that visually guided tasks of realistic complexity require a visual working memory (VWM) that allows access to more than four elements. W. X. Schneider (2013) proposed that the relatively transient VSTM is accompanied by a passive VWM structure in which task relevant representations can be transcoded and which does not suffer from storage capacity limitation.

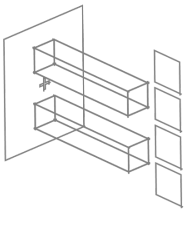
The iconic memory is a very short-lived storage but has scarcely any capacity limitation. Important evidence for such a memory stems from Sperling's (1960) PR experiments. In these, observers report only a subset of all shown stimuli. Intriguingly, it is sufficient to indicate the subset up to 500 ms after the display was switched off. For example, if colored letters are used, the instruction about letters of which color are to be reported can be delayed until after the presentation. Subjects show a reasonable performance under such conditions because they can access a persisting iconic memory representation of all items, even if these are more than four or five. The iconic memory can be disturbed by showing a mask after the presentation, which overwrites the representations that would otherwise persist in the system.

According to Pashler (1998), it can be questioned whether the iconic memory is a purposeful memory structure at all, or whether it is just a consequence of how information propagates throughout the system (p. 107). Situations in which the iconic memory can be used typically only occur in artificial circumstances. In real word perception, the continuing stream of incoming information is providing constant access to the original stimuli, if fixation remains stationary, or the iconic memory representations are overwritten by new stimuli if eye movements occur.

2.3.1 *Memory Structures*

This section provides an overview of different memory structures, how they interact, and how they are affected by attention. A foundation for this discussion is the modal model Atkinson and Shiffrin (1968). Such structural memory models assume different storage stages: sensory memory, short-term memory (STM), and long-term memory (LTM).

The sensory memory is available early in sensory processing. It holds sensory representations for very short durations. Important evidence for its existence originates from the already mentioned PR studies by Sperling (1960). There is less evidence for auditory sensory memories, where PR paradigms only find minute effects. However,



the sensory memory concept is typically accepted in the auditory domain as well (Pashler, 1998, pp. 321–322).

The STM can retain information over longer periods of time than the sensory memory. The representations stored are more abstract than those in the sensory memory. Pashler (1998) notes that this qualitative difference was demonstrated, for example, by Philips (1974) (p. 320). Philips presented abstract black and white matrix patterns briefly. Then a probe, the same pattern or a different one, was presented, and participants indicated when the patterns matched. The performance was best at the very short target–probe intervals, where the sensory memory could be used for a direct comparison of the percept. For longer delays, the performance declined; however, it became more robust against shifting the probe position, because now the more abstract STM representation was used.

To store information over long periods, the LTM can pick up and solidify information represented in the STM. In the classical view, the LTM is serially linked to the STM. Information is first represented in the STM and then transferred from there to the LTM. Studies with brain-damaged patients, however, show that depending on the injury either of these two memory systems may be unavailable while the other is normally functioning (Pashler, 1998, pp. 322–323). On the one hand, this supports the idea of a parallel connection to the storages. For the LTM to operate without the STM, it needs its dedicated connection to the input. On the other hand, studies with such patients support the idea that there are these two separate storage systems in the first place. As Pashler (1998) notes, original support for a distinction between STM and LTM was provided by the free recall paradigm Glanzer and Cunitz (1966) (pp. 323–325). In this paradigm, participants listen to lists of words and afterward have to report any elements they remember. The best performance is typically observed for the first words in the list (primacy effect) and the last words in the list (recency effect). The primacy effect is attributed to the fact that these first stimuli can be solidified in the LTM without much competition compared to the words from the middle of the list. The recency effect, however, originates from the fact that the last elements of the list are still available and easily accessible in STM.

In addition to giving up the notion of a purely serial connection between memories, another modification to the original model is necessary (Pashler, 1998, p. 328–331). There is overwhelming evidence that there is not single STM, but different ones for different modalities or stimulus material. Most prominent is the distinction between visual and verbal STM. Again evidence from brain-damaged patients, who suffer impairments in one but not the other form of STM, provides support (Warrington & Shallice, 1972). In normal subjects, the absence of interference between spoken and visually presented digits provides an important clue for separate systems (e.g. Henderson, 1972). Pashler (1998) notes that these memory systems do not have to be discrete entities, but that the similarities between the materials to be stored may play a significant role (p. 329). This idea originates from the observation that the capacity of both systems is inversely related to the similarity of the stimuli. Lower similarity results in more items being storable in each system. Representations of auditory and visual stimuli may just be very different and therefore not interfere with each other. Further support for distinct systems comes from positron emission tomography studies, which show that, depending on the type of stimulus material, different brain areas show stronger activation. In addition to visual and verbal STM, further memory systems appear to exist. These are, for example, STMs for spatial location or haptic information. W. X. Schneider's (2013) proposal of different forms of STMs even within the visual domain was already mentioned above. It provides another form of diversity in STMs.

Another distinction in memory systems is the one between declarative and procedural memory systems. The former handles explicit recall and recognition. The latter is revealed implicitly, for example, when subject learn how to perform certain motoric tasks (Pashler, 1998, pp. 331–334). One such task is keeping a stylus in contact with a rotor in motion. An important contribution of evidence originates from amnesic patients, who lack declarative memory, but procedural memory is preserved (e.g., they learn and later perform in the rotor task just like normal subjects). Pashler (1998) however writes, "[...] structural approaches seem to have fallen into a certain amount of disrepute, mostly based on criticisms that do not survive careful scrutiny, [...]. By contrast, the distinction between implicit and explicit memory system appears to have achieved wide acceptance even though the data taken to support it often seem well short of conclusive" (p. 334). He adds that the lack of support, of course, does not exclude eventually proving of the distinction.

In the past twenty years since Pashler's (1998) assessment, the views have strengthened. Support for the decentral organization of different memory systems stems from functional neuroimaging studies (Cabeza & Moscovitch, 2013). Evidence for the distinction declarative–procedural distinction originates, for example, from studies of interference in memory tasks (Gade, Druey, Souza, & Oberauer, 2014) and differences in their courses of development (Finn et al., 2016).

2.3.2 *Attentional Limitations in Memory Storage*

In contrast to the sensory memory, which seems to be free of attentional limitations, the VSTM is quite influenced by the distribution of attention. The influence can be seen in Sperling's (1960) PR paradigm. By cueing elements in the display (or rather in sensory storage) the VSTM capacity limitation and the selective influence of attention is revealed. Concurrent central processing tasks do not affect VSTM capacity (Pashler, 1998, p. 342). Exceptions may be tasks that require recoding representations, for example transferring visual to verbal memory representations by verbalizing them (Broadbent, 1989). Ignored stimuli are typically not transferred to the LTM. Pashler (1998) points out that LTM recall performance is heavily affected by additional tasks at the time the inputs are memorized (p. 343). Similarly, such interference by concurrent tasks during memory retrieval weaken the performance.

In short, in briefly exposed displays of visual stimuli, observers can only report a rather limited number of elements (around four). They have voluntary control about which targets they can report when more than four are presented. Because of the iconic memory, which keeps stimulus information available for a prolonged duration, observers can apply these selection mechanisms even until about half a second after the presentation.

Both VSTM and iconic memory are typically taken into account when measuring attention with methods such as TVA, the attention theory on which this thesis is based. To estimate parameters of the attention system, often masked whole report (WR) and PR experiments are conducted. In these experiments, typically masks are deployed after a controlled presentation duration to erase the iconic memory representation. Furthermore, the limitation of the VSTM is taken into account when analyzing the data (see Section 3).

2.4 MANIPULATING VISUAL ATTENTION: CUEING

The performance of information processing can be influenced by different attentional factors. In general, they are frequently referred to as "attentional set". According to Pashler (1998), the attentional set can be considered a disposition of the processing machinery that is established via information available in advance (p. 167). In psychophysical tasks, such information can be provided directly in each trial, via cueing (e.g., location or feature cues) or by holding certain relevant features constant for whole blocks of trials. It can be either orthogonal, that is, independent of the feature dimension of the task-relevant selection or report dimension, or it concerns a certain range within the task-relevant dimension (Pashler, 1998, p. 169). An example of the former is a location cue in a task where the participant has to report letter identities; the latter one is advance knowledge about which subset of letters can occur in the experiment.

The most important type of attention manipulation for this thesis is the use of direct peripheral cues. Peripheral cues are shown in close proximity to one target. How exactly such cues interact with the target is not clear. A great deal of this thesis, especially Manuscript C, is concerned with the mechanisms of the influence of peripheral cues on target encoding latencies. In the present section, the fundamental findings concerning cueing are discussed.

2.4.1 *Cueing Locations*

Already von Helmholtz (1867) demonstrated that advance information about the location of visual stimuli can enhance identification performance. He produced an electric spark in a dark box into which he peeked through a small hole. This flash lit up a display of letters, from which he was able to read those at the position to which he had directed his attention to in advance. Notably, this position was different from the central fixation mark to which he directed his eyes (Wright & Ward, 2008, p. 5). The experiments of Sperling (1960) mentioned above and similar studies (e.g., Averbach & Coriell, 1961) showed that delivering a position cue even after the presentation leads encoding stimuli into VSTM which would otherwise have been rejected.

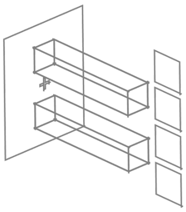
Influential studies of cueing locations in advance have been conducted—among others—by Posner and colleagues (e.g. Posner, 1980). A current review is presented in S. E. Petersen and Posner (2012). Wright and Ward (2008) summarize the main aspects of such experiments as follows: There is a central fixation mark participants have to fixate with their eyes over the whole trial. There is a probe stimulus, which participants have to respond to. A location cue is presented shortly before the target appears.

In a particular trial, the fixation mark is shown for some time. Then the location cue is shown. Different types of cues are discussed below. Typically, the cues are valid (indicating the correct target location) in 80 % of the trials. After the cue onset asynchrony, a delay depending on the type of cue, the probe is presented. Then participants react as fast as possible or in some studies identify the stimulus.

Cues can be symbolic, for example, central arrows pointing to the target location, or a letter or word identifying the location. By contrast, direct cues are at the target locations. These can consist of placeholder marks, such as lines which eventually underline the probe, boxes that highlight the target position or more compact stimuli which are covered by the probe when it appears.

2.4.2 *Costs and Benefits*

The typical ratio of 80 % valid and 20 % invalid cues leads to a particular pattern of costs and benefits observed in the performance (Wright & Ward, 2008, p. 19). For example, the reaction time in a neutral condition without a cue could be about 260 ms. In validly cued trials it could be reduced to 240 ms, whereas it gets prolonged 280 ms for invalidly cued targets. Such patterns are typically interpreted as ad-



vantages caused by valid cues shifting attention to the probe location in advance, and invalid cues shifting attention away from the probe location. Attentional analysis of the probe can then start earlier for validly cued stimuli, or later for invalidly cued ones for which the system has to make up for the false shift at the time the probe appears (Wright & Ward, 2008, see also Section 4.2.2 of this thesis for a similar interpretation in the context of temporal-order perception).

Another view is that attention increases the share of processing capacity allocated to the cued location and reduces it for the uncued location. Then processing does not necessarily start earlier, but it may proceed faster for the cued target.

Pashler (1998) notes that for explaining cueing effects in speeded reaction time tasks, there may be alternatives to benefits caused by attention speeding up processing (p. 180). Selective shifts of the decision criterion (initially suggested by Mulligan & Shaw, 1981) provide a plausible alternative explanation. The observed performance originates from the unobservable outcomes of the individual channels. Therefore, selective criterion reduction of the cued and criterion increase in the uncued trials can improve the performance without boosting the false alarm rate. This possible outcome can be understood by taking into account the following fact. The increase of false alarms by reducing the cued channel's threshold can be compensated by a decrease of false alarms caused by the higher criterion in the uncued channel.

2.4.3 *Symbolic and Peripheral Cues*

As already mentioned, there are various types of cues. The main distinction is whether a cue is symbolic or peripheral. Symbolic cues are stimuli presented well in advance, which have to be interpreted by the subjects who then direct their attention accordingly. For example, the phrase "attend left" or a leftward arrow can be used as symbolic cues for the left side of a display.

Peripheral cues are presented directly at the target location, shortly before the target is shown. They do not require a cognitive interpretation of their meaning. Wright and Ward (2008) write that their facilitative effect on target detection times appears to originate in part from cue-induced sensory activation at the target location (p. 25).

These two types cues differ in the time course of their effectiveness, which is described in the next section. Moreover, in the context of this thesis—the influence of attention on the perception of temporal order—peripheral cues are usually much more effective in distorting time perception than symbolic cues (K. A. Schneider & Bavelier, 2003; Shore et al., 2001).

A further difference between symbolic and peripheral cues can be found when testing whether or not a cue needs to be consciously perceived to unfold its effect. Symbolic cues do not work if presented below the threshold of conscious perception, whereas the cueing effect of peripheral cues still occurs (Wright & Ward, 2008, p. 26). Scharlau and Neumann (2003a) showed that a peripheral cue accelerated attention irrespective of whether it was masked (and virtually invisible) or not. Whereas symbolic cues may not work in endogenous attention orienting with unconscious stimuli, the existence of a feature-specific search template (e.g., if a particular shape or color is task relevant) can lead to endogenous attention orienting toward unconscious stimuli (Ansorge, Horstmann, & Scharlau, 2011).

2.4.4 *The Time Course of Cueing Effectiveness*

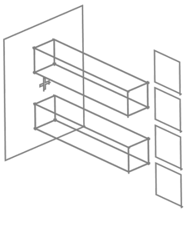
Peripheral cues are most effective around a cue onset asynchrony (COA) of 100 ms. Their effectiveness rises toward this maximum and then subsides until no benefit is present for COAs greater than 200 ms (Wright & Ward, 2008). Then, at even larger COAs, inhibition of return (IOR) sets in. IOR inhibits the previously attended location, so attention is more likely directed to other regions of the visual field (Klein, 2000).

Symbolic cueing has a different time course. Symbolic cues reach their maximum effectiveness much later than direct cues, at COAs around 300 ms. They then sustain this effectiveness for long COAs, probably up to 2 seconds (Wright & Ward, 2008, p. 25).

2.5 ATTENTION IN CONTROLLED PARALLEL PROCESSING

In his 1998 book, Pashler reviewed a large body of empirical results—a subset was discussed in the preceding sections—with the goal of reaching a final decision concerning attentional selection. Is selection early, late, or does it follow a still different scheme, after all? The overall picture that emerged about selection and capacity limitations can be compared to the theoretical concepts described in Section 2.1. First of all, the picture is not fully consistent with either, early or late selection theory. For instance, the fact that in certain situations with fairly simple stimuli, full parallel processing free of capacity limits is possible does not agree with early selection accounts. Similarly, that capacity limitations are found under certain conditions for attended and not for rejected stimuli, is in conflict with late selection theories. A table and a full point-by-point check of empirical findings against these theories can be found in Chapter 5 of Pashler's book (p. 217). The result of this check, however, is that CPP which is neither a fully late- or early- selection account offers good agreement with the empirical findings.

In CPP, filtering may exclude stimuli from the analysis, as in early selection, but it is also possible to grant more than one target a pass-



through. The post-filter processing is then subject to resource allocation and parallel processing. Hence, stimuli can be processed in parallel, but not necessarily are rejected stimuli identified. Most likely, perceivers operate the filtering mechanism in the manner that is most beneficial to solve the task. Depending on the task, participants are able to exclude rejected stimuli from processing, but sometimes they can process stimuli in parallel as well (Pashler, 1998, p. 224).

Pashler (1998) points out that even though CPP is consistent with the empirical evidence, it provides only a rough scaffold for a theory of attention (p. 224). The details of how capacity limitations affect attentional selection, and whether the filter determines which targets compete for capacity, have to be worked out. According to Pashler, these issues can be addressed in monitoring tasks with a sufficiently large set of stimuli that lead measurable effects of capacity limitations. Furthermore, the costs of relevant and irrelevant non-targets must be measurable (p. 224). Several studies are available in the literature which essentially agree concerning their outcome. One example is a study by Duncan (1979). Participants had to report targets that appeared in known positions. In one condition with eight stimuli, four of them were in relevant positions that could contain targets, and four were in rejected positions that never contain targets. Duncan varied the difficulty of distractors (by manipulating the confusability with targets) in relevant and irrelevant locations independently. He found that increasing the difficulty in relevant positions slowed the search times for the targets, whereas the search time was unaffected when distractors in irrelevant positions were made more difficult. Pashler summarizes the evidence from such studies and those presented earlier as follows:

"People can usually exercise control over what stimuli undergo extensive perceptual analysis, including, on occasion, selecting multiple stimuli for analysis. When this takes place, the stimuli that are selected compete for limited capacity. If the total load of stimulus processing does not exceed a certain threshold, parallel processing occurs without any detectable reduction in efficiency. Above this threshold, efficiency is reduced by the load of attended stimuli, and processing may sometimes operate sequentially, perhaps as a strategy to minimize loss of accuracy" (p. 226).

Thus, in the larger picture, the attention system includes filtering components and capacity allocation components. Either of these components can explain many aspects of attention that can be observed. For example, irrelevant stimuli can be rejected either by filtering these out or by denying them processing resources. Similarly, where a parallel search for feature targets is observed, this could be based on gating all stimuli through the filter and process them in parallel. Alternatively, in the capacity account, this could happen at the pre-attentive stage, which does not require resources, or whenever the available capacity is sufficiently large.

2.6 ATTENTION AND THE PERCEPTION OF TIME

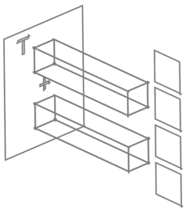
This thesis deals with the question whether and how attention leads to changes in processing speed. In this section, I provide a brief summary of the idea that attention influences the perception of temporal events. Detailed considerations can be found in the Introduction of Manuscript *A* and Section 4, where concrete models of temporal-order perception are discussed.

If attention enhances perceptual processing and speeds up reaction times, it may also influence the perception of time. Titchener (1908) included the law of "prior entry" in his set of laws which characterize attention. It states that an attended stimulus is perceived as appearing earlier that the same stimulus when it is not attended.

The interest in such effects predates experimental psychology. When early astronomers registered the exact times of celestial events, the distribution of attention may have affected their readings (e.g., see Hoffmann, 2007). Later, this situation was transferred to psychophysical laboratories as the so-called complication experiment (Boring, 1957): Participants observe a clock with a revolving pointer. At some point in time, a bell rings. The participants have to report the pointer position at the time of the ring. Because of the prior-entry effect, a difference should be present between conditions where perceivers attended to the sound and conditions where they attended to the pointer. Even though such differences were initially found, careful studies showed that prior entry caused by attention is most likely not their cause in the complication paradigm. The involvement of eye movements was more likely the cause (see Spence & Parise, 2010).

Nowadays, prior entry is typically studied in TOJ tasks, as in this thesis. In such experiments, observers judge the relative order of a few (typically two) targets which appear at different moments in time. If attention is directed to one of them in advance, this target should be perceived earlier than the other. In other words, attention manipulations should introduce systematic differences in order judgments. The TOJ paradigm is described in more detail in Section 4.1.

Pashler (1998) states that the literature that uses these methods presents a confusing picture (p. 259). Some researchers found prior-entry effects (Stelmach & Herdman, 1991; Sternberg, Knoll, & Gates, 1971; Stone, 1926) whereas others did not (Hamlin, 1895; Jaśkowski, 1993). He also points out that one would fail to find the effect if attention is not successfully manipulated, but, at least, some of the studies used strong manipulations. In some of the positive studies, response biases could be at work creating the effect. If uncertain, participants could prefer to judge in favor of that stimulus that is



somehow marked (e.g., with an arrow or peripheral cue). Similarly confounding, peripheral cues at the target locations could be mistaken for, or merged with the target representation. Hence, the target's onset would be reported earlier, leading to the prior-entry effect. These conflicting findings are discussed in the introductions of Manuscript *A* and Manuscript *C*. The latter article indeed focuses the question whether the cue is sometimes confused with the target.

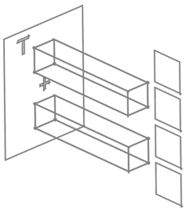
Finally, it should be noted that investigating the perception of time is a much more complicated business than it appears on the surface. The reason for this is that there are different dimensions of time involved in the psychological analysis of temporal phenomena (e.g., see Neumann & Niepel, 2004). For example, there is physical time involved in which the low-level biochemical processes unfold. Then, there may be fine structures involved with the representation of time in the visual system. For example, some theories assume that the system operates on sequences of discrete moments (Stroud, 1956). Finally, there is the perceived time, the timeline on which an observer would mark the occurrences of the perceptual events.

This complication can affect in different ways how observers report temporal order, simultaneity, or the duration of events. These aspects have been summarized, for example, by Weiß (2012). I will not go further into depth at this point. In the discussion of models of temporal-order perception some aspects, as the idea of perceptual moments, appear in the context of the models that make use of such notions in Chapter 4. Importantly, the theoretical framework developed in this thesis avoids many of the complications that arise from the different concepts of time in perception. This is because the proposed model is free of the notion of durations in perceived time. Events occur probabilistically based on physical time and are then compared in a deterministic decision mechanism.

To sum up—not only the discussion of attention and time but the whole chapter—attentional selection has long been studied experimentally. An account that fits well with empirical evidence is Pashler's (1998) CPP. It is a theory which allows "a bit of everything". Serial or parallel processing is possible, and unattended stimuli can be rejected or processed, depending on the situation. For a theoretician, such an opportunistic framework may not be very appealing. For a living organism, a visual system which—as Pashler has interpreted CPP—employs the best selection mechanisms in any situation it is quite appealing. Hence, the theoretician has to drop clear-cut conceptions of early or late selection and full processing or complete rejection of unattended stimuli. He or she has to face the challenge to go a level deeper and explain how such flexibility can arise in the vision system. One approach in this direction is Bundesen's (1990) TVA, which is described in the next chapter and on which the analyses in this thesis are based.

Further aspects of attention discussed above are its influence on memory and the possibility to manipulate an observer's attention by cueing. Concerning the memory systems, one of the most important aspects is that attention can control which elements are taken up into the VSTM. In the present thesis, the VSTM plays an important role as the entity at which stimuli arrive and where their temporal order is compared.

In general, the effect cueing has on visual perception is that the cued target benefits, potentially in different ways. It may increase the share of processing resources assigned to the cued stimulus, but especially peripheral cueing may also have other effects, such as preactivating the sensory circuitry or shifting decision criteria in reaction time tasks. In this thesis peripheral cueing is important because it is the most effective mean to alter temporal-order perception. Therefore, parts of the thesis deal with fine-grained models of cued TOJ and the differences between peripheral cues and other attention manipulations, such as visual salience.



3

TVA – A MATHEMATICAL MODEL OF VISUAL ATTENTION

In this chapter, the basic concepts and equations of Bundesen's Theory of Visual Attention are explained. Of course, they have been explained elsewhere at different levels of detail. In Bundesen and Habekost (2008) they are presented together with the historical account of how the theory came about. Empirical findings that justify the various components are discussed. The authors further explain neurophysiological mechanisms which are believed to implement the model in the human brain. A comprehensive and updated account is presented in Bundesen, Vangkilde, and Petersen (2015). In the manuscripts associated with this thesis, TVA and its equations have been explained at a level of detail appropriate for the research question at hand. This chapter is intended to present the theory at an intermediate level. Of course, it cannot have the textbook character of the work by Bundesen et al. mentioned above. It is focused on providing the fundamentals required for a discussion of prior entry and TVA-based TOJ models. This outline of the theory is tailored to the requirements of this thesis and will provide the reader a convenient place to look up the relevant aspects.

3.0.1 *Racing for VSTM Entry – Mathematics of Biased Competition*

"Homunculi are bogeymen only if they duplicate entire the talents they are rung in to explain. If one can get a team or committee of relatively ignorant, narrow-minded, blind homunculi to produce the intelligent behaviour of the whole, this is progress"
– Dennett (1981) (p. 123)

According to TVA, visual stimuli compete for being represented in VSTM. These representations are of the form "object x belongs to category i". The capacity of the VSTM is limited to three or four elements. Whether a certain stimulus can secure one of these slots depends on its processing rate $v(x,i)$.

This rate governs the probability $F(t)$ that a stimulus is encoded until a time t relative to the time at which the stimulus was shown. This probability follows the cumulative distribution function of a shifted exponential distribution,

$$F(t) = \begin{cases} 1 - e^{-v(x,i)(t-t_0)} & \text{if } t > t_0 \\ 0 & \text{else,} \end{cases} \tag{1}$$

where t_0 is the maximum ineffective exposure duration. Stimuli that are shown for a time shorter than t_0 are not being encoded at all.

there are more than K stimuli, the VSTM limitation needs to be taken into account. The probability of encoding an element x in category i before the VSTM is filled up until time t is given as

$$F(t) = \begin{cases} v(x,i) \sum_{j=0}^{K-1} \sum_{J\in\mathcal{P}_j(\widetilde{S})} \sum_{L\in\mathcal{P}(J)} (-1)^{|L|} & \\ \quad \times \frac{1-exp(-[t-t_0]\nu)}{\nu} & \text{if } t > t_0 \\ 0 & \text{else,} \end{cases} \tag{2}$$

where $\widetilde{S}$ are all shown elements except x, $\mathcal{P}_j(\widetilde{S})$ is the subset of the power set $\mathcal{P}(\widetilde{S})$ in which j of the shown elements occur in each combination, $\mathcal{P}(J)$ the power set of J, and $\nu = \sum_{m\in S} v_m - \sum_{l\in J} v_l + \sum_{k\in L} v_k$. Power sets contain all possible combinations of the elements (Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011). Because there are only two targets in TOJ tasks, the models employed in this thesis have been derived from the simple encoding model in Equation 1.

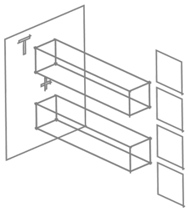
For most of the experiments presented in this thesis, it is the rate $v(x,i)$ in "elements per time unit" which is measured and which reflects the encoding speed of a stimulus. Note, however, that this parameter is specific to an object x and a category i. Consequently, the same object can invoke multiple races for different categories. Conversely, different objects might race for the same categorization. This may sound as if in common situations there would be an almost infinitive number of races going on. Fortunately, most of the rates of various objects racing for various categorizations are practically zero as will become clear shortly.

Taking into account that for all shown stimuli S and all possible categorizations R there is a definite amount $C = \sum_{x\in S}\sum_{i\in R} v(x,i)$ of available processing resources in a given situation. TVA further describes how these resources are distributed. The rate equation provides the fine structure of the processing rate parameter:

$$v(x,i) = \eta(x,i)\beta_i \frac{w_x}{\sum_{z\in S} w_z} \tag{3}$$

The rate equation consists of three factors. Parameter $\eta(x,i)$ models the sensory evidence that object x belongs to report category i. The value of β_i represents a bias for categorizing objects as members of category i. The bias is independent of the other factors. Finally, the factors mentioned above are multiplied with the relative attentional weight of object x. This weight is the object's individual attentional weight. It is normalized by dividing it by the sum of the attentional weights of all objects z in the visual field S. The calculation of the attentional weights is described by TVA's weight equation:

$$w_y = \kappa \sum_{j\in R} \eta(y,j)\pi_j \tag{4}$$



The attentional weight of an object y (e.g., $y = x$ or $y = z$ in the equations above) consists of different components. The κ parameter represents a stimulus-driven contribution based on local contrast (salience) of object y. The pertinence value π_j can be considered a top-down influence that models how important one specific selection category j is. The sensory evidence $\eta(y, j)$ for y belonging to selection category j is multiplied with the corresponding pertinence value. The terms $\eta(y, j)\pi_j$ of all categories j are summed up and multiplied with κ.

Note that in these equations, the η is the core part of the resulting processing rate. The other parameters, β, π, and κ are unit-less regulatory factors in the range of zero to one, which model the relative strengths of the different influences on the distribution of the processing resources.[3] Furthermore, it is important to note that for the majority of the report and selection categories various regulatory factors are zero. Hence, even if for one object there may be high η values associated with many categories (i.e., the sensory evidence is highly ambiguous), the π and β values for most of the selection and report categories tune down these contributions. For example, if the participant in an experiment is asked to report red letters and ignore blue letters, π will be high for red and low for blue or other colors. The β value will be high only for letter categories and low for any other type of stimulus categories.

The preference of certain report categories based on their high β values is often called *pigeonholing*. The selection of objects as targets based on perceptual categories is called *filtering* and is regulated by π and κ values which modulate the attentional weights. Pigeonholing and filtering are independent from each other. Pigeonholing regulates the probability that a report category is selected without influencing the conditional probability that a particular stimulus in the visual fields is selected given that the report category is selected (see Bundesen & Habekost, 2008, p. 66). Combined filtering and pigeonholing in the competition for VSTM entry provides a different perspective on attentional selection and stimulus identification that contrasts the classical early vs. late selection view (see Section 2.1). TVA can be considered a fleshed out version of Pashler's (1998) CPP proposal described in Section 2.5 because it describes how filtering and limited-capacity parallel processing lead to attentional selection and stimulus identification.

In the present context of prior-entry research, the expected value of the encoding time distribution plays an important role. It follows

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[3] The κ and π values do not necessarily have an upper bound at one. Because the resulting weights are normalized in Equation 3, π and κ values can take any positive real number and only the relative magnitude differences among them and between them and π and κ families of competing weights are relevant.

from the shifted exponential distribution that expected value of the encoding time E_x of stimulus x is

$$E_x = t_0^x + \frac{1}{v_x}, \tag{5}$$

where t_0^x and v_x are the respective TVA parameters of stimulus x. Consequently, a TVA-based estimate of relative prior entry between two targets p (potentially attended) and r can be calculated as

$$\mathrm{PE}_{\mathrm{TVA}} = E_r - E_p = (t_0^r + \frac{1}{v_r}) - (t_0^p + \frac{1}{v_p}). \tag{6}$$

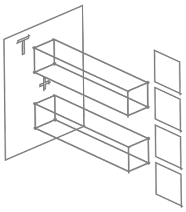
Note that typically t_0 parameters are assumed to be equal and, therefore, cancel out.

Before I turn to sketching the assumed neural underpinnings of TVA, I would like to clarify which parts of the theory and its formalism are the basis for the work described in this thesis. The letter report data from Experiments 1 and 2 are modeled with the traditional TVA model as formalized in equation 1. For all other experiments, a novel TVA-based TOJ model is utilized. This model is derived in Chapter 4.6 from equation 1, which describes encoding individual stimuli. When these models are fitted, the v parameters (or C and attentional weights w) are estimated. As described above, the constituents of these rate (or weight) parameters are typically not estimated. However, a recent study by Krüger, Tünnermann, and Scharlau (in preparation) extends the TVA-based TOJ model to estimate the κ.

For the experiments presented in this thesis, the estimated rate parameters are named, for example, v_p (subscript p stands for "probe", the attended stimulus). The reader might notice that writing parameter names like this does not include the notion that there are rate parameters with which an object x (here probe p) races for various categorizations j. The rate v_p can be considered the rate with which proper categorizations are made according to the task. Hence, it is the rate with which the object p is encoded as the probe stimulus.

3.0.2 *Typical Applications of TVA*

Many studies have applied TVA in WR and PR paradigms (Sperling, 1960). In these paradigms, stimulus displays with typically six letters are shown for varying brief presentation durations (10 to 200 ms) and then masked (see Figure 1). In WR tasks, participants are asked to report all letters they recognize (see Figure 1a). In PR tasks, they have to report targets defined by a certain attribute (in the example in the figure the attribute "is letter") and ignore the distractors (digits in the example). The number of targets is usually around six because this allows to estimate the VSTM capacity limit, TVA parameter K.



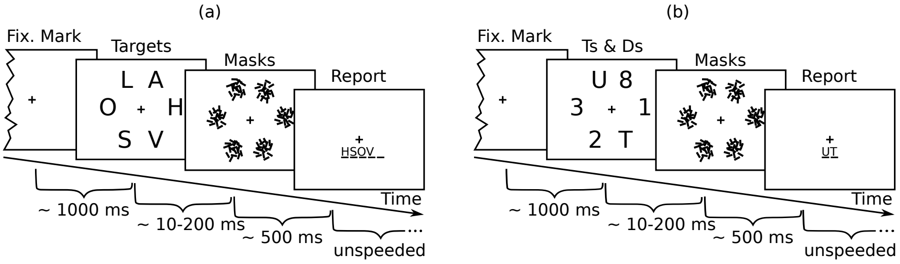


Figure 1: (a) WR and (b) PR paradigms typically used with TVA. In (b) letters are targets (Ts) and digits are distractors (Ds).

TVA parameters are estimated with models derived from Equation 2 (e.g., see Dyrholm et al., 2011). In addition to K, the WR task can be used to estimate C, the overall processing capacity, t_0, the threshold for perception, and spatial attentional weights, w, for example for the left vs. right visual field.

The PR task can be used to obtain estimates of α in addition to the parameters mentioned above. The parameter α models performance in selecting targets among distractors. Therefore, it can be regarded as a measure of top-down attention control.

This methodology has been applied in patient studies with different brain injuries or cognitive deficits and studies with external factors which are expected to influence visual attention. Bublak et al. (2005) showed that the WR and PR tasks can be used in clinical contexts to estimate the discrete attention parameters TVA provides. In their study, they found impairments in different TVA components in patients with lesions in parietal or frontal brain structures. In a study of the influence of nicotine on visual attention, Vangkilde, Bundesen, and Coull (2011) developed the *CombiTVA* paradigm. This paradigm includes both, full WR trials and a reduced set of PR trials (these have only one presentation duration, 80 ms). PR andWR, the *CombiTVA* paradigm, and further variations have been used in various studies. Recent examples are studies of synesthesia (Ásgeirsson, Nordfang, & Sørensen, 2015), processing speed in video gamers (Schubert et al., 2015; Wilms, Petersen, & Vangkilde, 2013), or children with attention-deficit hyperactivity disorder (McAvinue et al., 2015).

TVA has also been applied to fundamental attention research. Some studies in this domain used WR or PR, too. For example, Võ, Schneider, and Matthias (2008) showed the involvement of VSTM in transsaccadic scene memory. Nordfang, Dyrholm, and Bundesen (2013) investigated the conjoint influence of bottom-up and top-down components on attentional weights with a version of the PR paradigm. However, fundamental attention studies have also used more specialized paradigms and models. In some cases, simpler models of single stimulus encoding could be used, as in the investigation of temporal expectancy effects (Vangkilde, Coull, & Bundesen, 2012). Especially if the theory is extended to the temporal domain, for instance in the attentional dwell time paradigm (see A. Petersen, Kyllingsbæk, & Bundesen, 2012, and Section 3.0.4 of this thesis), or specialized models had to be derived from the TVA equations.

Note that in the more recent studies TVA parameters are often estimated with an approach that takes trial-by-trial variability of some parameters into account. According to Dyrholm et al. (2011), K and t_0 are subject to such variability. Therefore, in their approach t_0 is assumed to be normally distributed. This turns TVA's shifted exponential processing model into an ex-Gaussian one, a convolution of a Gaussian and exponential probability density function.

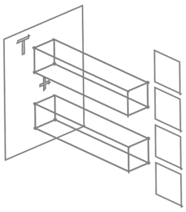
To sum up, WR and PR, their combination, and simplified or more specialized versions of them are the prevalent paradigms used in TVA-based research. Importantly, virtually all TVA studies were conducted using letters or digits, mainly because the item report tasks require relatively large sets of overlearned stimuli that can be efficiently reported. The TOJ-based TVA method advocated in this thesis improves on this limitation by allowing the use of almost arbitrary stimuli (see Section 4.6).

3.0.3 *A Neural Interpretation of TVA*

The psychological concepts and their mathematical description of TVA have been supplemented with a neural interpretation, the Neural Theory of Visual Attention (NTVA). This theory was suggested by Bundesen, Habekost, and Kyllingsbæk (2005). A detailed description can also be found in Bundesen and Habekost (2008), Part 2, whereas Bundesen et al. (2015) provides a brief summary. Here I will only briefly sketch the main ideas behind NTVA.

In the first wave of processing, neurons that represent specific features (or categories) are mapped to random locations in the visual field. When there is evidence for the presence of a neuron's feature (η value), and there is sufficient local contrast (κ value), it becomes active firing with a high frequency. The firing rate will then be attenuated according to the π values for most of the selection categories. A retinotopic priority map encodes the firing activity measured at the different positions in the visual fields.

Then, the second wave starts. Now all neurons are remapped with respect to the priority map. An object at a certain location is represented by any neuron with the probability reflected by the priority map. Hence, objects that are important according to the priority map are represented by more neurons than unimportant objects. In the second wave, again the firing rate depends on whether a neuron representing a certain feature was mapped to a location that contains evidence for this feature (η value). Moreover, again, it can (and most likely will) be attenuated. This time, it is the bias β which tunes down activity from all but those neurons that are associated with the cur-



rent report categories. The whole two-wave process is illustrated in Figure 1 in Tünnermann et al. (2015). Furthermore, the online version of Tünnermann et al. (2015) contains an animated figure of this process.

In summary, NTVA models filtering and pigeonholing via the activity (firing rate) of neurons and the number of neurons representing an object.

3.0.4 *Locking Resources – What Happens After the Race Toward VSTM*

The question of what happens to the representations in VSTM after the race has been addressed only recently in TVA-based research. This process may appear separate from encoding stimuli into VSTM and the resulting attentional selection. It is, however, highly important in tasks that include several TVA-conform encoding cycles, each with resource allocation, a race toward VSTM, and potential additional post-race processes (W. X. Schneider, 2013).

It is an assumption in NTVA that VSTM representations need to be kept active by engaging the encoding neurons in feedback loops. This engagement locks the neurons so that they cannot be used in subsequent cycles before they are disengaged (Bundesen et al., 2005).

Recent studies which considered the questions "what happens after the race" and "how are subsequent cycles affected" made use of the attentional dwell time paradigm (A. Petersen et al., 2012; A. Petersen, Kyllingsbæk, & Bundesen, 2013). In the attentional dwell time paradigm (e.g., see Ward, Duncan, & Shapiro, 1996), two backward-masked target stimuli are presented at different locations in temporal asynchrony. Intervals between the first and the second target of up to 500 ms lead to severe deficits in recognizing the second target. The effect is particularly strong around 100 ms and slowly decays afterward. The effect disappears at about 900 ms (A. Petersen et al., 2012).

A. Petersen et al.'s (2012) Temporal Theory of Visual Attention (TTVA) explanation of this effect is based on the resource-locking mechanism that was mentioned above. Furthermore, it is assumed that every target onset initiates a new TVA-conform encoding cycle with resource assignment and race toward VSTM. After the first target, T1, is encoded, it locks the resources that had been involved in the encoding process. A considerably smaller share of processing resources is now available to encode T1's mask. After processing of T1 and its mask started, a large part of the resources is locked. If T2, the second target, is shown within the critical interval, there are insufficient resources to guarantee that it will be encoded. It will secure a small portion of the overall resources only and progress at a low rate. In the majority of the trials, it is then not encoded successfully before being disrupted by the mask. The locking of resources explains the disadvantageous effect on T2 encoding. The gradual release of the resources explains the slow removal of the T2 impairment. A. Petersen et al. (2012) suggest that the VSTM representations have to be recoded into a more permanent format, such as auditory, motor, or amodal representations.

A similar mechanism was proposed to explain the beneficial effect of peripheral cues in the context of the present work (Tünnermann et al., 2015; Tünnermann & Scharlau, in review). There, the cued stimulus can seize resources engaged in encoding the cue, given that it is at the same location and shares low-level features.

W. X. Schneider (2013) has presented a theory similar to TTVA, which elaborates on the post-race mechanisms in a "third wave of processing", including how VSTM representations interact and subsequent races. His theory of Task-Driven Visual Attention and Working Memory (TRAM) postulates two types of VWMs. The *active* VWM corresponds to TVA's VSTM. The *passive* VWM is a more permanent storage.

The existence of these two types of VWM is deduced from theoretical considerations in line with TTVA and observations of how humans behave. Humans can make use of the encoded visual information across saccades (W. X. Schneider, 2013). A saccade, however, is assumed to end the current TVA-conform cycle and start a new one (Bundesen & Habekost, 2008, p. 162). Consequently, a VSTM representation can be kept active via feedback loops across cycles. This, however, also means that the resources stay locked over several cycles, and new visual information has to compete with whatever resources remain (W. X. Schneider, 2013).

For almost any real-world task, the point where all VSTM slots are in use and all resources are bound by active feedback loops is reached too early to complete the task successfully. W. X. Schneider (2013) explains this with Hayhoe and Ballard's (2005) example of making a peanut butter jelly sandwich. During such a task, humans perform a multitude of saccades toward relevant objects. They have to perform coordinated actions that involve several objects sampled across many saccades. Therefore, on the one hand, the VSTM needs to be cleared to allow encoding new objects; On the other hand, "old" representations need to be accessed to coordinate the actions.

The active–passive VWM distinction in TRAM resolves this issue. In the third wave of processing, that is, after priority-map forming and racing for active VWM (i.e., TVA's VSTM), active feedback loops lock the resources. If the encoded object is task-relevant, it is subject to a *protective maintenance* process (W. X. Schneider, 2013). Such a process protects the representation from the removal of its active feedback loop as long as recoding it into *passive* VWM goes on. For this period, the attentional weight of the object is *encapsulated*, which binds resources that are no longer available in subsequent cycles. These resources become available again after the transfer into *passive* VWM is completed. The system can access *passive* and *active* VWM, and therefore, humans can perform tasks, which require more than the three to four representations *active* VWM can hold.

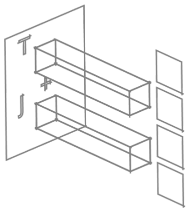
On the surface, mechanisms in TRAM look very similar to the TTVA mechanisms. However, there are some important differences. First of all, only task-relevant representations can benefit from *protective maintenance* and, therefore, lead to locking resources. Furthermore, in TRAM, a new TVA-conform cycle, with a race, is only triggered when there is a change in attentional weights. When the visual input changes but not the attentional weights, the current cycle continues, updating potentially changed categorizations. In contrast, TTVA assumes a new cycle for every change in visual input.

The interaction between the TRAM mechanisms can explain the attentional blink phenomenon, a T2 deficit similar to the attentional dwell-time effect. TRAM manages to explain several aspects of the attentional blink which other theories have failed so far (W. X. Schneider, 2013). Given that TRAM was derived by combining different theories with diverse empirical results, the explanation of the attentional blink phenomenon is the strongest support for TRAM as a whole. A TRAM-based view in the context of the question "what happens to the cue in TOJs" is discussed in Section 5.3.

3.0.5 *TVA as a Starting Point for Analyzing TOJs*

The goal of this thesis is to improve the understanding of how attention influences temporal-order perception. Specifically, fundamental questions such as "does attention speed up processing of attended information?" and "how do peripheral cues influence attention?" need to be answered. TVA provides a good starting point for this investigation. Its meaningful parameters, especially those concerning the speed of processing, can provide important information to answer these questions.

In the first two experiments reported in this thesis, item-report data from a combined TOJ and letter-report task is analyzed with the typical TVA method outlined in Section 3.0.2. The remaining experiments, however, went a step further and applied TVA directly to TOJ data. For this purpose, a novel TVA-based TOJ model was developed. Different specializations of this model have been applied in the analyses of the data from the different studies conducted in the context of this thesis. The following chapter starts with earlier approaches to model TOJs and ends with the derivation and description of a novel TVA-based TOJ model which is applied in the present research.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MODELING ATTENTION IN TEMPORAL-ORDER JUDGMENTS

In this chapter, I turn to models of TOJs and attentional influences. To clarify, the term model is used here rather generally for different things: arbitrary functions for approximating the pattern in the data, mechanistic explanations of attention influences, general processing frameworks, and process-based models whose parameters can be estimated. These different types of models are briefly introduced at this point to avoid future confusion.

Section 4.2 outlines the traditional psychometric approach for analyzing TOJ data. In this context, a model is a mathematical function that describes the general data pattern and allows to obtain attention and performance markers. Because the functions are chosen rather arbitrarily, the psychometric model does not by itself explain attention-induced temporal-order perception. Results from such analyses are often qualitatively linked to mechanistic models of attention that could generate such results. Two exemplary models of this kind are discussed in the second part of Section 4.2. As mentioned in the Introduction, the loose coupling between these two types of models, the arbitrary mathematical function and the mechanistic attention model, limits studies that follow this scheme substantially. Most importantly, mechanisms in the attention models cannot be directly—and quantitatively—linked to experimental data. Such a direct link is provided by a further class of models, which contains process-based approaches.

Process-based models formally describe—of course at some level of abstraction—the fundamental encoding processes which lead to the observation of attention-influenced order-perception. The independent-channels model (ICM; Sternberg & Knoll, 1973) is described in Section 4.3. Even though it still lacks a proper description of how the encoding of the individual stimuli proceeds, the ICM is an important framework for more specific models.

Section 4.4 discusses an approach based on temporal profiles modeled after light impulse propagation in the nervous system. The section investigates whether the Temporal Profile Model (TPM; Stelmach & Herdman, 1991) can be extended to a process-based model which can be fitted to data. To anticipate the result: Even though the model was originally suggested to explain attention effects in TOJs, it cannot be turned into a fittable process-based model.

From there on, fittable process-based models are explained. Three models with increasingly powerful descriptions of the individual encoding processes are discussed. First, in Section 4.5, two important models (Alcalá-Quintana & García-Pérez, 2013; K. A. Schneider, 2001) are outlined which use different arrival time distributions based on general assumptions. Finally, in Section 4.6, the TVA-based TOJ model, which was developed as part of this thesis, is discussed. Among all models presented in this chapter, this model is backed up with the strongest description of how encoding proceeds in the ICM channels. This is because stimulus processing is assumed to follow TVA, a strong theory of stimulus encoding, which is underpinned with a neural explanation (see Section 3.0.3).

Throughout this thesis and the manuscripts, the terms "model-free" and "model-based" refer to two different types of data analyses. The former indicates that the approaches proceed in the common way, fitting arbitrary functions to capture the data pattern and qualitatively link the results to mechanistic attention models. Therefore, the "free" in "model-free" does not mean that these approaches do not computationally fit the data to obtain the usual markers, nor does it mean that the respective authors are not entertaining any cognitive model. It only means that there is no process-based model, which could be used for parameter estimation or model comparison with respect to the fundamental encoding processes of individual stimuli.

Finally, one more convention which is used in the following requires explanation. In TOJs, there are typically two targets. The delay between their presentation is varied, and attention may be directed to one of them. The delay is called stimulus onset asynchrony (SOA), and its sign determines which stimulus leads. In classic psychophysics, the terms "standard" and "comparison" are used to distinguish the reference and the potentially attended stimulus. Here I use "probe" and "reference" instead (similar to Alcalá-Quintana & García-Pérez, 2013, who use "test" and "probe"). The "reference" can then be considered sitting at a virtual zero reference point on the SOA range, and the "probe" is put before or behind it when the SOA is varied. Furthermore, the "probe" is subjected to the potential influence on attention, thus "sensing" for actual effects on attention. Of course, such terminology is arbitrary, but this intuitive picture can help to follow the arguments without loss of continuity that would follow looking up the terms in one's memory or the literature.

4.1 THE TEMPORAL-ORDER JUDGMENT PARADIGM

The approaches described in this chapter model the TOJ task. A simple example of this task is shown in Figure 2. After the presentation of a fixation mark, typically for 500 to 1000 ms, the probe stimulus is shown. If the star is the probe stimulus in this particular trial, the example shows a negative SOA. After a delay according to the SOA, the reference stimulus is shown. For positive SOAs the reference stimulus

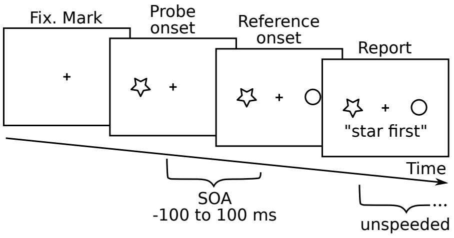


Figure 2: Illustration of a typical TOJ task. In this example, the sequence of a negative SOA is shown. The star is the probe stimulus, which leads at negative SOAs. At positive SOAs (not shown), the reference leads.

is shown first. Both targets are shown simultaneously at SOAs of zero. In an unspeeded report, participants indicate which target appeared first.

The order report can be implemented in different ways. For example, one possibility is pressing a key corresponding to the location where the first stimulus appeared (e.g., left vs. right, or top vs. bottom). To reduce response biases it has been suggested to use an orthogonal response dimension (Shore et al., 2001). That is, when, for example, attention is directed to the left or right side of the display, the response should be which shape, star or circle, appeared first. The mapping of identities, star or circle, to positions, left or right, is then varied independently.

Similarly, it is sometimes suggested to let participants report the second target, not the first. Reporting the second target usually leads to smaller prior entries (Shore et al., 2001).

In most experiments of this thesis, the order report is performed by letting participants type in the letters they saw. They can report the order by entering letters in the perceived order. Alternatively, they can enter letters in any order and toggle the order report afterward. In some experiments, spatially corresponding keys or order markers on the screen which the participants could toggle were used. Importantly, for all analyses, the order reports were converted into "probe first" judgments which follow an SOA-dependent course as illustrated in Figure 3.

Note that the TOJ task described here is a simple binary one. This task forces participants to report an order even if they are uncertain or perceive simultaneity. Such perceptions lead to "probe first" reports at the chance level for the SOA zero. Discussions of explicit simultaneity perceptions and the possibility to report them can be found, for example, in Weiß (2012).

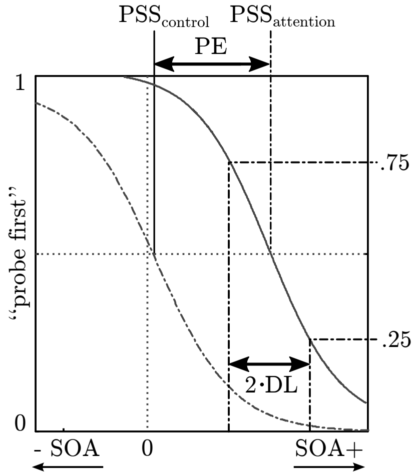


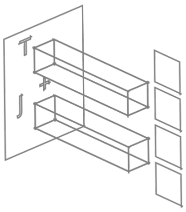
Figure 3: Idealized psychometric functions from a TOJ task. These functions of SOA show the relative frequency of the "probe first" judgments. They start at zero for large negative SOAs, at which the probe precedes the reference with a large interval. The 0.5 intercepts (PSS_{control}) are estimated for the control condition, in which no cue was present, and the attention condition ($PSS_{\text{attention}}$), in which the probe is cued. The difference of the PSSs is the TOJ-based prior-entry estimate (PE). The DL value is half the interval between the first and the third quartile. It is only illustrated for the attention condition.

4.2 TRADITIONAL PSYCHOMETRIC MODELING OF TOJ DATA

4.2.1 *Fitting TOJ Data with Arbitrary Psychometric Functions*

As shown in Figure 3, the data from TOJ tasks typically follows a sigmoid curve, a psychometric function. In general, a psychometric function relates the performance of an observer to an independent variable (e.g., see Wichmann & Hill, 2001; Woodworth & Schlosberg, 1954, Chapter 8). For example, the independent variable can be the intensity of a visual stimulus, the weight of a probe object or, as in the context of this work, the temporal interval between a visual probe and reference stimulus.

As illustrated for TOJs in Figure 3, summary parameters of the observer performance are estimated. Looking at stimulus differences in general, the summary parameters are the points of subjective equality and a measure of the discrimination performance, the difference limen (DL). The former is the difference level at which the probe is perceived as equal to the reference stimulus. Parameter DL is an index of the curve's slope. For TOJs, the point of subjective equality is the PSS. Hence, the PSS is the point in time, relative to the reference stimulus, at which the probe must be shown to achieve the perception of simultaneity. In binary TOJs—in which participants can only report the order but not simultaneity—both stimuli are then judged equally



likely as appearing first. Note that for this to be the case, perception of true simultaneity is not necessary. At the PSS, participants could just be maximally uncertain about the order and guess at chance level (see Weiß & Scharlau, 2011, for a discussion of this aspect). Despite this circumstance, throughout this thesis the term PSS is used to refer to the SOA at which a psychometric function crosses the chance level of 0.5.

The summary parameters are often obtained by fitting a smooth function to the data. Typical functions are, for example, the logistic function, the Weibull cumulative distribution function, and the reversed Gumbel cumulative distribution functions (Fründ, Haenel, & Wichmann, 2011). These can be fitted as generalized linear models (e.g., see McCullagh & Nelder, 1983). Taking the probability distribution of the observations into account (binomial in the case of binary TOJs), a link function (e.g., logit, for a logistic regression) is used to relate them to a linear predictor. Some frameworks provide great flexibility for fitting psychometric functions with this method. They allow, for example, to combine various inverse link functions with differently parameterized cores to fit psychometric data (e.g., the *psignifit* software, Fründ et al., 2011). Some cores allow to directly estimate psychophysically meaningful parameters for TOJ data, which correspond to the mentioned summary parameters PSS and DL. However, they do not constitute meaningful parameters of the fundamental processes that lead to the judgments. After noting that such a model-free approach may be helpful to roughly identify differences, for example, between TOJs and SJs, Alcalá-Quintana and García-Pérez (2013) write, "However, this strategy cannot indicate the cause of these differences, because the parameters of the fitted functions are not linked to the processes presumably governing performance. The functions, then, are mere descriptions of the data and do not permit testing hypotheses about differences in these underlying processes across tasks or across experimental conditions [...]", (p. 973). Much research in the last decades has linked mechanistic models of attention to the summary parameters in TOJs (e.g., Neumann & Scharlau, 2007; Scharlau & Neumann, 2003b; Sternberg & Knoll, 1973). Even though a model may be described in detail, the qualitative predictions for the summary parameters constitute an explanatory bottleneck when analyzing data. A different approach which avoids this bottleneck via directly modeling the underlying processes is employed in this thesis. Nevertheless, two exemplary mechanistic models, which were used with the common model-free approach just described, are outlined in the next section.

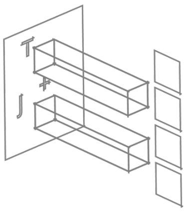
4.2.2 *Mechanistic Attention Models to Explain Prior Entry*

The two exemplary mechanistic attention models outlined in the following describe how the timing of encoding and attention processes interact. Summary parameters estimated as explained above are qualitatively linked to mechanisms of the models. Both models originate from research on visual backward masking. In this research area, the interaction between stimuli in close temporal succession is of interest. Besides the masking effects explained by these models—which will not be part of the discussion here—they predict facilitation which should lead to prior entry.

Asynchronous Updating Model

> *The chair squeaks as the meteorologist leans back. She takes a sip of her coffee. Then she takes a pencil out of the white coat's chest pocket and continues her crossword puzzle. What a relaxed workplace, this weather station, you may think. But wait, all the monitors and gauges! The pointers dance. Doesn't she have to keep track of all the values? She has! All important changes are to be reported directly to weather station headquarters via the state-of-the-art fax machine. Yes, fax. We have the late seventies or maybe early eighties. She's new on the job—just got her degree—so maybe she doesn't know that the instruments need to be monitored? Her precursor was sent into early retirement because he was so stressed out by running from one instrument to the other, checking whether or not some important change has occurred. By the way, his restlessness was the reason for the squeaky chair. So is our new meteorologist about to lose her job?*
>
> *On the contrary! She might be up for a promotion! We are just about to witness why. A bell rings. She puts the paper aside, calmly walks toward a meter, notes down some values on a form, and puts it through the fax. That's how her system works. Being a clever meteorologist, she set up little bells on all gauges. Now they ring when values reach critical levels. She even wrote some programs in assembler for the station mainframe that produces a ring for the computer-based meters. The system works great. She picks up her pencil and sits down. The chair produces another squeak, and the pointers dance on. She solves the puzzle until 42–horizontal and refills her coffee twice until another bell rings.*

This short story illustrates the primary mechanism of the weather station model of attention. This model originates from research on metacontrast masking in the early eighties (Neumann, 1982; Neumann & Scharlau, 2007). The short story is based on this weather station analogy.



Less metaphorically, the model is based on two main components and how they interact in time (e.g., see Carbone, 2001): a spatial map of the visual field and an internal representation. Most likely, the spatial map is a collection of retinotopic feature maps in the sense of Treisman and Gelade's (1980) feature integration theory. This was suggested, for example, by Scharlau, Ansorge, and Horstmann (2006). Importantly, the spatial map is updated quickly when the input changes, but its content is not consciously represented. To allow for conscious representation, attention has to be shifted to a location in the spatial map. Then, an uptake process starts to transfer the attended information from the spatial map to the internal representation. The attention shift is rather slow. Therefore, a prerequisite for conscious representation is that information in the spatial map was sufficiently strong to initiate a shift of attention and that sufficient time was available for attention to reach the location before the content of the spatial map has changed. The model has two important consequences caused by the asynchronous updating of the spatial map and the internal representation.

First, the information in the spatial map may have changed when attention "arrives". Then, the new information is transferred to the internal representation. In Neumann's (1982) weather station analogy, the meteorologist would start turning towards the meter alarmed by the warning sound. However, the value read off the display would already have changed when she looks at it. The meteorologist then sends the new value to the headquarters which represents the internal representation. Therefore, if two stimuli are shown in close temporal succession, a type of post-masking occurs. The information that triggers an attention shift, the prime, never becomes conscious. It is replaced by the new information which potentially becomes conscious instead. The second consequence is a latency reduction for the second stimulus. The time normally taken to shift attention towards the stimulus is reduced because the earlier stimulus has already started the shift. Consequently, a cued stimulus arrives earlier at the internal representation than an otherwise equal unattended one.

This explanation of prior entry was discussed in studies using TOJs (e.g., Scharlau, 2002, 2004; Scharlau et al., 2006). In this context, it is often called asynchronous updating model (AUM). Certain predictions, such as a COA-dependent increase of the latency reductions, are found in experimental data.

As explained above, the AUM describes the effect of a peripheral (masked) cue on TOJs. What does the model predict concerning the question whether attention facilitates the attended or inhibits the unattended stimulus? In the AUM, on the first look, attentional acceleration is a purely facilitating force. The initiation of the attention shift by the cue is time which is "saved" for the subsequent target. Hence, the stimulus is transferred faster than it would be otherwise.

This is how Neumann (1982) originally described it. However, it is conceivable that attention is always engaged at some position of the spatial map. Before any stimuli are present, it could rest at a totally random position in the visual field. In experiments, it could be at a random target location, the fixation mark, or diluted over a larger area covering all possible target positions (e.g., see C. W. Eriksen & St James, 1986). All of these initial distributions lead to an important consequence: In a neutral trial, on average attention is shifted and focused in equal time to either location. In a cued trial, it would be faster at the attended target. However, it would also take more time to revert a started or completed attention shift when the uncued target has to be encoded. Eventually, the uncued target is encoded and almost certainly it suffers from the cue having dragged attention away from its position. Hence, it is plausible that attention in the AUM has facilitative effects on the attended stimulus combined with inhibitory effects on the unattended one.

Unfortunately, because of the bottleneck that results from estimating summary performance parameters, it cannot be tested whether this is the case. Measured with the PSS, latency reductions and increases can be at work in an unidentifiable fashion. Therefore, the AUM does not help much in the investigation of these fundamental aspects. Furthermore, the rigid notion of attention as a unitary entity, which is shifted across the visual field, does not agree well with modern theories, such as TVA. In TVA, apparent attention shifts emerge from a biased competition of the fundamental encoding processes. Toward the end of the thesis, in Section 6.1.2, a second short story with a TVA-based view on prior entry is presented. Then, we will visit the meteorologist from above at her future job.

The Perceptual Retouch Model

The Perceptual Retouch Model (PRM) is similar to the AUM. Just as the AUM, it originates from visual masking research (Bachmann, 1984) and has been applied to explain prior entry in TOJs (e.g. see Scharlau et al., 2006). Also, its mechanics are similar. Again the asynchrony of two encoding processes leads to masking and prior entry.

However, there are also some differences between PRM and AUM. For instance, instead of sequential processes—the attention shift and uptake into the internal representation of AUM—the PRM assumes two parallel processes. There is a fast and stimulus-specific process that represents the actual information transmission to a conscious level. However, this process needs support from an unspecific boost of activation which is slower than the specific process. A stimulus can only reach conscious representation if the broad, unspecific signal has reached a certain level when it integrates with the specific process. A cue initiates the unspecific activation in advance, which therefore catches up earlier with the leading target. The target consequently benefits from the boost, reaching consciousness earlier. This mechanism explains prior entry in the PRM. For TOJs, it matches the general patterns observed in summary parameters. In some aspects, it matches them better than the AUM, for example, concerning the early peak of the latency effect at about 80 to 96 ms (Scharlau et al., 2006).

The PRM does not require an explicit notion of attention (Hilkenmeier, 2012), the cue is just another stimulus. Moreover, the boost which is triggered by the cue is truly accelerative. No resources are withdrawn from the uncued target. However, with the summary parameters of the typical analysis, the details and timing of the underlying processes cannot be directly inferred from TOJ.

To sum up, the discussed mechanistic prior entry models can only by qualitatively linked to data via summary parameters. Therefore, these approaches are not well suited to address the open fundamental issues of prior entry in TOJs.

4.3 A GENERAL MODEL FOR TOJS: PROGRESSING IN INDEPENDENT CHANNELS

The previous section described how data from TOJ experiments are frequently handled. Psychophysical summary parameters are obtained. They describe the observer's temporal discrimination performance and potential shifts in the PSS. In attention research, mechanistic attention models have been linked to the summary parameters.

Other factors, such as stimulus intensity or duration (see Boenke, Deliano, & Ohl, 2009), influence temporal-order perception as well. Different models of how stimulus encoding proceeds have been discussed in the context of TOJs. Sternberg and Knoll proposed a general framework for investigating the interplay between the encoding and decision mechanisms in TOJs, the ICM.

4.3.1 *The Independent Channels Model*

In the following I discuss the main concept of the ICM and its vital attributes. The ICM is well-suited for investigating different potential encoding and decision mechanisms. When Sternberg and Knoll presented it in 1973, it summarized all prevalent existing models of temporal-order perception. Many later researchers explicitly based their models on the ICM. Therefore, it provides a good starting point for the discussion of TOJ models. Secondly, their article describes the model and its implications formally and in great detail, so that the main concept and aspects relevant here can be extracted from this single source. For a full and generalized view on the ICM, the reader may refer to the original source.

One way in which the presentation here is selective is that the model is explained in the context of attention. Furthermore, the discussion is limited to the visual domain. The ICM as a basic framework is by no means restricted to visual attention. Quite the contrary, much of the considerations and the data discussed by Sternberg and Knoll (1973) stem from multimodal domains. Moreover, attention is rather a hard-to-control influence on the ICM in Sternberg and Knoll's article. They write, "Systematic attentional shifts that were correlated with conditions could cause the independent-channels model to fail in many ways", (p. 662). Of course, in attention research, where everything else is kept constant or controlled, the intendedly induced and condition-correlated shift of attention is just the influence one wishes to investigate.

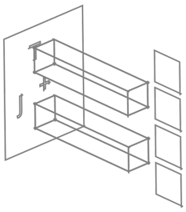
The ICM consists of three main components: Processing channels, a decision mechanism, and certain assumptions. The assumptions concern the independence among channels and of the decision mechanism. Each component is described in one of the subsequent sections.

Independent Channels

The channels of the ICM are assumed to be independent processing pathways that transfer stimuli to the decision mechanism. Different sensory modalities can constitute channels. They can, however, also be defined by different locations in one modality. For almost all considerations in this thesis, this is the relevant definition. Actually, for some considerations, channels come together even more closely: Two competing categorizations of the same stimulus at a single location are transmitted in different channels to be categorized as different percepts. Sternberg and Knoll's (1973) intendedly vague definition of a channel is completely in agreement with this conception. They only require the channels to be statistically independent.

Channels are also associated with the concept of transmission speed. In diagrams, channels are often drawn as horizontally elongated rectangles, in which time evolves from left to right, as for example in Figure 9a. The length of a channel in such diagrams represents the time required for a stimulus to pass through it. Hence, the delay between two targets entering two channels in a TOJ and their respective transmission speed determine the order in which they arrive at a decision mechanism. Factors such as stimulus intensity or presentation duration can influence the transmission speed (Boenke et al., 2009). Different modalities can have inherently different processing speeds (e.g., auditory vs. visual van Eijk, Kohlrausch, Juola, & van de Par, 2008).

The typical channel diagrams also suggest a potential confounding influence: If one channel is physically longer or shorter than the other, the order can be additionally influenced by this factor. This is indeed the case when the channels represent two different modalities, such



as auditory and visual, between which such delays are known to exist (e.g., see Zampini et al., 2005). In the context of this thesis, channel are always purely visual. Therefore, their length is assumed to be identical. However, it interesting that despite assuming they have the same length and transmission speed, the actual time it takes for a stimulus to pass through the channel remains unknown in typical TOJ experiments. This is because of the problem of TOJ relativity, discussed in Section 1.3.2.

The processing durations, that is, the time a stimulus needs to traverse a channel, are usually understood as random variables. This interpretation is rather intuitive. If one imagines an experiment that probes the channel latencies with hundreds of identical repetitions, one would probably expect a distribution of durations around a mean with some variance.

The Decision Mechanism

The decision mechanism is the entity that receives the incoming signals from the channels. Based on the arrival time difference, the decision mechanism decides which stimulus appeared first. This may sound straightforward, and indeed, the first of six decision rules described in Sternberg and Knoll (1973) is a simple *deterministic decision rule*. According to this rule, the perceived and reported order equals the arrival time at the decision mechanism. The different potential behaviors of the decision mechanism can be described with decision rules. The alternatives to the deterministic rule already stated will be explained briefly in the following.

It is important to note that the word "rule" can be misleading here. These "rules" are not recipes that prescribe how the mechanism has to operate. The operation of the mechanism depends on some assumed model of how the signals are compared. The "rule" therefore is rather the regularity observed from the outside. Different mechanisms can lead to the same rule. Sternberg and Knoll cite Rutschmann (1973) and Baron (1969) for assuming the deterministic decision rule, but none of these authors explain concrete mechanisms that lead to this rule. Intuitively, these could be mechanisms such as these: If arrival times are registered in a first-in-first-out short term memory that feeds, for example, verbalization, one would observe a deterministic rule. Similarly, if stimuli are encoded in a memory along with a timestamp, a mechanism that assesses these timestamps with perfect accuracy would lead to a deterministic rule as well.

Sternberg and Knoll (1973) found five alternatives to the deterministic rule. These alternatives were extracted from the literature or proposed by Sternberg and Knoll. As noted by K. A. Schneider (2001), rules four and five can be excluded from further considerations for the visual domain. He writes, "The attention switching models (their models 4 and 5) have had some success (e.g. Allan, 1975), but they make the assumption that only one stimulus can be attended at once, and that this assumption is violated within the visual domain (see e.g. Baron, 1973), so these models will not be considered". (p. 58) In addition to K. A. Schneider's concern, TVA, on which the models proposed in this thesis are based, neither requires nor supports a central attention switching instance. Therefore, only the *perceptual moment*, *threshold*, and *periodic sampling* models are described here. A recent, updated summary of all six decision models can be found in Weiß (2012) (in German).

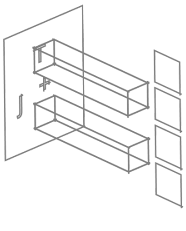
The *perceptual moment* model, typically attributed to Stroud (1956), assumes that there are successive, equally sized discrete time intervals. A pair of stimuli can only be discriminated when each stimulus is registered in a different time interval. If both fall within the same interval, reports of either stimulus appearing first are equally probable. Some researchers assume that the registration within the same interval entails the perception of simultaneity (see Weiß, 2012).

Threshold models (e.g. Alcalá-Quintana & García-Pérez, 2013; Baron, 1971; Ulrich, 1987) assume that a certain threshold must be reached in the arrival time difference to perceive sequentiality. If the difference is smaller, both orders are equally likely perceived (or simultaneity, see García-Pérez & Alcalá-Quintana, 2012a; Weiß, 2012). Sternberg and Knoll (1973) note that the this decision rule can also result from a triggered-moment process. In such a process, the signal arriving first starts a new perceptual moment. The other stimulus may or may not fall within in the associated interval. Only if it does not fall into this interval, order is perceived. Otherwise, the consequences are the same as for not reaching the threshold in the model described above.

The idea of *periodic sampling* for order judgments was introduced by Sternberg and Knoll (1973). It describes a process that discretely samples the channel output. It either alternates between the task-relevant channels, or sampling may include further channels. Either way, the effect is that the target channels are only visited periodically and checked whether a target has arrived.

The Assumption of Selective Influence

One important aspect of the ICM is that processing in the two channels is statistically independent. Stimulus encoding progresses in one channel without interacting with what goes on in another channel. Especially for TOJ research that assesses summary parameters of model-free psychometric functions, another assumption is important. This is the *assumption of selective influence*. Sternberg and Knoll (1973) write: "It is important to note that in using TOJs to measure the effect of any factor on perceptual latency, one implicitly accepts the validity of both the selective influence assumption and the independent-channels model", (p. 651). In its strongest form, the assumption requires the following: A factor, for example, the intensity of a stimulus,



only influences the corresponding channel. If of two stimuli, A and B, the intensity of A is increased, this cannot influence the processing of B. Furthermore, a factor which influences the channels does not act on the decision mechanism. The selective influence assumption assures that the effects of different factors can be attributed to additive components in the measured PSS. When an explicit description of processing in the channels, and how factors influence it, is available, these restrictions of selective influence can be released.

To summarize, the ICM provides a general framework for modeling TOJs. Sternberg and Knoll (1973) do not describe how stimuli are processed within the channels. Consequently, the arrival time distributions cannot be specified. In contrast, the approaches described from here on all contain some sort of description of the processing in the channels. For some of them, it becomes possible to fit them directly to experimental data and obtain parameters of the processes and how attention influences them.

4.4 THE TEMPORAL PROFILE MODEL

The concept behind the general model of temporal-order perception, which was discussed in the previous chapter, is the independent progression of concurrent visual stimuli through the visual system up to their arrival at an order comparator (the decision mechanism). As argued in Section 4.2.1, the main reason why fundamental aspects of the attention-influenced perception of temporal order cannot be targeted is the fact that common approaches assess the distribution of order judgments with model-free psychometric functions.

In 1991, Stelmach and Herdman published a study of attention effects in temporal-order perception. They employed simultaneity judgments with an adjustment procedure and TOJs with the method of constant stimuli. Their results support an attentional explanation of the shift in the response distributions. This shift was roughly 40 ms in favor of the attended stimulus. That is, the unattended stimulus would need to be presented 40 ms before the attended one to achieve the perception of simultaneity. In the analysis that lead to these findings, they used traditional psychometric methods as described earlier.

In the general discussion of their results, however, they propose the TPM. From this model, they derive explanations of how attention influences temporal-order perception. These explanations are qualitatively linked to the findings in their study and other well-established effects in the domain of temporal-order perception.

Why is it that this model deserves a substantially large section in this thesis? The reason is that the TPM includes a formal model of how visual stimuli proceed from the retina to the assumed temporal-order comparator. It must be considered as a candidate for a model which, if fitted to TOJ data, can help to pose and answer the unasked questions mentioned in the introduction.

The core of the TPM is a temporal impulse response function (TIRF) which Stelmach and Herdman (1991) borrow from Roufs and Blommaert (1981). Such a function models the response of the visual system when exposed to a pulse of light. Stelmach and Herdman assume that it also constitutes a reasonable model of how more complex stimuli are processed and that it provides a time-dependent measure of the evidence available for decision mechanisms involved in TOJs. Crucially for their research, the model is based on two comparators that evaluate the temporal profile of the difference of the TIRFs evoked by the two targets in a TOJ. One comparator yields an order response, and the other comparator evaluates the degree of simultaneity. A subsequent decision stage receives both comparators' outputs and generates the final order judgment.

In the upcoming section, the TPM will be described in more detail. Even though Stelmach and colleagues (Stelmach, Herdman, & McNeil, 1994) and others (Weiß & Scharlau, 2011) have occasionally consulted the TPM do derive qualitative conclusions, to my knowledge it has never been directly fitted to TOJ (or SJ) data. This observation is quite intriguing, given that the formal description of the TIRF and the detailed descriptions of how the comparators work seem to provide the basis for such an endeavor. As will become clear below, estimating the parameters of the TIRF with such an approach would allow to infer whether it is the attended stimulus which is sped up or the unattended one which is slowed down. Hence, whether the formalism of the TPM can be extended to produce a fittable model is discussed in Section 4.4.2.

4.4.1 *Comparing Temporal Response Functions*

The TIRF is a function of time t since stimulus presentation. It rises from zero to one and decays afterward:[4]

$$f(b,t) = 0.742 \cdot \left(\frac{t}{b}\right)^3 \cdot e^{\left(-\frac{t}{b}\right)} \tag{7}$$

The factor 0.742 normalizes the output so that the peak of the profile is always equal to one. The free parameter b determines the shape of the lobe (see Figure 4). The TPM is hinged on the idea that attention sharpens the profile of the TIRF. That is, an attended stimulus generates a brisker pulse than an unattended one. In the equation, the width of the pulse depends on parameter b, so that brisker pulses have smaller b values.

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[4] Note that the equation is erroneous in Stelmach and Herdman (1991). A correct form adapted from Roufs and Blommaert (1981) is printed here.

The comparators at the decision level monitor the pulses and perform calculations based on these inputs. The order comparator first subtracts the two signals. Then the resulting time-dependent difference profile is analyzed.[5] The order comparator evaluates the height of the first peak or dip in the difference profile. Based on the sign (peak or dip), it decides which of the two stimuli appeared first. According to Stelmach and Herdman (1991), the amplitude of the peak or dip is an index of the likelihood that this stimulus is perceived as appearing first. The brisker pulse peaks earlier than a broader one with the same (or even an earlier) starting time. This mechanism explains prior entry in the TPM.

The second comparator evaluates the input for evidence of simultaneous stimulus presentation. It receives the same TIRFs as input as the order comparator. Instead of taking the difference of the signals, however, it estimates the overlap of the two profiles. The ratio between the overlapping area of the profiles and the non-overlapping parts determines the strength of the simultaneity signal.

Both comparators feed their outputs into the decision stage, where their strength is compared, resulting in either one of the two possible order percepts, or in perceiving simultaneity. How exactly this comparison is conducted or which criteria determine one or the other response is not described by Stelmach and Herdman (1991). One result of their experiments was, however, that perceiving stimuli as asynchronous does not necessarily result in a defined order percept. The observer can notice an asynchrony but cannot decide which of the two targets appeared first. Hence, one possible interpretation of the TPM is that the decision stage produces a simultaneity percept when the evidence forwarded from the simultaneity comparator outweighs the evidence from the order comparator. If the order comparator produces the more prominent signal, the simultaneity percept is rejected. However, the order impression may be weak as well, which is reflected in small amplitudes of the difference function at SOAs close to zero (see, e.g., Figure 5). Below some threshold, the observer may not have sufficient evidence to report an order either. In this case, the observer would guess the order or make use of the simultaneity response, if one is available, in lack of a possibility to express the uncertainty (for a study that explicitly includes uncertainty judgments, see Weiß & Scharlau, 2011). Note that this is only one possible interpretation of the TPM. One can easily imagine a further view in which the order comparator is consulted first, and, in case that it yields an uncertain output, the simultaneity comparator confirms an uncertain order

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[5] Possibly, it would not be necessary that the full difference profile is produced. The subsequent decisions are based on the profile's first peak. Hence, once the sign of the slope changes, the comparator could use the current activity level for the subsequent steps without calculating the remainder of the difference function. This seems more natural than calculating the complete difference profile because the comparator can proceed along with the input signal in "real time".

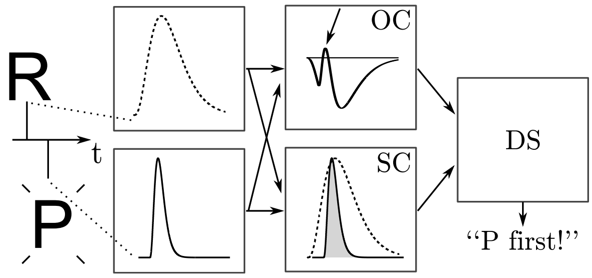


Figure 4: Illustration of the TPM. From left to right: Two stimuli P and R are shown at different times t. P is shown after R; attention is directed towards P, resulting in a brisker TIRF ($b = 12$ for P and $b = 40$ for R). Both impulses are fed into the OC and the SC. The OC calculates the difference between the signals and analyzes the amplitude of the first peak. The SC considers the shared area under the curves (gray) and compares it to the area not shared by the profiles (white). Based on the output of both comparators, the decision stage generates a response. Here it might produce a weak "P first" response. The perception of asynchrony would be plausible because the SC detects a larger amount of individual than shared area. A weak impression in favor of P would be plausible because the amplitude is rather small but in the positive domain.

or produces a certain simultaneity percept. Furthermore, whether the initial preference (the outweighing or being more prominent) is based on having a stronger peak, more activity integrated over time, or any other such feature is unclear. Fortunately, for a conclusive exploration of the TPM as a candidate for a TOJ model that can be fitted to data, it is sufficient to consider the case of a TOJ with binary response options, which is not subject to the unclearness involved with the mechanisms at the decision stage.

4.4.2 *A Candidate for a Model-Based TOJ Analysis?*

Stelmach and Herdman (1991) write, "If only two response alternatives are available (left first and right first), the decision is based solely on the information from the temporal order comparator" (p. 547). This simplifies the following considerations substantially. It allows to ask whether the output of the order comparator can be the basis for a psychometric function that can be fitted to data. Because of the formal description of the TIRFs and the simple signal difference the comparator evaluates, this appears rather straightforward. In their paper, Stelmach and Herdman show exemplary SOAs for hypothetical profiles in a neutral ("attend center") and attention condition ("attend left" or "attend right"). I have taken the TIRFs and Stelmach and Herdman's description of how the comparator works to produce a curve over a full and continuous range of SOAs from −100 to 100. That is, the difference of TIRFs is calculated, and the first peak is lo-

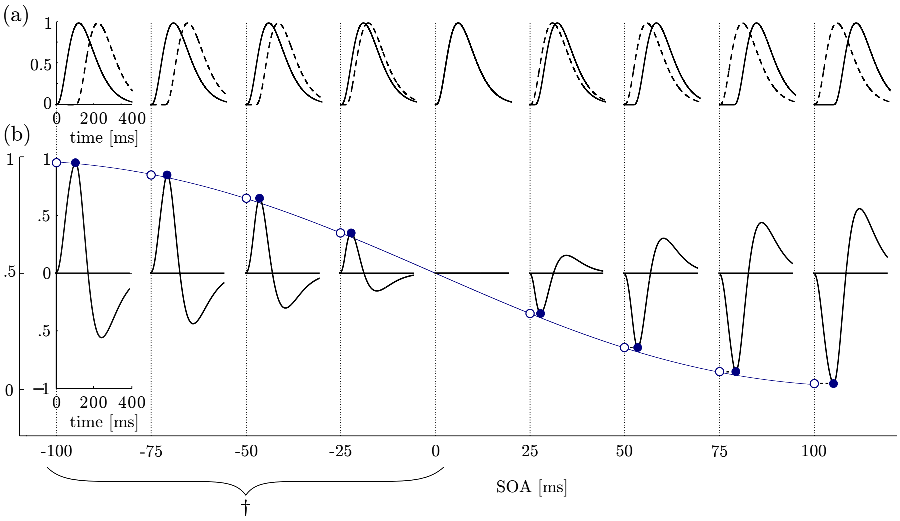


Figure 5: Deriving an order judgment function from the temporal profile model for a neutral condition: (a) Temporal profiles of two stimuli (both TIRFs with $b = 40$) separated by the SOAs indicated on the global x-axis. The solid curve corresponds to the probe, the dashed curve to the reference. (b) Corresponding difference functions. "First peaks" (closed markers), according to Stelmach and Herdman (1991), determine which stimulus is reported as appearing first. Local x-axes show time in milliseconds since stimulus presentation. The blue curve shows a "probe first" judgment function based on the height of the first peaks evaluated on fine-grained SOAs in the range from −100 ms and 100 ms. Open circles mark the elevation at the labeled SOAs. Those marked with † correspond to the same profiles shown in Figure 9 in Stelmach and Herdman's article.

cated in the resulting difference function. The height of this peak is then is plotted for every SOA (see Figure 6). According to Stelmach and Herdman, the height indexes the likelihood of judging the corresponding stimulus as appearing first. A simple interpretation would be that it directly represents the likelihood of judging the stimulus as appearing first, or, at least that it is proportional to it.

As can be seen in Figure 5, in a neutral condition in which both pulses have equal shapes (same b value), indeed a smooth sigmoid curve falling from 1.0 to −1.0 is achieved. The corresponding TIRFs and the resulting difference signals are illustrated for several SOAs in the figure. For the SOAs smaller than zero, these visualizations correspond to the ones shown in Stelmach and Herdman's Figure 9 (except that there these SOAs are positive; this is only a matter of definition, and it is different here for consistency with the next figure).

If one now considers a case where one TIRF is brisker because of attention (as in Stelmach & Herdman, 1991, $b = 12$ is chosen for the attended and $b = 40$ for the unattended stimulus), it can be seen that a smooth curve is no longer generated. The resulting curve does not

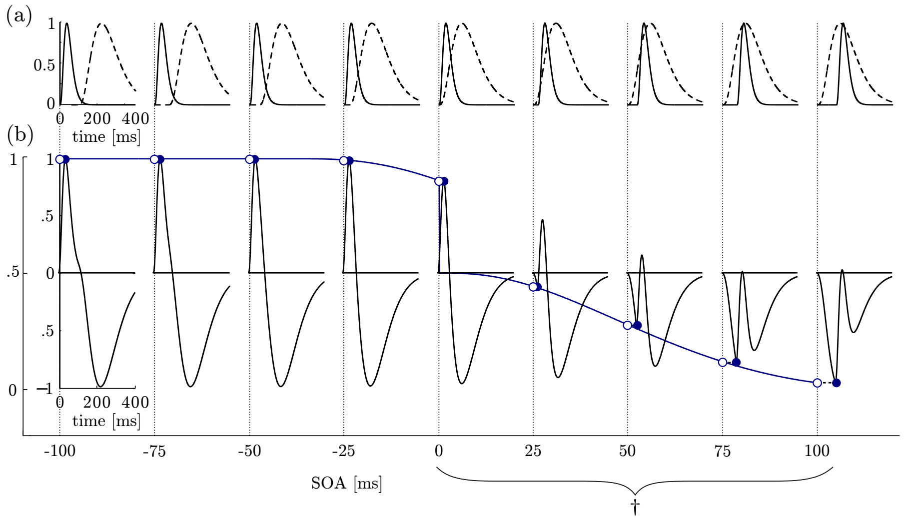


Figure 6: Deriving an order judgment function from the temporal profile model for an attention condition: (a) Temporal profiles of an attended probe (brisk impulse, $b = 12$, solid line) and an unattended reference (broad impulse, $b = 40$, dashed line) stimulus at different SOAs. (b) Corresponding difference functions. "First peaks" (closed markers), according to Stelmach and Herdman (1991), determine which stimulus is reported as appearing first. Local x-axes show time in milliseconds. The blue curve shows a "probe first" judgment function based on the height of the first peaks evaluated on fine-grained SOAs in the range from -100 ms and 100 ms. Open circles mark the elevation at the labeled SOAs. Those marked with † correspond to the same profiles shown in Stelmach and Herdman's Figure 10.

resemble a psychometric distribution of TOJs (see Figure 6). It contains a discontinuous jump at zero where the sign of the SOA changes. Even if one does not require the height of the first peak to equal the likelihood, such a discontinuity can hardly be removed by any reasonable transformation. Note that the discontinuity is within the range discussed by Stelmach and Herdman (1991), but because only a few SOAs are visualized in their article, it cannot be noticed there.

A similar visualization is shown in Figure 7. Instead of using $b = 12$ for attended and $b = 40$ for unattended stimulus, as in Stelmach and Herdman (1991) (their Figure 10) and my previous visualizations, a different pair of b values was used. Now b was chosen to be 40 for the attended and 68 for the unattended stimulus. Hence, this pair corresponds to a slowdown of the unattended whereas the former represented a speedup of the attended stimulus both with respect to the neutral condition described before (Figure 5), in which both targets were processed with $b = 40$. The profile in Figure 7 has a different shape than that in Figure 6. Most prominently, it has a shallower slope. However, again there is a problematic discontinuity at SOA of zero.

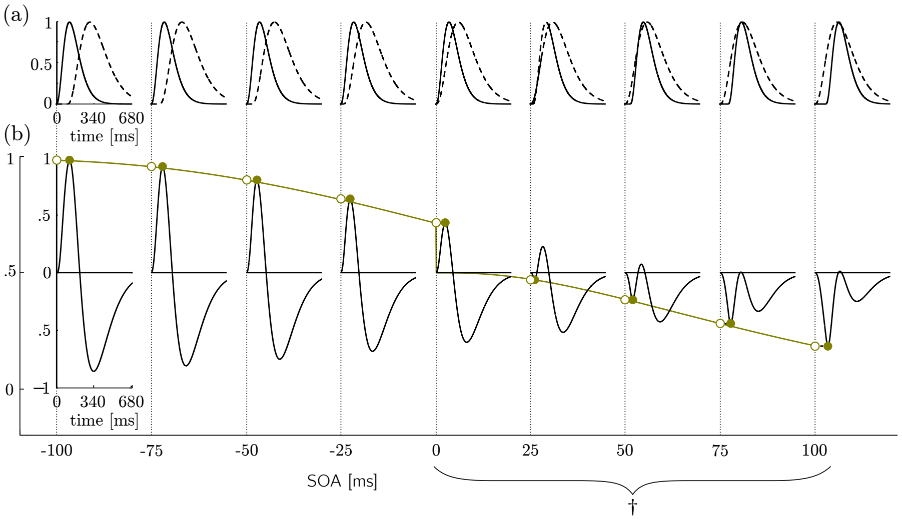


Figure 7: Slowdown of the unattended stimulus in the TPM: Instead of decreasing *b* of the attended TIRF from 40 to 12, as in the previous figure, here the unattended TIRF's *b* was increased to 68 (dashed line). Concerning the neutral condition which is shown in Figure 5, this represents a relative attentional benefit of the attended stimulus caused by a slowdown of the unattended one. (b) Corresponding difference functions. "First peaks" (closed markers), according to Stelmach and Herdman (1991), determine which stimulus is reported as appearing first. Local x-axes show time in milliseconds. The golden curve shows a "probe first" judgment function based on the height of the first peaks evaluated on fine-grained SOAs in the range from -100 ms and 100 ms. Open circles mark the elevation at the labeled SOAs.

In an attempt to rescue the TPM, one might be tempted to propose that the order comparator monitors the signal for a different feature than the height of the first peak. Could it not be the case that the system can differentiate the lobes in the difference signal that are generated by each of the two stimuli? That is, for calculating the likelihood of the probe stimulus appearing first, the comparator may evaluate the difference signal at the temporal position of the pulse associated with processing the probe stimulus. That such an approach does not lead to a useful curve can be seen in Figure 5. The lobe in the difference profile that corresponds to the probe stimulus is the second lobe at positive SOAs. Hence, in contrast to the reasonable "probe first" time course plotted in the figure, the suggested alternative would increase with positive SOAs instead of falling towards zero. For the situation where one stimulus is attended-to, such an approach would yield the curve shown in Figure 8a, in which the curve does not enter the y-range below 0.5. Consequently, considering a lobe in the signal difference that is associated with one particular target stimulus is no solution either.

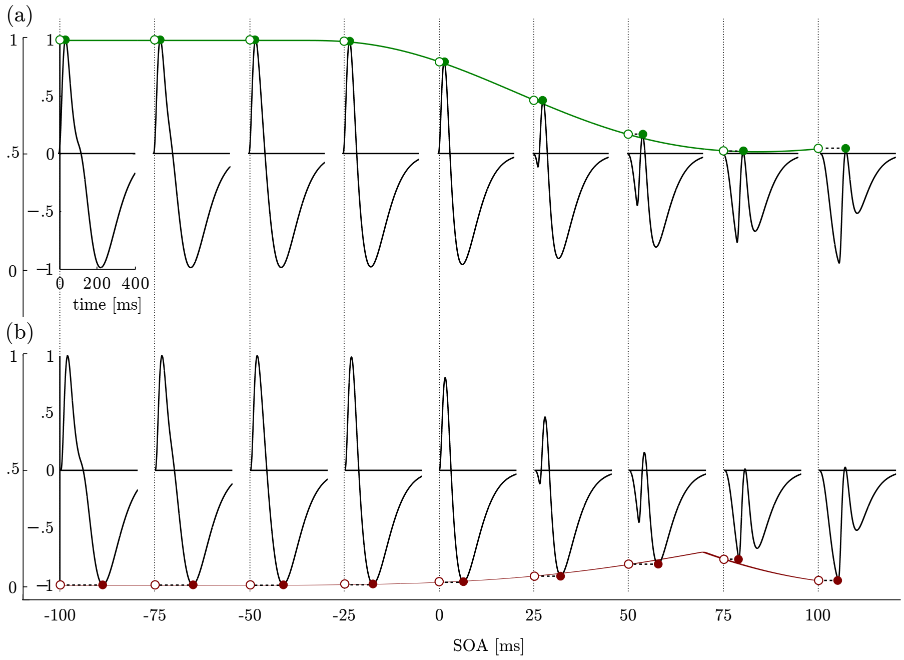
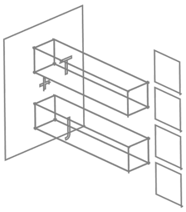


Figure 8: Considering alternative markers in the difference signal: Evaluation of the height of the peak (a) generated by the probe stimulus and (b) by the most extreme lobe over the relevant range (local x-axes). Neither alternative produces a reasonable order judgment function.

Yet another alternative could be to evaluate the height of the most extreme lobe encountered in the difference signal in the relevant range. The alternative is visualized in Figure 8b. As evident in the figure, the resulting curve cannot be the basis for a psychometric function. Not only is it possible that there are two equally large peaks (as in the left four SOAs of the visualized case), also the course at larger positive SOAs is not well-behaved.

Hence, on the basis of the time courses of possible markers in the difference signal—even when considering alternatives to the originally proposed ones—no possible SOA-dependent course of a value that indexes the likelihood of reporting a certain order can be obtained. Of course, some more complicated evaluation of the peaks in the difference signal could provide a yet unnoticed possibility to provide such an index. However, taking what was stated in Footnote 5 into account, Stelmach and Herdman's (1991) suggestion would have had the benefit that the difference signal could be evaluated on the fly. The alternatives suggested above would require the visual system to perform a retrospective assessment of the difference signal, as probably any other more complicated approach would.

In addition to the issues mentioned above for obtaining an index for the likelihood of judging a particular order, the TPM would face further difficulties when applied in situations different from simple two stimuli TOJs. How would an order judgment of more than two



stimuli be performed? There is no doubt that (given the SOAs are sufficiently large) an observer can determine the order of three successive events reliably. Would the TPM require the system to calculate three pairwise difference signals ("1 vs. 2", "1 vs. 3" and "2 vs. 3")? Then, again some comparison of these signals will be required to determine the order. How this could work is not clear at all, and the TPM appears to be specifically tailored to the case of two targets in a TOJ.

Along similar lines, Hilkenmeier (2012) noted that Stelmach and Herdman manipulated attention via instruction and peripheral cues have not been considered in their model. He writes "It is unclear how the model would deal with other forms of cueing. Would an additional cue get a temporal profile as well? Would it still change the temporal profile of the target in the same way? Would the temporal profile of the cue interact with the temporal profile of the target at the same location?", (p. 57).

Of course, simplification and abstraction are essential aspects of modeling cognitive processes. However, especially for the case of multiple targets, a generalization should be conceivable at least in principle.

To sum up the discussion of the TPM, it cannot be used as a basis for a model-based approach for TOJ analysis because of fundamental deficits. This conclusion is based on the lack of a smooth function to index temporal-order perception and the difficulties in generalizing the model for cases of only slightly increased complexity (e.g., three targets). In the case of ternary TOJs in which the observers can report simultaneity, the output of the simultaneity comparator could possibly mask the discontinuous portion of the order judgment function. However, as mentioned earlier, it is not clear how exactly the outputs of the two comparators are combined. Hence, it cannot be tested whether this is possible. Yet, there is something to be learned from the TPM. When modeling the processing of the individual stimuli with functions that describe how the evidence at the comparator for either order judgment evolves with time, changes in the parameters of these functions can be reflected in the shape of the curve generated by the comparator for assessing the order. Here, differently shaped order judgment functions were obtained based on the b values. The curves for speedup of the attended stimulus (Figure 6) follow a different course than the ones for slowdown of the unattended one (Figure 7). Hence, if a correct model is applied on the level of individual stimulus processing, and if the behavior of the comparator is described correctly, one may be able to obtain an order judgment function which can be fitted to data to estimate the parameters of the individual encoding processes. Consequently, it would become possible to decide whether the attended stimulus was sped up or the unattended one slowed down, based on experimental data. For this purpose, the models described in the next section have been developed.

4.5 model-based assessment of attention-influenced temporal order perception

Earlier, the ICM was described as a general framework for the perception of the order of stimuli in close succession. The ICM follows the concept that individual stimuli are processed in independent channels. Their arrival time at a decision mechanism can be understood as random variables. However, the explicit encoding processes in the channels remain unclear. Consequently, the distributions from which the arrival times originate are unknown.

In this section, two models are reviewed which are extensions of the ICM and can be and indeed have been fitted directly to experimental data. In this regard, they are similar to the TVA-based model which is proposed in the next section. The two models discussed here assume different arrival time distributions. Furthermore, they have been applied in different contexts.

First, I will describe a model suggested by K. A. Schneider (2001) and K. A. Schneider and Bavelier (2003), which is based on normally distributed arrival times. The second model was recently proposed by García-Pérez and Alcalá-Quintana (2012b) and assumes exponential distributions of arrival times.

4.5.1 *Schneider & Bavelier's Model with Normally Distributed Arrival Times*

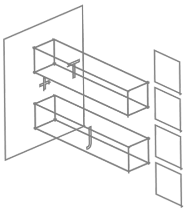
This model was developed in K. A. Schneider's (2001) undertaking to test whether or not attention affects stimulus latencies, leading to prior entry. A tenable alternative explanation was that attention acts on the decision mechanism, potentially via response biases.

In line with Sternberg and Knoll's (1973) idea of independent channels and decision mechanisms, K. A. Schneider (2001) proposed a rough model of processing in the channels by assuming normally distributed arrival times. It follows from this assumption that the arrival times difference, which is evaluated by the decision mechanism, is normally distributed as well. The potential influence of attention is modeled as an additive component α.

Casting this model in terms of probe and reference, the arrival times of the probe T_p, and the reference T_r, at the central decision mechanism are distributed as

$$T_p \sim \mathcal{N}(t_p + \delta - \alpha, \sigma_p), \tag{8}$$

and



$$T_r \sim \mathcal{N}(t_r + \delta, \sigma_r), \tag{9}$$

where t_p and t_r are the respective presentation times. Parameter δ is the transmission delay which is assumed to be the same in both channels. The latency of the attended stimulus is reduced by the attentional influence α. The ${\sigma_p}^2$ and ${\sigma_v}^2$ are the variances of the arrival times.

From the arrival time distributions, K. A. Schneider obtains the distribution of the arrival time difference as

$$\Delta T \sim \mathcal{N}(t_r - t_p + \alpha, \sigma). \tag{10}$$

The dispersion parameter σ replaces the actual combination of the joint channel dispersion $\sqrt{{\sigma_p}^2 + {\sigma_v}^2}$. The single σ "will be assumed to consume all of the variability in the central latency differences, including both those arising from transmission dispersion as well as those contributed by central mechanisms" (K. A. Schneider, 2001, p. 57).

The order-judgment function that follows from this distribution is combined with different models of a decision mechanism (see Section 4.3.1). The perceptual-moment and triggered-moment models are equipped with a response bias parameter β. The deterministic model does not include the additional β parameter.

For each of the resulting three models, which differ in the decision function, K. A. Schneider and Bavelier (2003) compared two versions. One used an α parameter fixed to zero, which models that there is no influence of attention on the encoding time. The other used a variable α, allowing for such effects. The fitted data was from different exogenous and endogenous cueing experiments and included TOJs and SJs. A large range of different COAs was tested.

For exogenous cues, K. A. Schneider and Bavelier (2003) found that a nonzero facilitation component α is required to explain data from both TOJs and SJs. They remark, however, that this is not necessarily a validation of attention-based prior entry. They argue that a non-attentional component could as well facilitate processing, which they tested in another experiment. That the effect is non-attentional was supported by the finding that is was already strong at zero COA, when attention would have had no time to be shifted to the location.

For endogenous cues, K. A. Schneider and Bavelier found no support for attention-induced prior entry. The SJs did not show evidence for an attention effect. The TOJs only required a nonzero α component when the deterministic decision rule was applied. Hence, K. A. Schneider and Bavelier concluded that this may have been caused by response biases or criterion shifts. This is supported by the finding that the perceptual-moment and triggered-moment models did not require a nonzero α because they have explicit response bias parameters which captured the variability.

One experiment tested whether the spurious facilitation with exogenous cues was non-attentional. To verify this, a display with many peripheral cues was employed. One of them cued the probe target, whereas the reference stimulus appeared at uncued positions. The rationale behind this was that an attention effect should be virtually removed because attention is either dispersed over all positions or at some randomly cued position. The effect of the cue decreases slowly with an increasing number of cues and reached a nonzero baseline. This baseline could represent a non-attentional component. Therefore, it is possible that both an attentional and a non-attentional effect are present.

Interestingly, even though K. A. Schneider and Bavelier (2003) do not discuss the possible connection, the acceleration caused by unspecific effects of the cue is similar to the predictions of the PRM (see Section 4.2.2). Multiple cues could trigger the spatially non-specific activation of the PRM. Possibly, at a COA of zero, the combined impact of cue and target could trigger activity stronger than the target alone, thereby explaining why K. A. Schneider and Bavelier's effect does not vanish at COA zero.

To summarize, K. A. Schneider and Bavelier's (2003) results speak for influences of attention on the decision mechanism and non-attentional effects. They did not find a genuine attention-induced change in transmission speed. They concluded, "In short these findings confirm that attended stimuli are consistently reported as perceived before unattended ones, but they reveal that this effect is more likely to arise from the influence of attention upon cognitive factors or the presence of attention-independent sensory facilitation, rather than through an attention-mediated acceleration of perceptual processing", (p. 356).

This conclusion is at odds with other studies that found evidence for genuine attention effects (see Spence & Parise, 2010), and some results in this thesis. It should be noted that attention effects were modeled as additive components which shift the means of rather arbitrarily chosen normal distributions. K. A. Schneider and Bavelier (2003) write, "For simplicity, these delays are implemented as normally distributed random variables, although in reality they must be positive and likely have a somewhat different structure", (p. 357). Indeed, skewed psychometric distributions, as shown in K. A. Schneider (2001), can only be explained by the response bias parameter in their framework. Using exponential arrival time distributions (Alcalá-Quintana & García-Pérez, 2013; Tünnermann et al., in review) allows such distributions to arise from attentional influences.

4.5.2 *García-Pérez and Alcalá-Quintana's Model with Exponentially Distributed Arrival Times*

Similar to K. A. Schneider and Bavelier (2003), Alcalá-Quintana and García-Pérez (2013) implemented a realization of the ICM. This model can also be directly fitted to experimental data. In contrast to K. A. Schneider and Bavelier, Alcalá-Quintana and García-Pérez assume exponentially distributed arrival times. They motivate their choice with the fact that several authors assumed exponential distributions to describe arrival latencies and peripheral processing times (e.g., Colonius & Diederich, 2011; Heath, 1984).[6]

Hence, when represented in the notation used in the previous section, the arrival times of probe, T_p, and reference, T_r, follow shifted exponential distributions:

$$T_p \sim \mathrm{Exp}_{\mathrm{S}}(v_p, t_p + \tau_p) \tag{11}$$

and

$$T_r \sim \mathrm{Exp}_{\mathrm{S}}(v_r, t_r + \tau_r), \tag{12}$$

where $f(t) = \mathrm{Exp}_{\mathrm{S}}(v, s)$ is $v \cdot e^{(v \cdot t - s)}$ for $t > s$ and $f(t) = 0$, otherwise. The actual presentation times enter as t_p and t_r. Parameters v_p and v_r are the processing rates.[7] Furthermore, parameters of delays within the channels, τ_p and τ_r, are included. From these distributions, a bilateral exponential distribution follows for the arrival time difference.

$$f(d, SOA) = \begin{cases} \frac{v_p \cdot v_r}{v_p + v_r} \cdot e^{(v_r \cdot (d - SOA - \tau))}, & \text{if } d \leq SOA + \tau \\ \frac{v_p \cdot v_r}{v_p + v_r} \cdot e^{(-v_p \cdot (d - SOA - \tau))}, & \text{if } d > SOA + \tau, \end{cases} \tag{13}$$

where $\tau = \tau_p - \tau_r$. For "probe first" judgments, integrating $F(-\delta, SOA) = \int_{-\infty}^{-\delta} f(z, SOA) \cdot \mathrm{d}z$ provides the following psychometric function:

$$\hat{P}_{p^{1st}}(v_p, v_r, \delta, SOA) \begin{cases} \frac{v_p}{v_p + v_r} \cdot e^{(v_r \cdot (-\delta - SOA - \tau))}, & \text{if } -\delta \leq SOA + \tau \\ 1 - \frac{v_r}{v_p + v_r} \cdot e^{(-v_p \cdot (-\delta - SOA - \tau))}, & \text{if } -\delta > SOA + \tau. \end{cases} \tag{14}$$

Parameter δ is a temporal resolution parameter, which implements a threshold or triggered-moment decision mechanism (see Section 4.3.1). Alcalá-Quintana and García-Pérez (2013) similarly derive further psychometric functions for "reference first" (which I here denote as $\hat{P}_{r^{1st}}$) and "simultaneous" judgments ($\hat{P}_{\mathrm{sim}}$). Such psychometric functions can be combined and fitted to data. However, García-Pérez and Alcalá-Quintana (2012a) note that these only describe an internal state. In

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[6] Interestingly, exponential arrival times also follow from TVA, the underlying processing model of the TOJ framework proposed in this thesis.

[7] Note that in Alcalá-Quintana and García-Pérez's work the rates are named λ. I switched their name to v to highlight the similarity to the TVA-based model described in the next section.

the process of turning the internal perception into an actual response, participants sometimes have lapses of attention during a trial or accidentally hit wrong keys (finger errors). Therefore, parameters ϵ_p, ϵ_r that account for such errors are suggested:

$$\begin{aligned} \hat{P}_{p^{1st}}(v_p, v_r, \delta, \xi, \epsilon_p, \epsilon_r, SOA) = \quad & (1 - \epsilon_p) \cdot \hat{P}_{p^{1st}}(v_p, v_r, \delta, SOA) \\ & + (1 - \xi) \cdot \hat{P}_{\text{sim}}(v_p, v_r, \delta, SOA) \\ & + \epsilon_r \cdot \hat{P}_{r^{1st}}(v_p, v_r, \delta, SOA). \end{aligned} \tag{15}$$

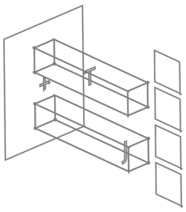
A response bias parameter ξ models the preference of one or the other judgment when the difference in stimulus arrival times is smaller than a threshold δ (Alcalá-Quintana & García-Pérez, 2013).

García-Pérez and Alcalá-Quintana (2012b) fitted their model to TOJ and SJ data in different contexts. For instance, they used it to resolve a theoretical issue. Ulrich (1987) and others worked out properties that versions of the ICM must satisfy, such as monotonicity and parallelism. These, however, are frequently absent in TOJ data. Using their model with error parameters, as outlined above, García-Pérez and Alcalá-Quintana could account for such deviations without discarding the ICM.

In another theoretical context, in García-Pérez and Alcalá-Quintana (2012a) the model was used to investigate the discrepancies between TOJs and SJs. García-Pérez and Alcalá-Quintana (2015a) concluded that the discrepancies arise from changes in the decisional parameter δ and that the TOJ task is contaminated by response biases. They advise against the use of the TOJ task in the investigation of temporal-order perception.

The model was also applied to investigate potential processing speed differences in visual hemifields—none were found (García-Pérez & Alcalá-Quintana, 2015b). Moreover, the model was recently applied in the investigation of the perception of asynchronous audio-visual speech, where it outperformed an alternative model (García-Pérez & Alcalá-Quintana, 2015c).

To sum up, the model by Alcalá-Quintana and García-Pérez (2013) includes parameters of the internal encoding processes and additional decision and error parameters. The model was derived from general assumptions of exponential arrival times and is similar to the model derived from TVA in this thesis. Up to now it has not been used to thoroughly investigate visual prior entry. In some of the analyses in this thesis, components from Alcalá-Quintana and García-Pérez's model are borrowed. For example, in Experiment 5, the delay parameter τ was included in the analyses to allow fitting the data of a cued TOJ. Such borrowing of components may help to fit the data, however the theoretical meaning of the parameters becomes unclear. Therefore, it is advocated in this thesis to derive TOJ models entirely from TVA's low-level encoding models, as done in Manuscript *C* for cued TOJs.



4.6 THE PROPOSED TVA-BASED MODEL OF TEMPORAL ORDER PERCEPTION

This section describes the TVA-based TOJ model developed as part of this thesis. The goal of the section is to bring together—in a comprehensive form—what has been developed to model the specific experiments reported in the published and submitted manuscripts with further theoretical advances which so far are only described in this thesis. Everything that originates from the manuscripts has been successfully applied to experimental data, and it has benefited substantially from the contributions by the respective coauthors, Ingrid Scharlau, Anders Petersen and Alexander Krüger. The additions which are introduced in this thesis have been developed with further experiments, theoretical considerations and simulations.

4.6.1 *A TVA-Based TOJ Model*

"[...] new data that we insist on analyzing in terms of old ideas, that is, old models which are not questioned, cannot lead us out of the old ideas. However many data we record and analyze, we may just keep repeating the same old errors, and missing the same crucially important things that the experiment was competent to find"
– Jaynes (2003) (p. xiv)

To investigate the fundamental mechanisms in TOJs, a strong model of stimulus encoding is required. For example, Sternberg and Knoll (1973) noted that for investigating the long known dissociation between TOJs and reaction times (RTs), an explicit description of the internal processes is required. In the lack of such a description, one has to fall back on statistical considerations which are based on further assumptions. Later, more explicit models have indeed been applied to this issue by J. Miller and Schwarz (2006). Their interesting approach was based on a drift diffusion model (DDM), which was able to resolve the dissociation between TOJ and RT.

The TOJ–RT issue is not the topic of this thesis, however, the solution may be similar. With an explicit description of the internal stimulus encoding processes, the open fundamental questions concerning prior entry in TOJs can be addressed.

Some attempts were made to use an explicit description of the internal response. Stelmach and Herdman (1991) did so with the TPM, the difficulties of which have been analyzed in Section 4.4. K. A. Schneider and Bavelier (2003) and Alcalá-Quintana and García-Pérez (2013) used probabilistic models of the internal response. K. A. Schneider and Bavelier used normally distributed arrival times as a simplification, noting that the actual responses most likely originate from a different distribution. Alcalá-Quintana and García-Pérez assumed exponentially distributed arrival times with additional delays. Their choice was motivated by the general use of exponentially distributed latencies in the literature.

The model I present here is based on exponentially distributed arrival times, too. The arrival time distribution follows from Bundesen's (1990) TVA (see Chapter sec:TVA). As a model of the internal response that leads to temporal-order perception, TVA is the most concrete one

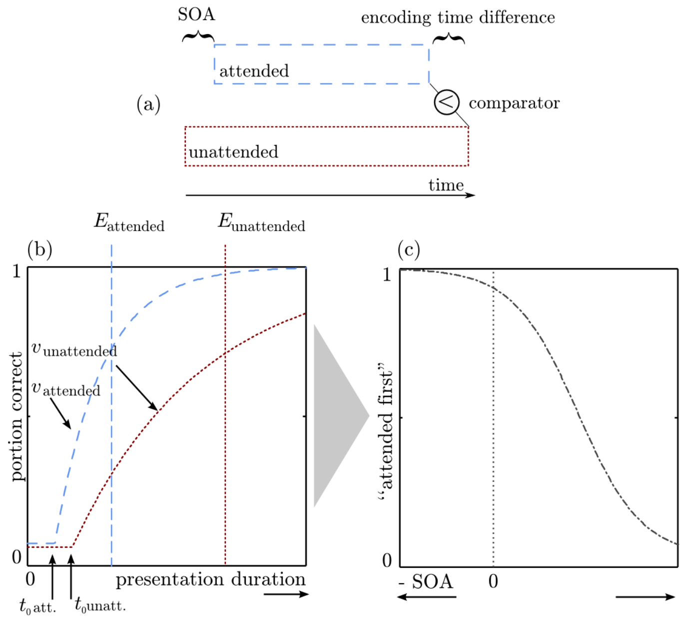
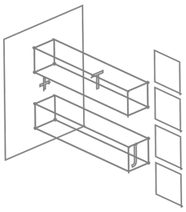


Figure 9: (a) Encoding in independent channels. (b) Probabilities of correctly encoding stimuli over presentation duration according to TVA. Annotated with TVA parameters, see Chapter 3. (c) Psychometric function for TOJs derived from the two encoding processes.

applied so far. The general concept of the model is illustrated in Figure 9. The ICM (see Section 4.3) is used as the general framework. The race within the channels is assumed to proceed according to TVA. In TVA, the arrival times at the VSTM follow a shifted exponential distribution. Therefore, in the masked WR and PR experiments, which are typically conducted to estimate TVA parameters, the pattern in the data looks as shown in Figure 9b. The probability of encoding a stimulus until a certain point in time (when it is masked) increases, starting at t_0, and converges to 1.0 for long exposure durations. The TVA-based TOJ model is hinged on the idea that if two stimuli race, as in the example shown in Figure 9, their order can be judged by comparing the VSTM arrival times. The result is a psychometric function of order judgments as illustrated in Figure 9.

Here it is assumed that the VSTM arrival time is directly turned into order judgments in a completely deterministic decision mechanism (see Section 4.3.1). This strong assumption and possible alternatives are discussed in Section 6.2.1. Moreover, the determinacy concerns the internal TOJ, which occasionally may be altered by finger errors or lapses. Such influences, however, are ignored in the work described here, because their importance is of rather theoretical nature (see García-Pérez & Alcalá-Quintana, 2012b). If the present model is applied to data from tasks highly prone to such errors, it should be considered to include error parameters as described in Section 4.5.2.



To return from the digression on error parameters, I would like to emphasize once more that the decision rule is deterministic. Interestingly, as will be shown in this section, assuming certain mechanisms associated with the encoding in the channels can lead to psychometric functions that resemble those distorted by non-deterministic decision rules.

Before different realizations of this TVA-based TOJ model are described, the next section provides a general framework for deriving TOJ models from TVA and for visualizing the model logic. Readers only interested in the models applied in the present empirical research may skip the next section. Note, however, that the visualization introduced in the next section is later used to illustrate models.

4.6.2 *A Box of Bricks for TVA-Based Psychometric Functions for TOJ Models*

This section briefly describes conceptual tools for deriving psychometric functions from TVA. After a quick reflection on simulations, which can guide early prototyping, visual modeling charts are introduced. They help to keep track of probabilities in more complex models. The purpose of this section is not only to provide the interested reader with these tools, but also to explain the chart-based modeling notation that is later used to describe models in this thesis.

4.6.2.1 *Simulations*

A useful first step for developing a TVA-based TOJ model is to create a simulation of the individual encoding processes and the assumed outcome. For a simple TOJ, this is straightforward: Draw one random arrival time from TVA's shifted exponential distribution (see Equation 1) for the probe and draw another one for the reference stimulus. Doing so, plug in each stimulus' processing rate and t_0 parameter. Add the SOA to the random probe arrival time. Now, check whether the probe's arrival time is lower than that of the reference, and increase the "probe first" count if this is the case. By repeating this step many times and for all SOAs of interest, a psychometric distribution is generated. An example of such a simple case can be found in Manuscript *C*, Figure 1. It is slightly more complex as the case described above.

Such simulations are rather simple to implement and therefore well suited to start prototyping new models. However, whereas models formalized in this manner are useful for visualizing the course of psychometric distributions, they are not very handy when it comes to fitting actual experimental data. Functions that model the course of psychometric distribution on the subject-level are better suited for this purpose than simulations of individual trial outcomes.

TVA-Based Psychometric Functions

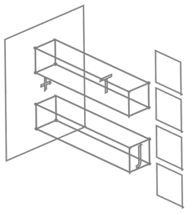
For a process-based analysis of TOJ data it is important to derive a psychometric function of TOJs from TVA. With the term psychometric function, I refer to an analytic mathematical function that describes the likelihood of “probe first” judgments. Importantly, such a function can be fitted directly to summarized subject-level data with various model-fitting approaches, such as maximum likelihood estimation. Summarized subject-level data are the sums of “probe first” judgments for each SOA. In many of the analyses of the experiments reported in this thesis, Bayesian model estimation was employed. In principle—and in practice for simple cases—generative trial-level models can be applied, implemented just like the simulations already discussed. However, for models with the complexity which the present research requires, this becomes computationally inefficient. Therefore, for Bayesian model estimation, too, a subject-level model of the summarized data is necessary.

Such a model can be obtained by combining the encoding probabilities prescribed by TVA. For someone like me, who does not manipulate large equations with probabilities on a regular basis, this can be a cumbersome endeavor. Fortunately, once relevant probability building blocks are identified, they can be combined rather easily. This combination can be aided with a chart-based model description. I describe the notation in the following, followed by how to translate the chart into probability equations. Note, however, that the resulting equations will not be the most aesthetic or economic ones to express the probabilities. If one cares about these aspects, subsequent simplification is required. However, I prefer to keep their form, because then the components can be easily related to the model charts and easily changed if required. Moreover, note that there are undoubtedly similar existing visual languages for probabilistic modeling. The approach presented here is tailored for modeling binary TOJs with TVA.

Charting TVA-Based TOJ Models

The chart-based model notation is best explained with an example of medium complexity. In Figure 10, a simplified version of a model discussed in Manuscript C is depicted (it roughly corresponds to the simplified simulation in Figure 1 of Manuscript C, except for the fact that the probe masks the cue in the version shown here). This example models a binary TOJ in which, alongside the rates of cue and reference, encoding the cue as the probe stimulus contributes to perceiving “probe first”.

To chart a model, separate diagrams are created for all different orders the stimuli can appear in. In the example shown in Figure 10, three different sequences can emerge depending on the combination of SCOA and COA. The basic elements of the charts can be seen, for



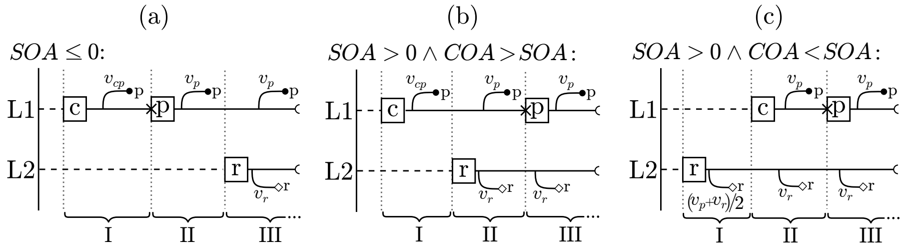


Figure 10: Example model chart.

example, in Figure 10a. For every location, here L1 and L2, the chart contains a lifeline which progresses with time from left to right. It is dashed if no stimulus is visible and solid over intervals in which stimuli are shown. The stimuli are drawn as square boxes on the lifelines. At stimulus onset times, a vertical dotted line marks the start of an interval. If one stimulus is masked by another stimulus, its lifeline is marked with an X at the onset of the mask (here p masks c). In the example, the intervals are marked as I to III. The open half-circles at the right end of the lifelines indicate that the interval is open, and started processes may continue. During each interval, encoding events can branch from the lifelines. At the end of a branch, a closed black circle indicates an encoding event that increases the "probe first" count. Such events will be called positive encoding events. An open diamond at the end of a branch indicates a negative encoding event which does not increase the "probe first" count. Additionally, labels with the rate of the encoding event are written next to the branches. The potentially encoded categorizations are written next to these branches. Hence, the leftmost branch of Figure 10a reads: the event that stimulus c is encoded as categorization p with rate v_{cp} during interval I (which is the coa in the example).

Combining Probabilities

Probabilities are combined by adding the probabilities of a positive encoding event occurring in the interval, given that processing has not been terminated in the earlier intervals, by positive or negative events. This nested combination is shown for three intervals in Equation 16.

$$\begin{aligned}
&P(\text{“probe first”}) = \\
&\quad P(\text{positive events in I}) + P(\text{no events in I}) \cdot (\\
&\quad\quad P(\text{positive events in II}) + P(\text{no events in II}) \cdot (\\
&\quad\quad\quad P(\text{positive events in III}) + P(\text{no events in III}) \cdot (\\
&\quad\quad\quad\quad \ldots \\
&\quad\quad\quad) \\
&\quad\quad) \\
&\quad)
\end{aligned} \tag{16}$$

The probability of a positive event associated with a stimulus x during interval y is calculated by integrating over the product of the density of encoding x at one point in time and the probabilities that no other encoding events occurred before, which would have terminated the process if there are any. The probability density for encoding stimulus x at time t is $v_x \cdot exp(-v \cdot t)$ according to TVA (ignoring t_0). The probability that another encoding event z_1 has not occurred until t is $exp(-v_{z_1} \cdot t)$.

For the example in Figure 10a, the first interval only contains one potential encoding event which is positive. Therefore,

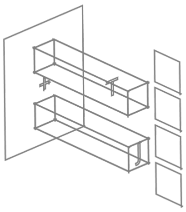
$$\begin{aligned}
P(\text{positive events in a-I}) &= \int_0^{l_1} v_{cp} \cdot exp(-v_{cp} \cdot t) \cdot \mathrm{d}t \\
&= 1 - exp(-v_{vp} \cdot t),
\end{aligned} \tag{17}$$

where l_1 is the length of interval I. Similarly, the second interval in the example is $P(\text{positive events in a-II}) = 1 - exp(-v_{vp} \cdot t)$. In the case visualized in Figure 10b, there is also a further event (encoding r) in the second interval, which must be considered with $exp(-v_r \cdot t)$:

$$\begin{aligned}
P(\text{positive events in b-II}) &= \int_0^{l_1} (v_c \cdot exp(-v_c \cdot t)) \cdot \\
&\qquad (exp(-v_r \cdot t)) \cdot \mathrm{d}t \\
&= v_c \cdot \left(\frac{1}{v_r+v_c} - \frac{exp(-v_r \cdot COA - v_c \cdot COA)}{v_r+v_c} \right)
\end{aligned} \tag{18}$$

As mentioned above, if there would be further encoding events in the interval II in Figure 10b, further terms in the form of $(exp(-v_r \cdot t))$ would need to be multiplied with the present factors. If there are further positive encoding events, these need to be considered in the same way as the encoding of c. Their probabilities would be added here and added to the present terms. In general, for all positive events n:

$$\int_0^{l_1} \sum_n \left(v_n \cdot exp(-v_n \cdot t) \prod_{m \neq n} exp(-v_m \cdot t) \right) \cdot \mathrm{d}t \tag{19}$$



Typically, the integrals become not much more complicated than in Equation 18 and they can be easily solved by a computer algebra system.[8]

For the open intervals at the right end of the lifelines in Figure 10a–c, where time goes to infinity, the aforementioned calculation can be replaced by the simple fractions $\sum_n v_n / \sum_q v_q$, where n are all positive encoding events and q all negative encoding events. Hence, interval III in Figure 10a yields $v_p/(v_p + v_r)$. This simplification follows from Luce's choice axiom (e.g., see Luce, 1977).

When the individual intervals are analyzed in this manner and combined as described in Equation 16, the case for a particular sequence is fully described. If this is done for all possible sequences, in the present example, the three cases shown in Figure 10a–c, the complete psychometric function is constructed. A full example of this can be found in the appendix section "Deriving probe first probabilities for cued TOJs from TVA" in Tünnermann and Scharlau (in review).

So far, TVA parameter t_0 has been left out of the equations for simplicity. Sometimes, however, it is useful to represent the t_0 periods with additional intervals in the chart, for example, in the description of the "t_0-Reset Model" in Section 4.6.3.

As a final note on constructing psychometric functions in this manner, comparisons with the outcomes of simulations as described in the previous section can be of great help in verifying the correctness of the function.

4.6.3 *Realizations of the TVA-Based TOJ Model*

The general concept of the TVA-based TOJ model was already explained. So was a framework for deriving new models. In this section, model realizations used to analyze the empirical data in this thesis are described. The term "realization" highlights the fact that the different variations originate from the same general TVA-based TOJ model. Depending on where they have been applied, they may model different stimuli presentations and use different simplifications. In every subsection, I will also indicate the situations in which it is appropriate to apply a certain realization. For simplicity, however, I will simply use the term "model" in the following to refer to the different realizations. This should not be mistaken as an indication that what is described is based on a conceptually different model.

The Simple Model

The simple TVA-based TOJ model was first described in the discussion of the second experiment in Tünnermann et al. (2015), Manuscript

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[8] In the OpenSource computer algebra system Maxima, for example, the result in Equation 18 can be obtained with the command "integrate(v_c*exp(-v_c*t)*exp(-v_r*t),t,0,COA);".

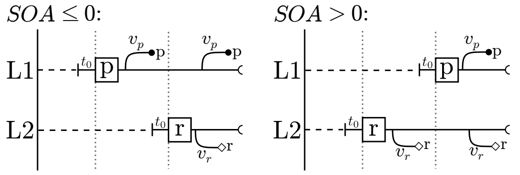


Figure 11: Chart of the simple TVA-based TOJ model. Small vertical bars left of the stimulus squares indicate the actual presentation time, whereas the races start after a duration of t_0.

A. There it was used to illustrate a discrepancy between prior entry estimated with letter report data and TOJs. Later it was fitted directly to data for obtaining TVA parameters (Tünnermann et al., in review, Manuscript *B*).

In the simple model, the SOA and the t_0 values of probe and reference determine the delay Δt between the moments when probe and reference start to race.

$$\Delta t = \text{SOA} + t_0^p - t_0^r \tag{20}$$

The probability of encoding probe before reference is given as a function of the processing rates v_p, v_r and Δt. If $\Delta t < 0$,

$$P_{p^{1st}}(v_p, v_r, \Delta t) = 1 - e^{-v_p|\Delta t|} + e^{-v_p|\Delta t|}\left(\frac{v_p}{v_p + v_r}\right) \quad \text{for } \Delta t < 0, \tag{21}$$

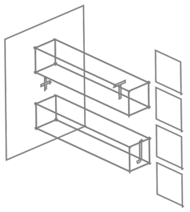
where $1 - e^{-v_p|\Delta t|}$ is the probability that the probe is encoded before the reference stimulus starts to race. If the probe is not encoded before the reference stimulus starts to race, given by the probability $e^{-v_p|\Delta t|}$, the probe is encoded before the reference with probability $v_p/(v_p + v_r)$ (see Section 4.6.2.1).

If instead $\Delta t \geq 0$, the "probe first" probability is calculated as

$$P_{p^{1st}}(v_p, v_r, \Delta t) = e^{-v_r|\Delta t|}\left(\frac{v_p}{v_p + v_r}\right) \quad \text{for } \Delta t \geq 0. \tag{22}$$

This represents that the reference is not encoded before the probe stimulus starts to race with probability $e^{-v_r|\Delta t|}$. If this is the case, both race together and a "probe first" perception occurs with probability $v_p/(v_p + v_r)$. A chart of the simple model is depicted in Figure 11.

Theoretically, t_0 is equal for both stimuli, and it is not considered to vary in experiments. Therefore, a simplified version of the model ignores t_0, setting $\Delta = SOA$. Variations in t_0 caused by experimental factors have been observed sometimes (e.g., Tünnermann et al., 2015; Vangkilde et al., 2011). It should be noted, however, that because of their additivity, the individual t_0^p and t_0^r parameters cannot



be identified when they are included. Only changes in $(t_0^p - t_0^r)$ can be measured, which can originate from changes in t_0^p, in t_0^r, or in both.

Note that for neutral conditions, the model can be parameterized with $v_r = v_p = v_n$, rendering it a one-parameter model. Furthermore, it should be noted that in attention conditions, the rates v_p and v_r are assumed to be biased from the start. That is, at times when one stimulus is shown alone, it races with the same rate as if it has to share resources with the other stimulus. This is reasonable for attention manipulations that bias the attentional weights before the stimuli are shown. Such a model was used, for example, with salience as attention manipulation (Krüger, Tünnermann, & Scharlau, 2016; Tünnermann et al., in review).

Because the TVA-based TOJ model assumes the same internal processing as TVA models of letter report tasks, a prediction which needs to be tested in the future is that the same processing rates are estimated for equal stimuli in both tasks.[9] If this is not the case, it does not necessarily invalidate the TVA-based TOJ model, but it points to possible differences. For instance, another form of short-term memory (see Section 2.3) may be involved. Furthermore, the different tasks may require different attributes to be encoded, or a non-deterministic decision mechanism could distort the TOJ results.

A Model of Cued TOJs

Largely shifted psychometric function are found for TOJs with peripheral cues. It has been suggested that the strong effects of peripheral cues may result from a sensory mixup or integration of cue and targets (K. A. Schneider & Bavelier, 2003). In Manuscript *C* (Tünnermann et al., in review) we investigated this possibility with a TVA-based TOJ model.

The basic idea behind this model is that the cue sometimes is encoded as the probe target with a low rate (cue–probe categorization). This increases the "probe first" count especially at large COA, where there is much time for categorizing the cue.

Another aspect which was added to the model is a form of IOR (inhibition of return; Klein, 2000). In case the cue is encoded as the cue (cue–cue categorization) during the COA, that is, it has been recognized, the race is aborted. The location of the cue is then inhibited, leading to a definitive "reference first" judgment. This component of the model lowers the left convergence point of the "probe first" psychometric functions (see Figure 3 in Tünnermann & Scharlau, in review).

This model is visualized in Figure 12. As shown in the figure, cue–probe categorizations are modeled as positive events. In contrast, cue–cue categorizations are modeled as negative events. That is, cue–cue

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[9] The estimates obtained so far agree with those of common TVA experiments, cf. Tables 2 and 3 in Appendix B.

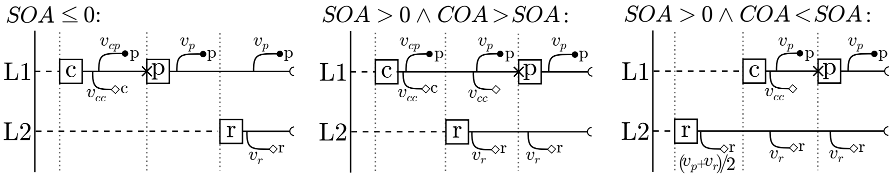


Figure 12: Chart of a TVA-based model of cued TOJ.

categorizations immediately lead to "reference first" percepts, assuming the probe target always loses in a subsequent race that determines the order. This is a simplification because, depending on the strength of IOR, the probe target could retain some nonzero rate in the subsequent race that enables it to occasionally win races. In other words, as modeled here, IOR has its strongest possible effect within the TVA-based TOJ model.

Note that in this model, the biased resource distribution in favor of the probe is only available after the cue was shown. Consequently, in the case $\text{SOA} > 0 \wedge \text{COA} < \text{SOA}$, the rate of the reference stimulus in the first interval is assumed to be half of the sum of all rates. It obtains half of the overall available resources, just as a target in a neutral condition according to the simple TVA-based TOJ model (see Figure 11). This share of resources is plausible, because up to the point where the cue is shown, the reference is indistinguishable from a target in neutral conditions.

The equations one obtains translating the chart in Figure 12 into probabilities can be found in appendix section "Deriving probe first probabilities for cued TOJs from TVA" in Tünnermann and Scharlau (in review). As shown in the manuscript, the model can capture effects on the PSS caused by cue–cue and cue–probe categorizations in rate parameters v_{cc} and v_{cp}, and effects on the main processing rates of probe and reference, v_p and v_r.

Models of this form should be applied when additional stimuli, such as the cue, may lead to positive or negative encoding events.

The t_0-Reset Model

The t_0-reset model is a tentative model to explain central plateaus sometimes observed in neutral TOJ conditions (e.g., see Neumann & Scharlau, 2007). It is used in Experiments 8 and 9 reported in this thesis.

The main idea is that if the second stimulus appears within the t_0 interval of the first stimulus, its processing is reset and both stimuli race again with a common start (see Figure 13).

The suggestion of this mechanism is not entirely arbitrary. According to TVA, during t_0, calculations of the resources which are later provided to the stimuli take place. The appearance of a new stimulus during this time could trigger the system to cancel the current

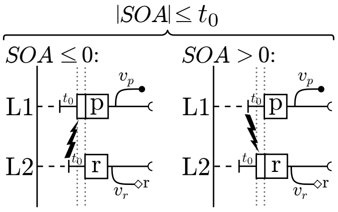


Figure 13: Chart of the t_0-reset model. The lightning symbols indicate that the second stimulus elicits the reset.

calculation and recalculate the resource distribution, taking all stimuli present at the moment into account. In contrast, once the race is started, the system may not be able to revoke processing of the first stimulus.

To obtain a smooth psychometric function, t_0 is modeled as a normally distributed random variable with a variance of ${s_0}^2$. A normal distribution for t_0 was also suggested by Dyrholm et al. (2011) to account for trial-by-trial variability in t_0.

Figure 13 only visualizes the case that the reset event occurs. If it does not occur, that is, if the SOA is larger than t_0 in a particular trial, processing proceeds as in the simple TVA-based TOJ model. This can be expressed as

$$P^{\text{reset}}_{p^{1st}}(v_p, v_r, t_0, s_0, SOA) = \begin{cases} \Phi\left(\frac{SOA+t_0}{s_0}\right) \cdot \frac{v_p}{v_p+v_r} \\ + \left(1 - \Phi\left(\frac{SOA+t_0}{s_0}\right)\right) \cdot P_{p^{1st}}(v_p, v_r, SOA), \\ \hfill \text{if } SOA \leq 0 \\ \left(1 - \Phi\left(\frac{SOA-t_0}{s_0}\right)\right) \cdot \frac{v_p}{v_p+v_r} \\ +\Phi\left(\frac{SOA-t_0}{s_0}\right) \cdot P_{p^{1st}}(v_p, v_r, SOA), \\ \hfill \text{if } SOA > 0, \end{cases} \tag{23}$$

where $\Phi(x)$ is the cumulative distribution function of the standard normal distribution and $P_{p^{1st}}(v_p, v_r, SOA)$ the psychometric function of the simple TVA-based TOJ model (see Equations 21 and 22).

A plateau in psychometric distributions can be produced by nondeterministic decision mechanisms. In Alcalá-Quintana and García-Pérez's (2013) model, the position of the plateau is controlled by three parameters. Its width is determined by threshold δ. The horizontal position depends on the delay τ and the vertical position on the response bias ξ. In the t_0-reset model, a plateau results from the resetting of the race. In this model, the width depends on TVA-parameter t_0. Its vertical position depends on the ratio between the processing rates v_p and v_r. If the rates are equal, the plateau lies centrally. Conceptually, the main difference between the two models is that the

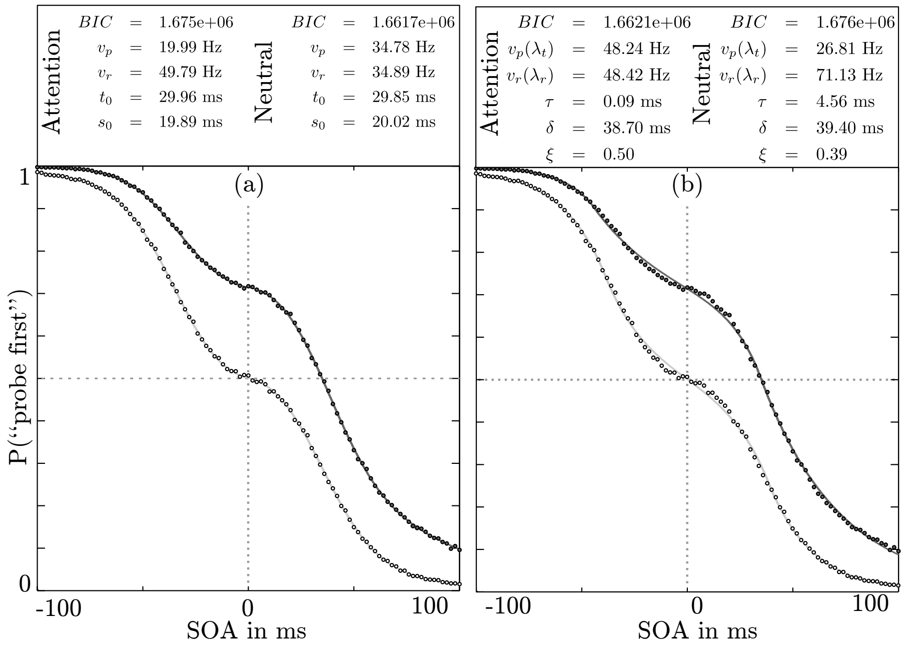


Figure 14: Simulation of the t_0-reset model. Neutral condition simulated with $v_p = 50\,\text{Hz}$, $v_r = 50\,\text{Hz}$, $t_0 = 30\,\text{ms}$, $s_0 = 30\,\text{ms}$. 20000 repetitions at 201 SOAs. (a) Fitted with the t_0-reset model. (b) Fitted with Alcalá-Quintana and García-Pérez's model.

t_0-reset model produces the plateau without a threshold or response bias in the decision mechanism.

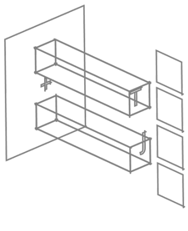
A simulation of the model is shown in Figure 14. Subfigure (b) shows the simulated data fitted with Alcalá-Quintana and García-Pérez's model. It can be seen that their model, too, fits the simulated t_0-reset data well. The estimated processing rates are about 10 Hz higher than the one obtained with the TVA-based model. Because of the rather small deviations from the simulated data, testing these models with real data requires highly accurate data sets with many SOAs and repetitions. Such an investigation is conducted in Section 5.4 of this thesis.

The most interesting aspect of this model is that allowing for resets during t_0 leads to patterns in the psychometric functions which are typically attributed to non-deterministic decision mechanisms. The model presented here, however, follows a strictly deterministic decision rule based on VSTM arrival. This becomes possible because the model violates ICM's assumption of selective influence—which was made because no explicit description of the encoding processes was available—by allowing one stimulus to reset the resource distribution of the other.

Further Variations

In the explained realizations of the TVA-based TOJ model, the encoding processes were parametrized via the rate parameters v_x. However, sometimes it is useful to express these rates in the form of relative attentional weights multiplied with the overall processing rate C (e.g., see Krüger et al., 2016). For example, if the simple TVA-based TOJ model is applied to data with a neutral and an attention condition, the rates for the neutral condition can be calculated as $v_n = C/2$ and the rates of the attention condition as $v_p = C \cdot w_p$ and $v_r = C \cdot w_r$. This relationship constraints the model to use the same overall amount of resources in both conditions. Then, C and the w parameters are estimated.

Such constrains may or may not be reasonable on theoretical grounds for a particular experiment. The opposite approach can be useful as well. Considering a complex situation as shown for cued TOJs in Figure 12, earlier stimuli can possibly influence the later ones. Such interference in TOJ was described, for example, by Weiß and Scharlau (2011). If every branch in Figure 12 is provided with an individual encoding rate, it may be possible to investigate whether and how earlier rates influence later ones. A model with that many free parameters requires to sample at a sufficient number of data points. A first approach to this is presented in Section 6.3.2 of this thesis.



5

EXPERIMENTS

> *"Nature uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry"*
> *– Feynman (1965) (p. 34)*

5.1 DOES ATTENTION SPEED UP PROCESSING? DECREASES AND INCREASES OF PROCESSING RATES IN VISUAL PRIOR ENTRY (MANUSCRIPT A)

5.1.1 *Introduction and Rationale*

In Section 1.3, important questions have been raised concerning the phenomenon of prior entry. One of the most intriguing ones is addressed the first two experiments, which have been reported in detail in Manuscript *A* (Tünnermann et al., 2015). It is the question of whether attention truly accelerates processing in visual prior entry. This may sound like an old question that has been positively answered already. Especially with TOJs, advantages of attended stimuli compared to unattended ones can be reliably shown (e.g., Shore et al., 2001; Spence & Parise, 2010; Stelmach & Herdman, 1991; Weiß et al., 2013).

However, there are several reasons why this issue has not yet been satisfactorily resolved. These reasons are hinged on the main problem of TOJ relativity, which was illustrated with the race car metaphor in the introduction (see Section 1.3.2). The "one-before-the-other" type of judgment in the typical TOJ task is of relative nature. Therefore, without entertaining a model of the encoding processes which predicts a certain SOA-dependent course of the judgment proportions, it remains unclear whether the attended stimulus is truly accelerated. Alternative explanations, such as that processing of the unattended stimulus is inhibited, or that varying degrees of slowdown of the unattended and speedup of the attended stimulus are involved, cannot be ruled out. Models from similar experimental paradigms (e.g, from the attentional blink paradigm, Olivers & Meeter, 2008) have no clear implications for TOJs. Electrophysiological studies, which looked at TOJs directly (McDonald, Teder-Sälejärvi, Di Russo, & Hillyard, 2005; Vibell, Klinge, Zampini, Spence, & Nobre, 2007) provide no clear conclusion concerning the speedup versus slowdown question, either (Tünnermann et al., 2015).

To avoid the problem of TOJ relativity, in the two experiments of Manuscript *A*, we followed an approach similar to the one employed by Weiß et al. (2013). Weiß and colleagues combined the relative TOJ task with a second measure of perceptual latency. In their TOJ task, participants judged the order in which moving hands appeared in stylized clocks. In addition, observers reported the times they read on the clocks at the hand onset. At their onsets, the hands pointed to random times and immediately begun spinning. The mismatch between the starting time reported by the participants and their actual angles is a measure of perceptual latency (Carlson, Hogendoorn, & Verstraten, 2006; Weiß et al., 2013). By comparing latencies measured in this manner for the individual targets between the attention and control condition, estimates of facilitative and inhibitory contributions to prior entry were obtained. The main result of Weiß et al.'s experiment is that the larger part of prior entry is caused by a prolongation of the unattended stimulus' perceptual latency, possibly caused by inhibitory effects. This finding speaks strongly against the usual assumption that prior entry arises due to a purely facilitative influence of attention.

However, the latency measure used by Weiß et al. (2013) is rather indirect. It is based on the conversion of a spatial mislocation into a temporal one. The motion in their stimuli could entail interactions between attention and localization (e.g., flash-lag and Fröhlich effects, see Müsseler, Stork, & Kerzel, 2002) beyond those the measure is intendedly based on. Therefore, it is desirable to employ a more direct measure which provides parameters of attention, such as the TVA-based method.

In the following experiments, the common TOJ task is combined with the letter report paradigm commonly used in TVA-based research. Hence, the theoretical framework of TVA (see Section 3) can be used to obtain processing speed measurements of the individual targets in an attention condition and a neutral control condition. These TVA parameters can then be assessed to answer the question whether prior entry originates from an attentional speedup of the probe target, or if it is caused by a slowdown of the reference stimulus.

5.1.2 *Experiment 1*

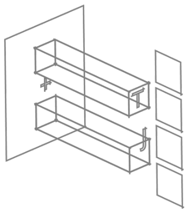
Participants

Twenty-five subjects participated in a single 1-hour session.

Procedure

The experiment followed the TOJ procedure as described in Section 4.1 combined with a masked letter report task as described in Section3.0.2. Participants judged the order in which two letter targets (probe and reference) were presented on a computer screen and additionally reported which two letters were shown.

The stimuli were made of little squares on a 5 × 7 grid that extended about $0.8^\circ \times 1.3^\circ$ of visual angle. The letter targets of this type, which were used in this and several of the experiments described later, are shown in Figure 15a. A box cue used in the same experi-



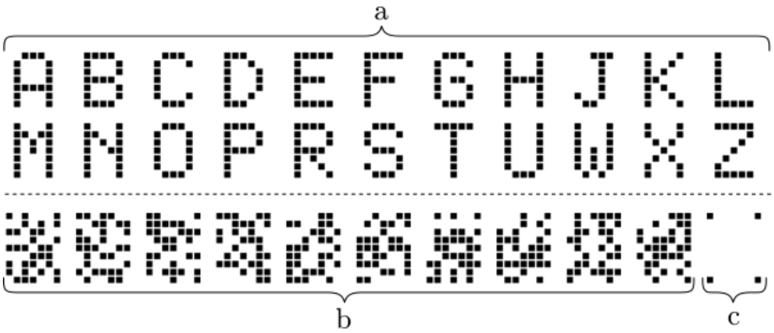


Figure 15: Stimuli used in the cued TOJ experiments reported in this thesis. (a) Letter targets. Some letters of the alphabet have been omitted because of their similarity to other letters or digits in this font. All masks (b) and the box cue (c).

ments is shown in Figure 15c. The masks depicted in Figure 15b were used only in the two experiments reported in this section, because these are the only ones which included a masked letter report task.

We varied the SOA and presentation time until masking independently. That is, for every SOA and each target stimulus, all possible durations were included. In half of the trials, a peripheral box cue was shown with a 100 ms COA before the probe target and stayed on until the target appeared. The resulting possible presentation sequences are visualized in Manuscript *A*, Figure 5.

After the presentation sequence finished, participants provided an unspeeded response. They entered letter reports and toggled order markers to indicate the perceived order via the computer keyboard.

Results

The main result of this experiment is that the cue sped up processing of the attended target, and it slowed down processing of the unattended one. This differential influence was revealed by a TVA-based analysis of the letter report performance. In the neutral condition, the expected value of the encoding duration (see Section 3) was estimated at 59 ms. It was reduced for the cued target in the attention condition by 10 ms and prolongated by almost 16 ms for the unattended one (the one which was not cued in the attention condition, when the cue was at the other target's location). Taken together, the TVA-based estimates represent a prior entry of about 25 ms.

Inspection of TVA parameters showed that the changes in the processing rates v contributed to the effect, but there was also an unexpected contribution from a t_0 reduction for the cued target. Even though they are sometimes observed, changes in t_0 have no clear interpretation in the common TVA framework.

Furthermore, with roughly 60 ms, the traditional prior-entry estimate, which was obtained by comparing the PSSs of attention and control conditions, was substantially larger than the 25 ms TVA-based prior entry. This issue was addressed in Experiment 2.

One more interesting observation was made in Experiment 1. TVA's overall processing rate C was estimated a few Hertz below 60 Hz in both the attention and control condition. Because the C estimates were not constrained to be equal in both conditions, the highly similar estimates indicate that the same processing resources are used but shifted in favor of the cued stimulus at the expense of the uncued one.

Detailed statistics and plots of the subject level data of these results, can be found in Manuscript *A*.

5.1.3 *Experiment 2*

The purpose of the second experiment was to investigate the unexpected prior-entry magnitude difference between TOJ- and TVA-based measurements and the changes in t_0. The rationale behind this experiment is to vary the amount of attention directed to the probe target and observe how these effects behave. The amount of attention can be controlled by varying the COA. Typically, the size of prior-entry increases with the COA, reaching 50 to 80 % of the COA duration (see, e.g., Scharlau & Neumann, 2003b). In this experiment, we tested whether the spurious effect on t_0 and the discrepancy between TOJ- and TVA-based prior entry scale similarly, or if these effects remain constant.

Participants

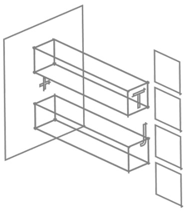
Fourteen subjects took part in the second experiment.

Procedure

The same procedure as in the first experiment was employed. In addition to the block with a COA of 100 ms, as in the first experiment, blocks with a shorter COA (50 ms) and a longer COA (200 ms) were added. The order of the blocks was randomized over subjects. The overall experiment duration was about three hours. Therefore, participants were allowed to take breaks whenever they wanted.

Results

As a surprising result, comparing the TOJ- and TVA-based prior entry results revealed a dissociative behavior of the two estimates. The TOJ-based estimate increased with the COA as expected. It reaches 15, 51, and 213 ms for COAs 50, 100, and 200 ms, respectively. This interaction between TOJ-based prior entry and COA is significant. The estimate of 213 ms at COA 200 is accompanied by large error bars (the standard error of the mean is about 70 ms). The TVA-based estimates (calculated



according to Equation 6) did not vary much with the COA. They have magnitudes of 19, 28, and 23 ms. Hence, the effect appears to peak around the COA of 100 ms and decays afterward. This course is in agreement with many theories of attention (see Section 2.4.4). Note, however, that the differences in the TVA-based prior-entry estimates are not statistically significant. The magnitude dissociation between TVA- and PSS-based prior entry is discussed in the next section.

Again, t_0 of the probe targets was affected by the cue. For the short COA of 50 ms, the reduction for the cued target was even stronger than at the 100 ms COA. For the COA of 200 ms, there was no difference in t_0 between cued, uncued and neutral targets. Therefore, the t_0 reduction appears do be a direct consequence of a spatially and temporally close cue, possibly providing beneficial local pre-activation. In Tünnermann et al. (2015), we discussed a potential mechanism behind the t_0 effects that is based on the target seizing low-level resources of the cue at short intervals. A process like this could allow the target to start earlier into the race. This interpretation is similar to the TRAM view described at the end of Section 3.0.4. According to TRAM, the categorization of the cue could be updated with the target attributes at short COAs. If in some of the trials, the t_0 period is skipped in this way, a reduction may be observed in the aggregated data.

In addition to the t_0 effect, there was a main effect of cueing condition on the v estimates, reflecting a pattern of processing rate increases for cued and decreases for uncued targets. Again, the overall processing rate C was more or less constant. It was slightly above 60 Hz in both conditions.

5.1.4 *Discussion*

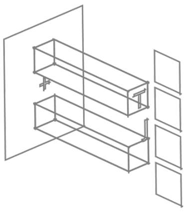
The first two experiments provided answers for the questions whether and how attention speeds up visual processing. Additionally, further new questions emerged, as can be expected whenever one takes a closer look at an old problem with new methods. In the following, I discuss these findings keeping in mind how they fit in the broader scope of this thesis. For more detailed discussion in their original more focused context, the reader is referred to the experiment discussions and general discussion of Manuscript *A*.

Does Attention Speed Up Processing?

In the light of the findings of the two experiments reported above, the question raised in the title of Manuscript *A*, "Does attention speed up processing?" can be answered with "yes", but this answer has to be directly followed by "However, deceleration is also involved". This qualification is necessary because the relatively shorter latency of an attended target, compared to an unattended one, is not only due to an attentional speedup. In addition to increases in the processing rates of attended stimuli, we observed decreases in the processing rates of unattended targets, when comparing both to a neutral baseline condition. Importantly, finding a constant C parameter suggests that the overall available processing resources are the same in the attention and the control condition. In the attention condition, their distribution is biased toward the attended stimulus, removing resources from the unattended one.

The findings described above are purely based on the TVA-based evaluation of the letter report data which shows a prior-entry magnitude dissociation with the traditional PSS-based estimates. This dissociation is discussed in the next subsection. As argued in Manuscript *A*, the TVA-based results provide a valid measure of prior entry in their own right. Hence, at this point, the finding that there are differential speedups and slowdowns involved in prior entry in cued TOJs can be appreciated and put in relation to the observations in the earlier similar study by Weiß et al. (2013).

Weiß et al. (2013) found that a large part of the relative latency difference emerged from the latency of the unattended target being increased. They write "Despite its eponymous, traditional interpretation, the temporal illusion which has been known for over 150 years as the prior-entry effect is primarily due to deceleration of an unattended stimulus (145 ms) instead of acceleration of an attended stimulus (31 ms)." In general, our observations agree with this account, which can be seen in Figure 7 of Manuscript *A*. Concerning the encoding times, there is always a larger latency prolongation of the unattended stimulus than latency shortening. How does this fit with the observation that the overall processing rate C is constant? Does it not mean that whatever resources are taken away from the unattended stimulus are given to the attended one, and hence, acceleration and deceleration should be equally important? This behavior emerges from the exponential processing model of TVA. For the rate parameters $v_{\text{probe}} = v_{\text{neutral}} + v_{\text{ch.}}$ and $v_{\text{reference}} = v_{\text{neutral}} - v_{\text{ch.}}$ ($v_{\text{ch.}}$ being the processing rate change), the latency reduction of the attended stimulus $E_{\text{neutral}} - E_{\text{probe}}$ ($= 1/v_{\text{neutral}} - 1/v_{\text{probe}}$; see Section 3) is always smaller than the latency increase of the unattended stimulus $E_{\text{reference}} - E_{\text{neutral}}$ ($= 1/v_{\text{reference}} - 1/v_{\text{neutral}}$), even though the same value $v_{ch.}$ is subtracted from one rate and added to the other. Transferring Weiß et al.'s observation into the TVA domain, this relation is as follows: If neutral targets are processed according to TVA with 12.68 Hz, and the rate of the cued one is increased by 8.21 Hz ($12.68 + 8.21 = 20.89$ Hz) and the rate of the unattended stimulus is reduced by the same 8.21 Hz ($12.68 - 8.21 = 4.47$ Hz), one obtains the 176 ms overall prior entry observed by Weiß and colleagues. It consists of a 144 ms latency prolongation of the unattended and a 31 ms latency reduction of the cued target. How such TVA processing rates



can be calculated from reported latency prolongations and shortenings is explained in a general form in Appendix A.

The rates described above are rather low. Given that encoding the stylized clocks (which are presumably less overlearned than letters or digits which are commonly used with TVA methods) may be a relatively difficult task, they are not implausible. Hence, in this view, the rather large slowdown component and the quite small speedup component detected by Weiß et al. originate from a rate increase of the attended and rate decrease of the unattended stimulus of equal size. The already cited statement by Weiß et al. contained the conclusion that the "prior-entry effect is primarily due to deceleration of an unattended stimulus". Taken together, the results of the present experiments and those of Weiß et al. with a TVA-based interpretation allow for a refinement of this observation: A fixed amount of processing resources may be evenly reassigned, increasing the attended stimulus' rate by the same amount the unattended one's rate is decreased. Due to the exponential processing model, the reduction, however, results in a more severe latency increase of the unattended stimulus compared to the latency decrease achieved for the attended stimulus. Hence, in processing, slowdowns may not be more important than speedups, but they may lead to stronger effects on the encoding latency.

Therefore, in response to the question of whether or not attention speeds up processing—yes, it does,selectively, while also slowing down unattended information. These experiments provide the first insight into how processing resources are distributed under attentional manipulations in TOJs. Manuscripts *B* and *C* will continue and deepen the investigation of attention-induced rate changes.

Dissociative Behavior of TVA- and PSS-Based Prior Entry Estimates

The results and conclusions so far ignored the dissociation of TVA-based and PSS-based prior entry estimates. Because we not only aimed to answer the question whether attention speeds up processing, but also how this leads to prior entry in TOJs, an explanation for the dissociation was required.

In the discussion of Manuscript *A*, we suggested a stage-based model. In this view, different tasks can require processing of different depth. That is, to solve the letter report task, there may be a certain threshold of evidence needed to report a particular letter. For reporting the temporal order, there can be a different threshold of evidence, which possibly also involves evidence for different attributes. Independently of the COA, the same depth of processing is required to perform letter reports. For TOJs, the temporal uncertainty may increase with the COA and call for an increased level of temporal-order evidence. This view is in line with an increase in DL, which we observed for increasing COAs, and which is occasionally reported in the literature (e.g., see Scharlau & Neumann, 2003b).

formulate a stage-based model, which allows varying depth of processing for different tasks and COAs, we described a Poisson counter model (similar to the one proposed in Kyllingsbæk, Markussen, & Bundesen, 2012) in Manuscript *A*. In this model, letter reports and TOJs at $COA = 50\,\text{ms}$ require to accumulate $k = 1$ tentative categorizations. TOJs at $COA = 100\,\text{ms}$ require $k = 2$, and TOJs at $COA = 200\,\text{ms}$ $k = 4$ tentative categorizations. The consequence of such a model is that with the same fundamental processing resources, encoding duration differences are produced which agree with the pattern in the TOJ data for varying COAs.

5.1.5 *Conclusion*

The combined letter report and TOJ task used in Experiment 1 and Experiment 2 showed that attention increases the processing rate of attended and decreases the rate of unattended stimuli in cued TOJs. In addition to this conclusive result, rather puzzling ones, the t_0 reduction at a short COA, and the dissociation of TVA- and PSS-based prior entry for varying COAs were observed. The latter was approached with a tentative explanation, the "k model".

5.2 measuring attention and visual processing speed by model-based analysis of temporal-order judgments (manuscript b)

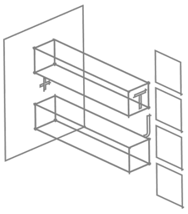
5.2.1 *Introduction and Rationale*

The previous section came to the conclusion that attention speeds up processing of the attended stimulus and slows down processing of the unattended one. However, participants had to perform a rather difficult dual task—combined letter report and TOJ—with many temporal signals produced by cue, targets, and masks.

The difficulty of the task and the spatiotemporal complexity caused psychometric distributions of TOJs with shallow slopes. Furthermore, the TOJ-based results deviate from the letter report outcomes in the size of prior entry. Also, TOJ-based prior entry scaled substantially with the COA, whereas the estimates based on letter report did not show significant changes.

The experiments summarized in the present section (originally reported in Tünnermann et al., in review, Manuscript *B*), continued the investigation of prior entry in TOJs, focusing on two main aspects.

First, the perceptual situation was simplified by removing the requirement of a dual-task, the masking, and the cue. This was accomplished by using simple binary TOJs and analyzing the data with the



TVA-based TOJ model introduced in Section 4.6.3. Estimates of TVA parameters (see Section 3) could then directly be obtained by fitting this model to the TOJ data. This substantially simplified the task for the participants and removed task-difficulty effects from the results.

The second aspect on which this investigation focused was the question whether different attention manipulations lead to the same or different patterns of rate increases and decreases in prior entry. In the previous experiments, only a peripheral cue was used. Such cues are known to be highly effective, but it has been suggested that they also have non-attentional components, such as confusing cue target onsets (see Section 4.5.1). Therefore, Experiments 3 and 4 used other attention manipulations, salience and context in natural images. Experiment 4 then reverted to using a peripheral cue, but in a substantially simplified presentation compared to the earlier experiments. This allowed a comparison of the effects induced by the peripheral cue and the other attention manipulations.

The article itself focuses on the method of TOJs in a model-based framework. Moreover, it aims at demonstrating that the novel TVA-based method can be used with highly different stimulus types. A discussion in the context outlined above is conducted here in this synopsis.

5.2.2 *Experiment 3*[10]

In this experiment, attention was manipulated via visual salience in the color dimension. For this purpose, pop-out patterns were shown to the participants. They contained a large array of line segments, all tilted at the same angle, which was randomly chosen for each trial. The stimuli were reused from a study in which salience was induced via orientation pop-outs (see Krüger et al., 2016). Here, the pop-out was in the color dimension. TOJ targets could appear at two fixed locations on either side of the fixation mark. In the attention condition, one target differed substantially in color (it was orange among blue background stimuli or—at random—vice versa). In the control condition, both targets had the same color as the background (see Figure 2a in Tünnermann et al., in review).

Participants

Thirty subjects participated in the experiment. One participant was excluded from the analysis. The data showed that this participant did not follow the instructions and instead always pressed the same key.

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[10] Experiment 1 in Tünnermann et al. (in review).

Procedure

The presentation followed the usual scheme of TOJ tasks. Eleven SOAs were used in each of the two conditions (for further details concerning the SOAs, see Figure 2b in Tünnermann et al., in review). One important difference to the typical TOJ presentation, in which participants judge stimulus onsets or offsets, is that flickers of the two targets were judged. Deciding the flickering order of elements in pop-out displays was found to be the best method to induce salience effects in TOJs (see Krüger et al., 2016). Furthermore, the fact that the potentially salient targets are present from the beginning of the trial agrees with an assumption in simple TVA-based TOJ models. These assume that the influence on attention is already present when the first target appears (see Section 4.6.3). Participants reported the order that they perceived by pressing one of two keys on opposite sides of a computer keyboard.

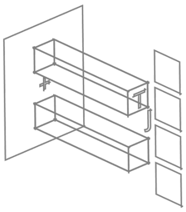
Results

To obtain the TVA parameters, the data was fitted with a hierarchical Bayesian implementation of the TVA-based TOJ model.

In the neutral condition, the attentional weight of the probe stimulus was estimated at $w_p^n = 0.5$, which reflects a perfectly even distribution of attention—as expected in the neutral condition. In the attention condition, the weight of the pop-out was increased to $w_p^a = 0.59$. This increase is a reliable change according to the 95 % highest density interval (HDI) of $w_p^n - w_p^a$, the upper boundary of which is at $-0.08\,\text{Hz}$. Hence, as hypothesized, salience biased the distribution of attention in favor of the color pop-out. Interestingly, however, it was not processed faster. The processing rate of the pop-out was estimated at $v_p^a = 41.06\,\text{Hz}$, which is roughly the same as the neutral target rates of $v_p^n = 43.04\,\text{Hz}$ and $v_r^n = 43.23\,\text{Hz}$. The rate of the reference stimulus, however, is only $v_r^a = 27.16\,\text{Hz}$. This is because the relative advantage of the pop-out reflected in the attentional weights is accompanied by a reduction of overall processing capacity C. The capacity is reduced from $C^n = 85.79\,\text{Hz}$ in the neutral condition to $C^a = 67.11\,\text{Hz}$ in the attention condition (lower boundary of the 95 % HDI on $C^a - C^n$ at $3.27\,\text{Hz}$).

Calculating prior entry according to Equation 6 yields a relative size of 12.46 ms. As outlined above, it originates purely from slowing down processing of the unattended stimulus.

To summarize, color salience led to a relative advantage and prior entry for the pop-out stimulus. However, the origin of this is a genuine slowdown of the non-salient target. That is, the pop-out reduced the overall processing rate. Possibly, the overall processing rate is exceptionally high when all stimuli of the pattern look the same. Whether this is the reason, remains unclear. Note, however, that with



orientation salience, Krüger et al. (2016) found that the overall rates *C* were constant across conditions in various similar TOJ tasks, which were analyzed using the same method. An overview of parameter estimates, their contributions to prior entry, and whether or how *C* changed, can be found in Table 3 in Appendix B. The overview includes Krüger et al.'s salience experiments.

5.2.3 *Experiment 4*[11]

A further possibility to influence attention is scene context with action possibilities. This was done in the fourth experiment. On the one hand, employing the model-based TOJ approach in this context demonstrated its versatility. On the other hand, it was expected to provide further insight concerning how inhibitory and facilitative components conjointly lead to prior entry under different attention manipulations.

Objects that afford actions, such as grasping, are known to attract visual attention (e.g., see Garrido-Vásquez & Schubö, 2014). In unpublished experiments we found such benefits in natural images with a change-blindness task (e.g., see Simons & Rensink, 2005). This advantage was partially removed when images were presented upside down, disturbing the perception of the natural scene layout (Kelley, Chun, & Chua, 2003).

The rationale behind the present experiment was to provide a TOJ task in which objects with similar visual attributes appear in the action space or background parts of natural images. Prior entry was expected to occur for the upright images, in which the action space position is apparent, but not for inverted ones, for which scene layout perception is disturbed.

Participants

In the attention condition, 39 participants took part. In the control conditions, 38 people participated. The same participant was removed from the analyses for the same reason as stated above.

Procedure

Thirty-eight photographs of indoor environments with action possibilities (e.g., desktops, kitchen sinks and bookshelves) were used. The scene had been arranged so that two target objects were present, one in the action space and one in the background. Photographs were taken with and without both objects, and were later edited so that all required combinations were available: no object present, both objects present, action space object (probe) present, and background object

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[11] Experiment 2 in Tünnermann et al. (in review).

(reference) present (see Tünnermann et al., in review, for further details on stimulus creation and type of scenes). These images enabled the presentation of sequences with the different object onset orders required by the TOJ task.

Again, eleven SOAs between -100 and 100 ms were realized. After an initial presentation of the image with both target objects removed, probe and reference appeared according to the SOA. After the presentation, participants toggled and confirmed order markers to report the order in which the objects appeared.

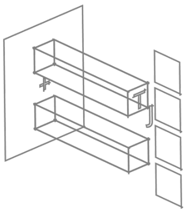
Results

Interestingly, the results from both conditions are rather similar. Both show an increase of the attentional weight of the probe stimulus. With $w_p^n = 0.54$, the attentional weight of the action space object in the control condition (inverted images) is even slightly higher than in the attention condition ($w_p^a = 0.52$). The overall processing rates are similar, with $C^n = 62.32\,\text{Hz}$ and $C^a = 64.94\,\text{Hz}$. The individual processing rates in the control condition are $v_p^n = 33.4\,\text{Hz}$ and $v_r^n = 28.84\,\text{Hz}$. They are reliably different because the lower boundary of the 95 % HDI on $v_p - v_n$ is 3.57 Hz. In the attention condition, the pattern is similar. The rates are $v_p^a = 33.54\,\text{Hz}$ and $v_r^a = 30.96\,\text{Hz}$, the lower HDI boundary on $v_p - v_n$ is 1.66 Hz. Further details on the magnitudes of possible action space advantages that could have been overlooked due to lack of power are discussed in (Tünnermann et al., in review). In short, only rather small effects could still be plausible.

In summary, the action space objects had attentional advantages in both the attention and control conditions. This observation speaks against the hypothesis that the placement of an object in the action space is the reason for the observed attentional advantage. Furthermore, the prior entry that results from the differences of probe and reference rate is rather small. It is only 2.5 ms in the attention condition and 4.8 ms in the control condition (calculated with Equation 6).

What could be the reason for the presence of the effect in the previously mentioned change-blindness data and its absence in the TOJ paradigm? The appearances of the changed objects were only roughly matched. In the change-blindness task, a slight advantage for foreground objects also remained in inverted images. Hence, foreground objects may be more conspicuous than background objects. Possibly, the influence of salience on perceptual latencies is stronger than the contextual scene effects. In change detection, it may be the other way around.

Alternatively, the persistence of the foreground-object advantage in TOJs could be caused by repeating the same images multiple times in the task. In the one-shot change-blindness paradigm, every image was shown only in a single trial for a few hundred milliseconds. In the present TOJ experiment, each of the 36 images was displayed 21



times throughout the experiment. Furthermore, the images remained visible until the response was given. Therefore, it is possible that the deleterious effect of image inversion on the perception of the scene layout vanishes if participants have ample opportunities to scrutinize the pictures.

To conclude, the action space character of the objects only lead to a small prior entry of 2.5 ms in the attention condition and 4.8 ms in the control condition. As discussed above, the control condition did not constitute a neutral condition with equal attentional weights. Therefore, it cannot be decided whether this small effect is based on accelerating the attended stimulus or slowing down the unattended one.

5.2.4 *Experiment 5*[12]

In both previous experiments with simple TOJs, prior entry was successfully established, even though it was tiny in the second experiment with the natural images. The goal of the next experiment was to investigate the effects of a peripheral cue in the simple TOJ paradigm and evaluate the results with the simple TVA-based TOJ model. Peripheral cues are known to be highly effective in TOJs (see Scharlau & Neumann, 2003a; Shore et al., 2001; Tünnermann & Scharlau, in review) and appear to exert an additional speedup of the processing resource acquisition before the race toward VSTM even starts (see Tünnermann et al., 2015). Therefore, a strong effect on the processing rates was expected in this experiment, possibly governed by a speedup of the attended stimulus due to the direct influence of the peripheral cue.

However, it is known that the large shift in psychometric functions cannot be purely accounted for by influences on the processing rate (see Tünnermann et al., in review). Therefore, it was expected that this simple TVA-based TOJ model reaches its limits and requires to be extended.

Participants

Thirty-three people took part in this experiment.

Procedure

Again, the simple TOJ procedure was carried out with the letter targets shown in Figure 15a. In a random half of the trials, the box cue shown in Figure 15b was presented before the probe stimulus with a COA of 110 ms. This established the attention condition. In the control condition, no cue was shown.

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[12] Experiment 3 in Tünnermann et al. (in review).

Eleven SOAs were realized in the range between -100 and $100\,\text{ms}$ for the control condition. In the attention condition, the distribution of SOAs in the range from -80 to $160\,\text{ms}$ was roughly centered at the expected PSS as suggested, for example, by Sternberg and Knoll (1973).

The presentation followed the usual TOJ procedure (see Section 4.1), and the order response was entered as in Experiment 1. Note that in this experiment the letters were not masked.

Results

The overall processing capacity in the neutral condition, C^n, was estimated at $60.79\,\text{Hz}$. Consequently, both stimulus rates in the neutral condition were estimated at approximately half this value, with $v_p^n = v_r^n = 30.36\,\text{Hz}$.

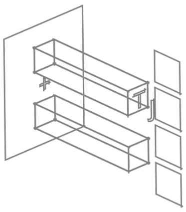
Curiously, in the attention condition, the probe weight was estimated at $w_p^a = 0.42$, which reflects an inhibition caused by the cue. Consequently, the processing rate of the probe at $v_p^a = 28.32\,\text{Hz}$ was smaller than the rate of the reference stimulus, $v_r^a = 36.76\,\text{Hz}$. The difference is reliable according to the 95 % HDI on $v_p^a - v_r^a$, the upper boundary of which is $-3.82\,\text{Hz}$. In the attention condition, the overall processing rate $C^a = 65.07\,\text{Hz}$ has a similar value as in the neutral condition.

The reason for the fact that the psychometric functions show large shifts (see Figure 4 in Tünnermann et al., in review) despite the opposite influence of the cue on the processing rates is the additional τ parameter. This parameter models a delay between the races of each stimulus and was borrowed from Alcalá-Quintana and García-Pérez's (2013) model (see Section 4.5.2). The value of τ was estimated at $-53.27\,\text{ms}$, and negative sign means it is a relative delay which is in favor of the attended target.

To sum up, the cue exerted a disadvantageous effect on the processing rate of the probe stimulus. This slowdown led to a rate-based prior entry of $-8.11\,\text{ms}$ (according to Equation 6). However, in effect, this is overcompensated by the τ parameter, leading to an effective prior entry of about $45\,\text{ms}$.

Hence, the question whether attention speeds up processing of the probe or slows down processing of the unattended reference stimulus is more complex in the model applied here. The cue leads to a processing rate advantage of the reference stimulus. However, it also reduces a delay of the probe or prolongs a delay of the reference. The delay has a stronger impact on the effective prior entry than the processing rate effect.

This result is not satisfying. In TVA, the only delay in stimulus processing is the t_0 duration. Reductions of t_0 caused by peripheral cues have been observed before (Tünnermann et al., 2015). However, the results here are difficult to explain with TVA. It is unlikely that t_0,



which is often estimated at approximately 20 ms (see Table 2 in Appendix B), is reduced below 10 ms. Consequently, to achieve a delay difference of about 50 ms, as captured by the τ parameter, t_0 of the unattended stimulus must increase at least to 60 ms. Under normal conditions, stimuli are very likely encoded within 60 ms, and here they would not even start to race. Therefore, it is unlikely that the large shifts of psychometric functions originate from cue-induced t_0 differences.

5.2.5 *Discussion*

In three experiments, very different stimulus materials and attention manipulations were used. The results were evaluated with the simple TVA-based TOJ model, which was slightly extended for the last experiment. The most important results of the individual experiments have been discussed in their respective section. Here, the discourse turns to the more general question whether attention-induced facilitation or inhibition lead to prior-entry effects. Furthermore, the role of the different attention manipulations, especially the peripheral cue in the last experiment, is discussed.

Experiment 3, the experiment reported first in this section, provided the most consistent picture using a color-salience manipulation. The pop-out had a relative processing speed advantage, which was driven by slowing down processing of the non-salient distractor. Hence, a purely inhibitory form of prior entry was revealed. As expected, the simple TVA-based TOJ model was apt to assess the influence of salience. This is most likely the case because the stimulus pattern that provides the attentional bias is present before the events the order of which is to be judged. Krüger et al. (2016, in preparation) continue to use the TVA-based TOJ model for research on quantifying visual salience. For this purpose, they have extended the simple model by introducing a salience parameter as a component of the attentional weight (see Section 3). Such more advanced models are then applied in experiments in which several levels of salience compete in different dimensions (Krüger et al., in preparation).

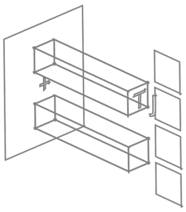
The experiment with natural images depicting action space and background objects was the least conclusive. A small prior-entry effect was induced, but because no proper baseline could be established, it is impossible to decide whether attention acted by facilitation or inhibition. Furthermore, it is not entirely clear whether the action space placement of the objects really leads to their small advantage in this task, or if these objects were conspicuous due to other reason such as visual salience. Because these difficulties were not present in a change-blindness task, in which the stimulus material had been previously used, a tentative conclusion about the influence of scene context in TOJ is possible. Scene context appears to play a minor role as an effect on perceptual latencies. Its influence may be stronger in change detection, for which the response may not depend on perceptual latencies. Instead, it possibly utilizes the low-level representations involved with direct parameter specification (Neumann, 1990; Neumann & Scharlau, 2007). In an "attention-free" response mode, sensory information can be utilized to execute actions. This fits well with observations that change detection is improved when participants perform direct actions as responses (Tseng et al., 2010).

With the peripheral cue in the third experiment of this section, a large effective prior-entry was found. However, it was based on a relative delay between probe and reference, which was captured by an additional parameter. The effect on the TVA processing rates was rather weak and opposite the hypothesized direction. Taking together Experiments 1 to 5, large shifts of the PSS, which cannot be explained by rate changes, occur when peripheral cues are used in the TOJ task. They did not appear for other attention manipulations, and they did not appear in the letter report task in Experiment 1. In the literature it is often found that peripheral cues are more effective, leading to larger PSS shifts than central cues (e.g., K. A. Schneider & Bavelier, 2003; Shore et al., 2001). Sometimes this effectiveness is linked to non-attentional factors (K. A. Schneider & Bavelier, 2003) as conceivable in the PRM theory (see Section 4.2.2).

The finding that the bolstered shift of the PSS occurs when an additional stimulus is present at the probe location (the cue), in combination with the fact that it is observed in TOJs but not in letter report tasks, points to a specific hypothesis. Could it be that the cue is at some level confused with the probe whose order in relation to the reference is to be judged? K. A. Schneider (2001) came to a similar tentative conclusion. The TVA-based framework provides a perfect test bed for this hypothesis, because the event of encoding the cue as the probe target can be modeled mathematically. This line of reasoning is followed up in the Manuscript C, which is summarized in the next section.

5.2.6 *Conclusion*

In conclusion, the three experiments summarized in this section showed that prior entry can arise purely by inhibition of the reference stimulus, as in the color salience experiment. Because of results by Krüger et al. (2016), however, it is clear that this does not necessarily have to be the case for visual salience in other feature dimensions. Furthermore, scene context effects via object affordances may only have a weak influence on perceptual latencies. When they produce response advantages, they do so most likely by enhancing low-level representations used in action execution. Finally, peripheral cues lead to widely shifted PSSs. However, in agreement with previous research,



they do so via effects other that attention-induced changes of encoding speed. Importantly, further investigation of the effects of cues in TOJs is necessary.

5.3 PERIPHERAL VISUAL CUES: THEIR FATE IN PROCESSING AND EFFECTS ON ATTENTION AND TEMPORAL-ORDER PERCEPTION (MANUSCRIPT C)

5.3.1 *Introduction and Rationale*

Throughout the experiments presented here and in earlier research, peripheral cues produced largely shifted PSSs in TOJ, but doubt remained if this is due to selective attention advantages of the cued stimulus. The doubt originates from different findings. For example, peripheral cues shift the PSS more effectively than symbolic manipulations (Shore et al., 2001) or other attention manipulations that do not involve a direct cue (Tünnermann et al., in review). Attentional influences on the processing rates can not explain such large PSSs shifts (Tünnermann et al., in review).

The time course of peripheral cueing is conspicuous, too. For instance, the effect is relatively large and varies with COA (Scharlau et al., 2006), in contrast to the TVA parameters from letter report tasks (Tünnermann et al., 2015). Scharlau et al. (2006) noted that even at large COAs, the effect is positive and no inhibition of return is observed. K. A. Schneider and Bavelier (2003) reported that cues at a COA of zero already facilitate the cued target. This effect is intriguing because attention would have had no time to be directed towards the target. K. A. Schneider and Bavelier also successfully reduced the latency of a cued target when at the same time they cued a lot of different places. With increasing the number of coincident cues at various locations, the cueing effect should converge to zero, which was not the case. K. A. Schneider and Bavelier suggested that the peripheral cues exhibit non-attentional influences on the processing speed, or that the cue may be confused with the target at some level.

Especially the latter explanation is interesting in the TVA-based framework. According to TVA, all stimuli race for all possible categorizations. Hence, a cue also races for being encoded as the probe target. If the rate of this event is rather small, it will happen only occasionally. How often such a cue–probe categorization succeeds depends on different factors, most importantly on the time available. The time increases with the COA, which would explain the COA-dependence of largely shifted PSSs.

A simulation of the hypothesis can be found in Tünnermann and Scharlau (in review); it shows that the mechanism outlined above indeed leads to larger shifts PSSs. To test the hypothesis experimentally, the two experiments reported in this section were conducted. In the first experiment, the delay between cue and probe was varied. With increasing time for encoding the cue as a probe, the farther shifted PSSs become possible just as the simulation shows. In the second experiment, the cue was spatially shifted away from the target. The distance should reduce the contribution of cue–probe categorization to the PSS shift. The data was analyzed with the advanced TVA-based model of cued TOJs, which is described in detail in Section 4.6.3.

5.3.2 *Experiment 6*[13]

In this experiment, a TOJ task with four different cueing conditions was realized. There was a neutral control condition without a cue. Then there were three experimental conditions with a cue at COAs 40, 80, and 140 ms, respectively. Varying between these COAs was expected to cause the COA-dependent increase in cue–probe categorizations.

According to the cue–probe confusion hypothesis, the shifts of PSSs can be entirely explained via the rate of cue–probe categorizations. The target processing rates v_p and v_r would remain unchanged by the cue.

Participants

Thirty subjects participated in this experiment.

Procedure

As in the experiments summarized in the previous section, participants performed in a simple TOJ task. Again, the target stimuli which are shown in Figure 15a and the cue from Figure 15c were used. The presentation and response procedures were the same as described in for Experiment 5 in Section 5.2.

This time, there was a neutral condition and three attention conditions with varying COAs. The COAs were 40, 80, and 140 ms. For each condition, nine SOAs were realized, centered at the expected PSS of each condition, roughly in a range from -120 to 210 ms (for an detailed overview of the SOA distribution, see Table 1 in Tünnermann & Scharlau, in review).

Results

The results were submitted to a hierarchical Bayesian estimation that used the model of cued TOJs explained in Section 4.6.3. This model has four rate parameters. Two for categorizations of the cue (cue–cue: v_{cc}; and cue–probe: v_{cp}). Furthermore, it includes the usual two target rates v_p and v_r of the probe and reference stimuli, respectively.

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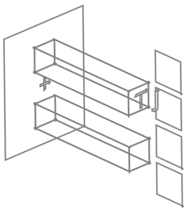
[13] Experiment 1 in Tünnermann and Scharlau (in review).



According to the hypothesis stated above, the large shifts of PSSs in the presence of peripheral cues could be explained via nonzero estimates of v_{cc}. Additionally, the v_p and v_r parameters would be equal to each other and across all attention conditions.

The actual results are more complex than the hypothesis, however. Indeed v_{cp} took nonzero values. The group-level estimate lies roughly between 1 and 1.5 Hz in the different attention conditions. On the subject level, v_{cp}^{140} values larger than 15 Hz were observed for participants with very wide PSS shifts in the COA 140 ms condition. Hence, encoding the cue as probe indeed contributed to the large shifts in PSSs.

However, the cue also had an effect on the processing rates. The group-level estimates of the processing rate of neutral targets was estimated at 28 Hz. The group-level estimates in the attention conditions are as follows. In the COA 40 ms condition, the $v_p^{40} = 35$ Hz and $v_r^{40} = 37$ Hz estimates are not much different, with entirely overlapping 95 % HDIs.

In the COA 80 ms condition, the processing rate of the reference stimulus was estimated close to the neutral target rate at $v_r^{80} = 28$ Hz, and the cue boosted the probe stimulus to a rate of $v_p^{80} = 56$ Hz. The lower boundary of the 95 % HDIs of $v_p^{80} - v_r^{80}$ is at 9.2 Hz, therefore the difference is reliably larger than that.

With the largest COA of 140 ms, it is the reference stimulus which intriguingly is boosted to high values around $v_r^{140} = 100$ Hz. The probe is near the neutral target rate at $v_p^{140} = 33$ Hz (lower HDI boundary of the difference $v_r^{140} - v_p^{140}$ at 13.03 Hz). This pattern of rate increases and decreases caused by the peripheral cue is interpreted shortly.

First, however, note that at the subject-level, it was revealed that approximately 20 % of the participants show a pattern in which the cue had an inhibitory effect in all conditions, increasing with the COAs (see the bottom row of Figure 4 in Tünnermann & Scharlau, in review). This inhibition acts via the probe and reference rate and not by inducing large changes in the v_{cc} rate which was included to model strong IOR. The rate-based effect in these participants leads to equal probe and reference rates in the COA 40 ms condition on the group level.

Taking this into account, the overall pattern that emerges is as follows: At COAs of 40 ms, the cue leads to a medium rate-based attention advantage for the probe stimulus. At COAs of 80 ms, the effect of the cue on the probe stimulus is the strongest leading to strong facilitation. For COAs of 140 ms, the reference is sped up substantially. Its relative advantage is possibly based on the cued target's disadvantage caused by IOR (Klein, 2000). A COA of 140 ms is relatively short for IOR to occur, which is often observed only after a few hundred milliseconds. However, sometimes it is found even earlier when the cue predicts a target to be detected in a different location Danziger and Kingstone (1999). In TOJs, in which most of the SOAs are much shorter than 140 (and a cue is only present in half of the trials), the participants might be encouraged to disengage attention early in expectation of the next stimulus.

In addition to this pattern, the overall processing rate (the sum of all processing rates) increases strongly with the COA. This can be explained by assuming that the cue triggers a non-attentional boost of available resource (see General Discussion in Tünnermann & Scharlau, in review).

In short, in addition to the non-attentional effect just mentioned, the cue boosts the processing rate of the probe if the COA is not too long. At longer COAs, the cue leads to a rate-based IOR, decreasing the probe rate relative to the reference. A concurrent contribution from encoding the cue as the probe is most prominent at the large COAs, concealing the disadvantageous IOR effect completely. This is inline with experiments that investigated the time course of facilitation in TOJ via the PSS. Such experiments did not find IOR in the PSS measurements (see Scharlau et al., 2006). With the strong contribution from cue–probe encodings, the present findings and theory offer an explanation why this is the case.

5.3.3 *Experiment 7*[14]

The purpose of this experiment was to test whether the rate of cue–probe categorizations is reduced, when the co-locality of cue and probe is reduced.

In this experiment, the effective 80 ms COA was used for three attention conditions. They differed this time by a spatial displacement of the cue. Again, a no-cue neutral condition was included.

Participants

In this experiment, 26 subjects took part.

Procedure

The procedure was the same as for the previous experiment, except for the constant 80 ms COA. Hence, all attention conditions were identical to the previous experiment, except for the variation of the cue location displacement (CLD). The three CLD levels were 0, 15, and 60 pixels. With a CLD of 0 px, the cue was shown exactly at the probe location. When the CLD was 15 px, the cue was shifted roughly half the probe stimulus width. It was shown completely next to the probe at a CLD of 60 px (see Figure 5 in Tünnermann et al., in review). Note that the cue was always shifted horizontally or vertically by the CLD toward the center of the screen. That is, it was always within the square that encloses the four possible target positions.

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[14] Experiment 2 in Tünnermann and Scharlau (in review).

Results

The cue encoding rates, v_{cc} and v_{cp} were similar to those in Experiment 1. Only at a CLD of 60 px ,the v_{cc} rate was rather large, estimated at 1.25 px. This may not seem surprising because the rate models recognizing the cue as the cue, which undoubtedly is easier when it is shown next to the probe and not at—or overlapping with—its location. It should be noted, however, that this rate only captures cue–cue encodings that influence the TOJ by inhibiting the probe location completely. The majority of cue–cue encodings at a CLD of 60 px are not expected not interfere with the TOJ and simply lead to a separate VSTM representation of the cue.

Interestingly, the processing rates of probe and reference changed with varying the CLD. The following pattern was revealed in the group-level estimates. The reference rate v_r is always around 30 Hz as in the previous experiment. The cue boosted the probe processing rate effectively at the zero CLD to v_p^0 = 97 Hz. The lower boundary of the 95 % HDI of $v_p^0 - v_r^0$ lies at 34.8 Hz; therefore this is a reliable difference. In the CLD 15 px condition, the probe rate was boosted less, but was still as high as 60 Hz, being reliably different to the reference, too (lower HDI boundary of $v_p^{15} - v_r^1 5$ at 7.97 Hz). When the cue no longer overlapped with the probe, at a CLD 60, its effect on the probe rate was virtually removed. The rate was estimated at $v_p^{60} = 37$ Hz. The 95 % HDI completely encloses the HDI of the reference rate $v_r^{60} = 35$ Hz in this conditions.

In this experiment, the facilitative effect of the cue on the probe rate appears to be larger than in the previous experiment. The COA 80 ms condition of the previous experiment was identical to the CLD 0 px of this experiment. The former showed a probe processing rate of 56 Hz and the latter a rate of 97 Hz. Most likely, this increase is explained by the fact that the cue had the same COA throughout the whole session in the last experiment, whereas it was varied between three levels in the previous experiment. Probably the attention system optimized the temporal orientation of attention based on the predictable COA.

Similar as in the previous experiment, subject-level parameter estimates and posterior predictive plots again showed that for a subset of participants the inhibitory effect of the cue overpowered the beneficial one (see Figure 7c in Tünnermann & Scharlau, in review).

In summary, moving the cue away from the probe target indeed reduced its effectiveness. However, it did not so by removing the influence of cue–probe categorizations. Instead, displacing the cue lead to decreases in the probe processing rate.

5.3.4 *Discussion*

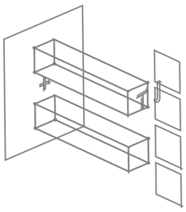
Both experiments reported in this sections showed that cue–probe categorizations contribute to the PSS shift found in cued TOJs. These contributions are necessary especially to explain the large shifts found for some participants. However, the study also showed substantial genuine attention effects on the probe and reference processing rates. At relatively short COAs (especially at 80 ms), the cue boosts the probe processing rate. At the large COA, a strong disadvantage was found. There the probe rate was substantially smaller than the reference rate. Spatially moving the cue away from the probe reduced its processing rate but did not have a substantial impact on the rate cue–probe categorization.

How the complex pattern of rate changes can emerge in an extended TVA view is described in the General Discussion of Tünnermann and Scharlau (in review). In essence, a non-attentional boost elicited by the cue increases the overall available processing resources. This mechanism is in line with K. A. Schneider and Bavelier's (2003) observation of non-attentional effects of peripheral cues. Additionally, the cued target can inherit preactivated resources from the cues shown briefly before the target, explaining the beneficial effect on the probe rate at small COAs. Such a mechanism was also suggested in Tünnermann et al. (2015). If the cue is shown long before the target, the resources cannot be inherited by the probe. Instead, they get blocked, as suggested by S. E. Petersen and Posner (2012). This resource distribution scheme is visualized in Figure 8 in Tünnermann et al. (2015).

In conflict with the hypothesis that cue–probe categorizations drive the entire large PSS shift in cued TOJs, the present experiments showed important contributions from cue-induced processing rate changes. At the large COA, the processing rate of the probe was much smaller than that of the reference. This finding most likely is related to IOR, which had been reported missing before in PSS estimates (Scharlau et al., 2006; K. A. Schneider & Bavelier, 2003). According to the present results, the contributions of cue–probe encodings hide the IOR-effect on processing rates in PSS estimates.

Before concluding the discussion, and alternative theoretical view to the one presented above and in Manuscript C is outlined. It is based the TRAM extension of TVA (see Section 3.0.4) and is very similar to the view described above.

One mechanism of TRAM is that a VSTM/VWM representation can be updated instead of being replaced in a new encoding cylce. W. X. Schneider (2013) writes that "updating is issued if a VWM object receives visual input that fits in terms of its priority map region characteristics (location, rough region shape and attentional weight) to the predicted (expected) region characteristics maintained by the



VWM object. In other words, updating is called if the visual system signals for new visual input to a VWM object (e.g., after a saccade) object continuity". Consequently, if cue and probe share such low-level attributes, the presentation of the probe might lead an update for the cue representation. If the VSTM arrival time is crucial for the TOJ, as assumed in this thesis, the arrival time of the cue would now be associated with the target representation. Hence, just as in the explanation with cue–probe encodings described above, the low-level similarity of cue and probe is the reason of the large shifts of psychometric functions.

Both theories also make similar predictions when the presentation of the cue is changed: If the COA is relatively short (probably shorter than 150 ms), TRAM predicts that the updating mentioned above takes place. For larger COAs, for which the attentional weight of the cue has substantially decayed, a new encoding cycle would be evoked. This produces a non-obscured probe arrival time. Similarly, cue–probe confusions would be low in the confusion-based view because the cue and probe would participate in totally separate races. In future work, fine-grained comparisons of the time courses predicted by the two theories could help to decide which one is a better explanation for obscured VSTM arrival times that drive the large shifts in psychometric functions from cued TOJs.

5.3.5 *Conclusion*

In cued TOJs, encoding the cue as the probe and cue-induced processing speed changes conjointly lead to the typically observed large PSS shift. The genuine rate-based part of the effect increases with the COA and inverts at large COAs due to IOR. In the PSS, this inversion is hidden due to the fact that the influence of cue-probe categorization gets especially strong at large COAs. The substantially different patterns which emerge in psychometric functions on the subject level (e.g., see Tünnermann et al., in review, Figure 4) may be caused by different manifestations of these factors that contribute to the PSS.

Probably the most important result of this study is that encoding events associated with stimuli other than the probe or reference can substantially alter the shape of psychometric functions and the magnitude of PSS estimates. As revealed for the cue in the present experiments, this is true even if these events occur only at subtle rates.

5.4 RESETTING THE RACE: PLATEAUS IN PSYCHOMETRIC FUNCTIONS WITH A DETERMINISTIC DECISION RULE (UNPUBLISHED EXPERIMENTS)

5.4.1 *Introduction and Rationale*

In Section 4.6.3, the "The t_0-Reset Model", a version of the TVA-based TOJ model, was suggested in which the preparation phase before the race can be stopped and restarted. Such a reset is expected to occur when the second target is shown within the t_0 period of the first target.

This mechanism is interesting for two reasons: In the first place, it is a plausible possibility for how TVA-conform processing could include further stimuli in the competition if the race has not already started. Secondly, the mechanism produces a plateau in psychometric functions which is indeed sometimes observed in TOJ-data (Neumann, 1982). In other models such a plateau originates from the convolution of a non-deterministic decision function with the arrival time difference function (Sternberg et al., 1971). The non-determinacy is usually caused by a resolution parameter which models a threshold on the arrival time difference below which temporal order cannot be discriminated. For arrival times within this range, observers are equally likely to report either order (see Section 4.3). The TVA-based TOJ model with a reset during t_0 generates a plateau with a totally deterministic decision rule.

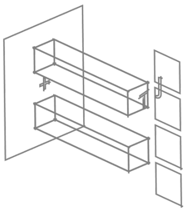
Alcalá-Quintana and García-Pérez (2013) have provided a framework for fitting their psychometric functions (see Section-4.5.2) and calculating the Bayesian information criterion (BIC). Alcalá-Quintana and García-Pérez's model includes the non-deterministic decision rule (via resolution parameter δ). The simple versions of the TVA-based TOJ model can be conveniently integrated in their framework. It is then well suited to compare the two models.

5.4.2 *Experiment 8*

In TOJ data, the plateau is often prominent in neutral conditions, where it is located in the center of the psychometric distribution. Such shape alterations in psychometric functions are often hard to distinguish from noise. Therefore, the first experiment aimed at obtaining highly accurate data for a neutral TOJ, which can then be used to compare the two models.

Participants

The experiment had four participants, including the author and adviser of this thesis who are identified by their initials in Figure 16.



Procedure

The procedure was the same as the neutral condition in Experiments 5, 6, and 7, except for the fact that a larger number of repetitions were presented at fine-grained SOAs. The twenty-one SOAs ranged from -100 to 100 ms in steps of 10 ms. Every SOA was repeated 240 times. The 5040 trials were presented in 10 sessions which participants could conduct over several days.

Results

The data was fitted on the subject level with Alcalá-Quintana and García-Pérez's (2013) framework. The evaluation included the TVA-based TOJ model with the "t_0 reset" (see Section 4.6.3) and Alcalá-Quintana and García-Pérez's model without error parameters. Additionally, the τ parameter was fixed to zero. This parameter is not expected to vary in a neutral condition of a TOJ and fixing it secured that both models have the same complexity with four parameters (see second and third row of Figure 16). A third model based on a simple bilateral exponential distribution of the arrival times was included to provide a comparison with a model without a plateau-generating mechanism. This simple model is a special case of both the TVA-based TOJ model and Alcalá-Quintana and García-Pérez's model.

The most prominent feature of the results of this experiment is reflected in the BIC scores[15] and can be easily seen by visual inspection of the plots: The model the fits of which are shown in the left column of Figure 16 shows the strongest deviations from the data. This is the model that does not include any mechanisms which generate central distortions. Hence, it can be concluded that some mechanism that generates such plateaus needs to be included to model TOJ data accurately.

The model in the second row is the model by Alcalá-Quintana and García-Pérez (2013) with τ fixed at zero. In this model, the plateau is controlled by the resolution parameter δ, which is estimated at values between 12 and 27 ms. The vertical position of the plateau is controlled by ξ, the potential response bias. Here it was estimated at values around 0.5, no bias.[16]

In the third row, the results of the TVA-based TOJ model are shown. Here t_0 and its standard deviation s_0 control the plateau via the reset mechanism. The t_0 parameter is estimated at values of approximately 15 ms with a similarly sized standard deviation. One subject, IS, shows a t_0 value smaller than 6 ms with a large standard devia-

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[15] If a BIC score for one model is smaller relative to another model, the model with the smaller score is to be preferred over the model with the larger score. The BIC takes the quality of the fit and the complexity of the model into account (Schwarz, 1978).

[16] In this attention-neutral TOJ, the ξ parameter is expected to assume the 0.5 value of no bias. It was, however, not fixed in order to provide both models with the same number of degrees of freedom for their plateau mechanisms.

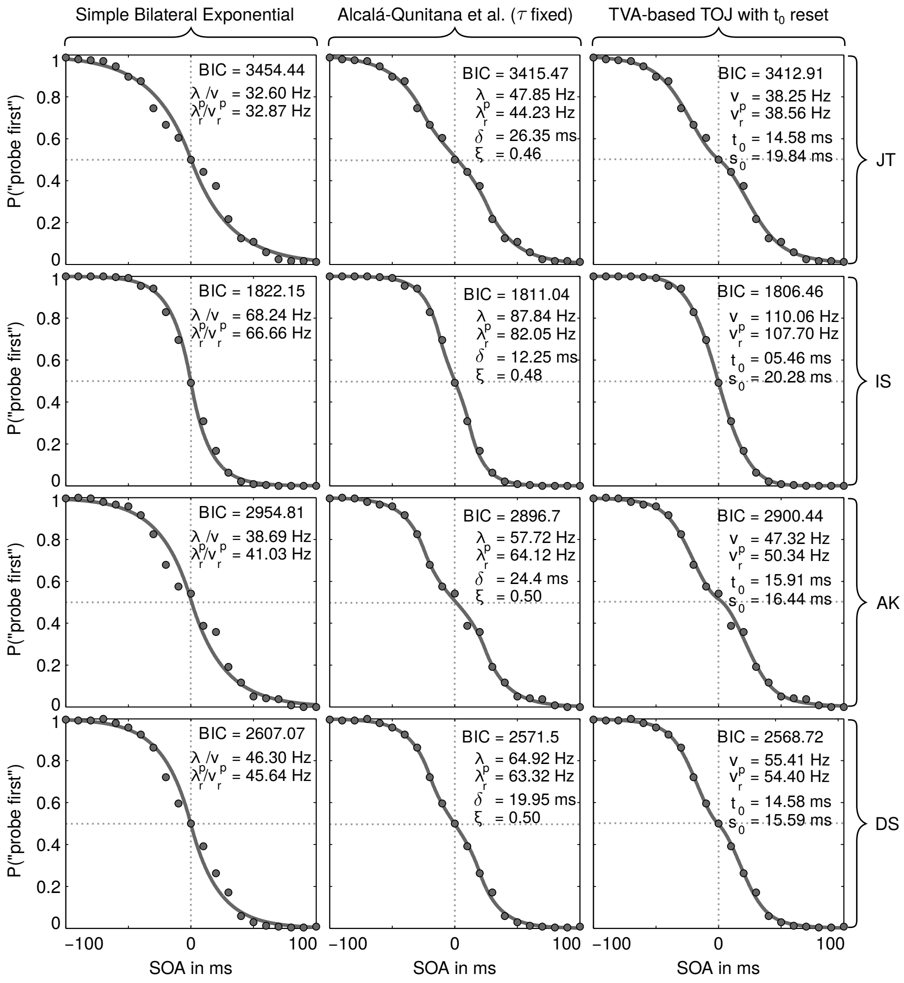
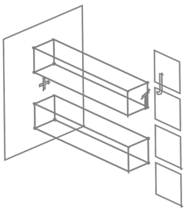


Figure 16: Results of Experiment 8. Subject-level plots of the fitted functions and parameter estimates.



tion of 20 ms. In general, the mean of t_0 is plausible. The values of s_0 indicate that t_0 varies over a relatively large range.

Interestingly, the rate parameters obtained by the two models differ in different directions for the two models. For participants JT, AK, and DS, the TVA-based estimates are smaller than those obtained with Alcalá-Quintana and García-Pérez's (2013) model. For participant IS, who produced the steepest TOJ curve, it is the other way around.

Both models with plateau-generating mechanisms yield good fits. For three of the four participants (JT, IS, DS) the lower BIC score signifies that the TVA-based model is to be preferred. However, differences in the fits appear to be rather small, and the neutral condition is rather special. Therefore, further investigation is required before a conclusion can be reached.

5.4.3 *Experiment 9*

Experiment 9 further investigates the question whether an early pre-race reset and a deterministic decision rule can explain the distortions of TOJ curves typically attributed to a non-deterministic decision mechanism. In this experiment, an attention condition was included as well.

However, the investigation presented here is tentative in several ways. First of all, the data is not as precise as in the previous experiment. Participants were not available for as many sessions as before and due to the additional attention condition, the number of trials is divided among two conditions. Second, only the simple TVA-based TOJ model with an additional delay parameter, τ, could be integrated into Alcalá-Quintana and García-Pérez's (2013) framework in the scope of this thesis. The model of cued TOJs developed in Section 4.6.3 is structurally different with more parameters, rendering the integration more difficult. In future work, a fully Bayesian model comparison including this model is desirable. Hence, the model here is a simplification as argued in Manuscript C. Therefore, any conclusions should be considered as preliminary.

Participants

Four participants produced data in five to ten sessions (see Table 1 in Appendix B).

Procedure

The procedure was the same as in the previous experiment, except that a peripheral cue was presented in a random half of the trials. The cue was presented as in Experiment 5 but with a COA of 140 ms. The trial distribution was optimized to include many trials in the interesting region around the expected PSS (see Table 1 in Appendix B).

Results

The same models as in the previous experiment were used, except the one without any plateau-generating mechanism. The only difference was that the delay parameter τ was added to both models. This parameter is part of Alcalá-Quintana and García-Pérez's (2013) original model. As already mentioned, for the TVA-based TOJ model it constitutes a simplification of the more complex processes associated with a peripheral cue (see Manuscript C).

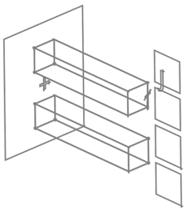
The estimated parameters and fits are shown in Figure 17. For the neutral condition, the BIC scores again provide a mixed picture. Subjects LS and MG are approximated better with Alcalá-Quintana and García-Pérez's (2013) model, subjects JG and HM show better fits with the TVA-based TOJ-model. For the attention conditions Alcalá-Quintana and García-Pérez's model is preferred for all participants except JG.

For subject LS, who produced the steepest TOJ curve, both models capture the shift in the τ parameter. The same goes for Alcalá-Quintana and García-Pérez's (2013) model and subject JG. For all other attention condition results, both models produce rather strange results. In Alcalá-Quintana and García-Pérez's model, the temporal resolution parameters, the δ, take very large values of 60 and 70 ms. Similarly, in the simplified TVA-based TOJ model, implausibly large t_0 estimates emerge (50 to 110 ms) with similarly large standard deviations. Both models appear to capture the cue-induced PSS shift by producing a broad plateau. In Alcalá-Quintana and García-Pérez's model, this also includes a strong response bias for the attended target (ξ close to 0).

5.4.4 *Discussion*

The two experiments described above investigated distortions in psychometric distributions, which are usually attributed deterministic decision rules. With highly precise data for the special case of a neutral TOJ condition, the t_0-reset interpretation of the TVA-based TOJ-model seems to be a reasonable alternative explanation, but further investigation is required.

The second experiment tested the competing models in the general case where attention is not equally distributed but biased toward one target by a cue. Both models produced strange results for at least some of the subjects although on the basis of rather noisy data. For the TVA-based TOJ-model, this is most likely the case because it cannot account for large PSS shifts without introducing a delay parameter which is not theoretically justified (see Manuscript C). Alcalá-Quintana and García-Pérez's (2013) model seems to suffer from similar problems when large shifts are present in rather noisy data.



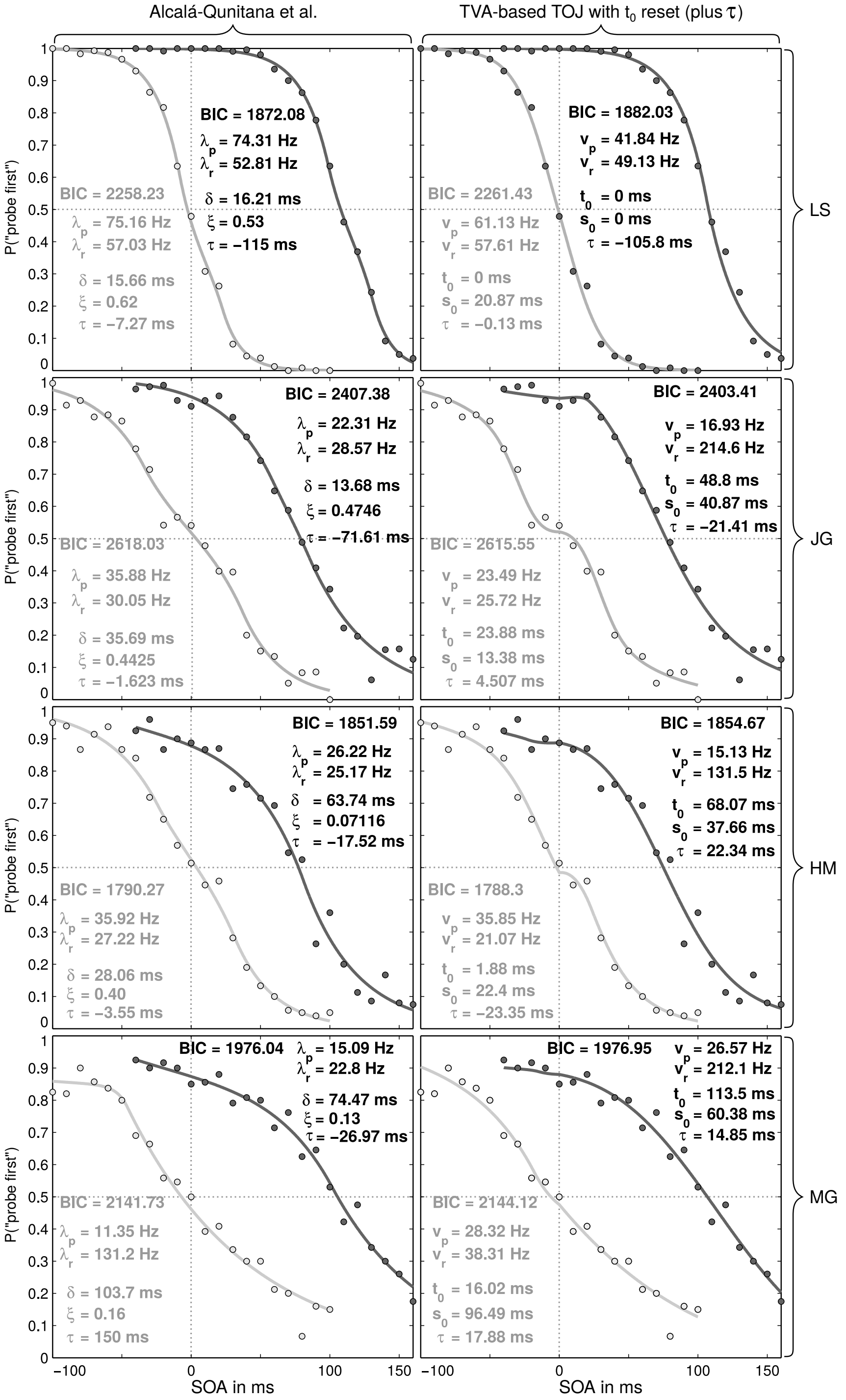
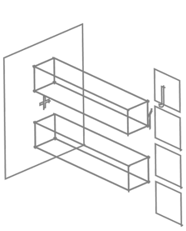


Figure 17: Results of Experiment 9. Subject-level plots of the fitted functions and parameter estimates.

5.4.5 *Conclusion*

The analysis remains inconclusive concerning whether the plateau is generated by a pre-race reset or a post-race decision mechanism. For future research, the following points should be taken into consideration: (1) For model-based analysis of such subtle–but important–differences, very precise data of individual participants is needed, as the data collected in Experiment 8. With attention manipulations, more repetitions should be used if possible. (2) With peripheral cues, explicit models should be used as suggested in Manuscript *C*. The simplification represented by the additional delay parameter τ interferes with the parameters controlling the plateau and should, therefore, be avoided. (3) It may be advantageous to work with other attention manipulations first. For example, a salience manipulation as in Experiment 3 would remove much of the complexity added by the cue. This could allow the assessment of plateau-producing mechanisms free of the interference from the peripheral cue. Either of the alternatives, explicitly modeling the cue (2) or removing it from the presentation (3), should be complemented by precise data (1).

On a final note, it may be advantageous to include prior information and conduct a fully Bayesian model comparison. This could help to prevent the models from assuming highly improbable parameter values as they did for the majority of the fits in Experiment 9.



6 GENERAL DISCUSSION AND CONCLUSION

"[. . .] while you are swimming and not sinking you should aim for rough water. [. . . A] student told me that he wanted to go into general relativity rather than the area I was working on, elementary particle physics, because the principles of the former were well known, while the latter seemed like a mess to him. It struck me that he had just given a perfectly good reason for doing the opposite"
– Weinberg (2003) (p. 389)

6.1 SUMMARY

This thesis set out to answer fundamental questions concerning how attention influences the perception of temporal order. For this purpose, the problem of TOJ relativity (see Section 1.3.2) had to be overcome. This was accomplished by integrating an additional task to measure absolute encoding times in Experiments 1 and 2 with common TOJs, and by developing a novel quantitative model based on Bundesen's TVA, which was fitted directly to TOJ data in the other experiments.

This section summarizes the answers that were obtained for the important open questions as introduced in Section 1.3.3. These answers are described in detail in the respective manuscripts and experiment descriptions in this synopsis (see Chapter 5). Here, a comprehensive summary of the main results is provided. Furthermore, the main aspects of the TVA-based TOJ model are summarized.

6.1.1 *New Answers for Old Questions*

The Speed Question – Answered

The speed question was whether prior entry really originates from attention speeding up processing of the attended stimulus. The answer to this questions is that a speedup is only one source of the observed advantages. Varying degrees of attentional speedup of the attended stimulus and slowdown of the unattended one, conjointly cause prior entry in different situations. In the presence of peripheral cues, other components contribute to the shifts of PSSs.

The genuine components of attentional speedup and slowdown were measured with TVA processing rate parameters. Manuscript *A* measured these rates in experiments that combined cued TOJs with TVA-based letter-report experiments. The main finding in this study was that the processing rate of the attended stimulus was increased at the expense of the unattended one. That is, the available resources were redistributed.

In Experiments 3 (Experiment 1 in Manuscript *B*), with an attention manipulation based on color salience, prior entry was found to emerge from a pure slowdown of the unattended stimulus, the non-singleton. That this is not generally the case for salience manipulations was shown by Krüger et al. (2016, in preparation). They found with an extension of the TVA-based TOJ method that, similarly as in

Experiment 1 and 2, equal amounts of rate increases for the attended stimulus and decreases for the unattended stimulus contribute to prior entry. These experiments used orientation, luminance, and color singletons (see Table 3 in Appendix B).

For Experiments 4 (Experiment 3 in Manuscript *B*), TVA parameters were successfully estimated for action space and background objects in natural scenes. However, establishing a control condition by turning the images upside down failed and, therefore, no inference about the respective contributions of rate increases and decreases can be made. The attention effects probably resulted from salience or visibility advantages of the action space objects. In an earlier change-blindness study, an action space advantage was found. Therefore, a tentative inference about the alterations of processing speed in the setting of Experiment 4 is that scene layout and potential action possibilities do not influence perceptual latency, whereas they may influence processes in action preparation that can be utilized in change detection (see Tseng et al., 2010).

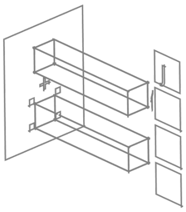
In the remainder of the experiments, a peripheral cue was used to modify the observer's attention. These experiments confirmed that in agreement with earlier suggestions peripheral cues activate further components that influence TOJs, not only attention-induced changes in the processing speed. This is discussed in the next subsection.

In conclusion, slowing down the unattended stimulus contributes substantially to prior entry in the most situations. This agrees with earlier results by Weiß et al. (2013). Weiß et al. therefore suggested that prior entry is actually posterior entry. One could argue for this. However, slowdown having a higher impact on the perceptual latency than a speedup follows from the exponential processing model of TVA (see the discussion of Manuscript A in this synopsis). Therefore, it may be true that delays of the unattended stimulus contribute more than the lead times of the attended one, but this does not mean inhibition is more prominent than facilitation in processing.

To sum up, the old view, which many prior entry studies (tacitly) take—attention leads to an absolute speedup in information processing—must be discarded. In future research, it will be important to determine the boundary conditions under which a resource-invariant redistribution—equal rate increase and decrease—is present or when absolute slowdowns or speedups occur.

The Peripheral Cue Question – Answered

As suspected in earlier research (Pashler, 1998, p. 260; K. A. Schneider & Bavelier, 2003), the experiments and the model-based analysis of cued TOJs performed in this thesis showed that components other than attentional increases and decreases of processing speed contribute to the PSS shifts observed in TOJs. Discrepancies which also point in this direction were found in Experiment 2 (from Manuscript *A*)



and Experiment 5 (Experiment 3 in Manuscript *B*). In the former, a dissociation between the PSS-based time course of prior entry and the TVA-based estimate indicated that the cue has some additional impact on prior entry in TOJs. In the latter, an artificial delay parameter had to be introduced to account for the large shift in PSS in the TVA-based TOJ analysis.

A full model-based assessment of cued TOJs was conducted in Manuscript *C*. It showed that the process is rather complex. The cue exerts three principal effects which combine differently with increasing COA. (1) The cue alters the processing rate of attended and unattended stimuli. This is similar to the attention manipulations discussed above. It appears to be very effective at 80 ms. At large COAs, 140 ms in Experiment 6 (Experiment 1 in Manuscript *C*), the effect reverses. This most likely reflects IOR. Though expected, IOR was absent in earlier studies. That it could be detected now is because of the second principal effect of the cue. (2) The second effect is that the cue is occasionally confused with the target at a perceptual level. That is, a categorization of the type "cue encoded as probe" takes place with varying frequency. Such misperceptions were modeled formally for the first time, and it was shown that they drive the large shift of the PSS. Notably, the likelihood that such categorizations, which race toward VSTM, finish successfully increases with the COA. Because they become more prominent at larger COAs, they conceal the aforementioned IOR. (3) The third effect of the cue is a location unspecific increase of the overall available processing resources with increasing COA.

In summary, complex interactions of attentional processing rate alterations, spurious contributions from cue–probe confusions, and a location unspecific increase of available resources conjointly lead to the typical pattern of largely shifted PSSs in cued TOJs. This result should be verified in future research by manipulating the three different components individually. For example, the likelihood of cue–probe confusions could be varied by manipulating the cue–probe similarity.

Decision Rules

As noted by Sternberg and Knoll (1973), the shape of a psychometric function is determined by the arrival time distribution at the order comparator and by the type of decision function in an independent-channels model (see Section 4.3.1). A feature of the shape that is sometimes observed in psychometric functions is a central plateau (e.g., see Alcalá-Quintana & García-Pérez, 2013; Neumann & Scharlau, 2007). According to current models (García-Pérez & Alcalá-Quintana, 2012b), it is caused by a non-deterministic decision function.

In Experiment 8 and 9 of this synopsis, an alternative explanation was explored, which was dubbed the t_0-reset model. The model is formally described in Section 4.6.3. This model assumes that if the second stimulus is presented before the t_0 period of the first one has passed, the current resource distribution is canceled and starts anew. As the experiments showed, this mechanism can produce a plateau in psychometric functions which is highly similar to the one typically observed in the data. In contrast to the usual view, the t_0-reset model removes the non-determinacy at the decision end and inserts one before the start of the race toward VSTM. Because both of these alternatives fit even high precision data similarly well, based on model selection criteria for now it cannot be decided which version should be preferred.

The experiments demonstrated, however, that the shape of a psychometric function does not necessarily prescribe certain decision functions, if mechanisms such as restarting the race can take place during stimulus encoding.

If future work proves that the t_0-reset model is correct, it will constitute a useful method to estimate TVA's t_0 parameter with simple TOJs. Furthermore, it would advance TVA by identifying mechanisms that are involved with the resource distribution in spatiotemporally distributed presentations.

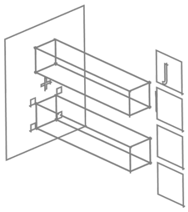
Measuring Meaningful Attention Parameters with TOJ

Another question posed at the beginning of this thesis was whether it is possible to measure TVA parameters with TOJs. The experiments in this thesis show that this is the case for the processing speed parameters. TVA's overall rate C and the attentional weights w_p and w_r can be measured with simple TOJs. Alternatively, two rates v_r and v_p can be measured. As mentioned above, t_0 can be estimated with a tentative model.

TOJ-based measurement of TVA's processing speed parameters shows great potential for the use in studies with patients, children, or animals, who cannot easily perform the usual WR and PR tasks. Later in the subsequent discussion, some exemplary assessments are presented.

6.1.2 *A New Model for New Answers*

The TVA-based TOJ model that was developed in this thesis allows to pose old questions more precisely and obtain answers for them. The model was formally described in Section 4.6. In the present chapter, I will present the central ideas. Furthermore, I will provide the updated Version of the meteorologist's short story promised earlier in this thesis (see Section 4.2.2).



The Main Concepts of the New Model

The main concept behind the proposed TOJ model is that the encoding processes of both targets are explicitly modeled. When this new TVA-based TOJ-model is fitted to data, it returns parameters that describe the underlying encoding processes. Typically, these are the processing rates for each stimulus. In some cases, the perceptual threshold t_0 can be estimated, too. Unlike the usual estimates of prior entry via PSS shifts, the TVA based-processing rates can be considered an absolute measure of the processing speed. This allows to decide to which degree acceleration of the attended stimulus occurred, and by which amount the unattended one was slowed down.

The Updated Meteorologist Story

> *It's the year 2030, and the location is Jupiter's ice moon Europa. To be exact, we are beneath a 100 km thick shield of ice in a small research submarine. The vessel is commanded by the meteorologist we met earlier in a weather station. She's quite a bit older and studies fluid dynamics of extraterrestrial oceans now. The main objective is to map the rare connections between the underground oceans and the surface. Her great talent for setting up efficient environment monitoring systems has earned her this great opportunity. The task is very challenging because the submarine's reactor provides quite limited power, and transmitting through all that ice and the atmosphere attenuates the signal drastically. From all the interesting events, it has to be selected which ones are sent out to mission control. But let's see how her system works. They just may have picked up an interesting eddy!*
>
> *Her chair—she managed to bring it from the weather station—squeaks as she turns 90 degrees to a control panel on the starboard side. In the corner of the screen, it reads, "report eddies, vortices, and whirlpools", the objective provided by mission control. Currents in many different locations have been measured today, not all of them may be important. Only mission control can put together the larger picture to see if they point to one of the long-sought connections to the surface. On the control panel, she draws virtual connections between the measurements and the submarine's transmission dishes. She connects half of all available transmission dishes to a single measurement that looks most promising to her. The remaining less interesting measurements are submitted through fewer dishes.*
>
> *Mission control has programmed their satellites in Earth and Europa orbits according to a scheme developed by our meteorologist when she was still on Earth. The trick is that the satellites*

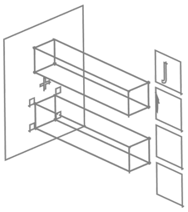
> *are tuned by mission control to invest more power in amplifying those signals that are of interest for mission control to complete the larger picture. Just now, the researchers get lucky. The many dishes submitting the promising measurement from the submarine and the beneficially tuned satellite repeaters lead to the important signal being picked out of the noise already after 40 minutes. It won't get much faster. Happily, mission control transmits back a message, sending the sub to a new location to visually confirm the discovered feature. They call in once more a few hours later, reporting that the other measurements got through now. They are not useless, but they are less interesting. Luckily, the important signal had a prior entry, and the sub is already halfway to its new location. The captain leans back in her old chair satisfied with the efficiency of the mission.*

The updated short story provides a TVA view on prior entry. In this view, the available resources—power and transmission dishes in the story—need to be coordinated in a fashion that ensures that the important information gets through. The challenge in this coordination is that mission control does not know what kind of measurements are being made at a certain time in the environment. The submarine has no information about which details mission control is interested in at a certain time to complete the larger picture. The information transfer is lossy and slow. So each side tries to set up the link in a way that it is beneficial for that information to pass through which they regard important. At the lower level, where the measurements are being made, this is done via filtering by the pertinence value. This conveys coarse information of the type "look for eddies, vortices, and whirlpools". The higher level, where the larger picture is constructed, sets up its channels to bias the transmission of information belonging to its report categories, for example, "turbulence with a main direction north-west and moderate speed". Consequently, important information is selected and categorized to provide a basis for reasoning about the next action to take.

In the story, less important information got through late. But obviously, in such a system when there are many different measurements, less important information may get lost because the link was cleared for the next update of new information, or because the target storage (VSTM) was filled up.

In this view, prior entry is an artifact of the competition of elements for VSTM encoding. There may be no important benefit due to prior entry making information available earlier. The real benefit might be that important information gets through when there is much competition, unlike in the experiments of this thesis, in which only few stimuli were shown.

Weiß (2012, p. 126) reasoned that posterior entry, a prior entry purely based on slowing down the unattended stimulus may serve the pur-



pose to shield the system from irrelevant information but at the same time keep time perception undistorted for the attended and action relevant target. In the experiments of this thesis, both facilitation and inhibition were found. The slowdown has usually a greater impact on the VSTM arrival times, in agreement with Weiß's reasoning.

6.2 REVISITING CENTRAL ASSUMPTIONS

Many of the inferences about how attention-altered stimulus encoding leads to prior entry are based on a novel model of TOJs, which was derived from the fundamental stimulus encoding model of TVA. When a model shows a certain internal consistency and good agreement with the data—which I believe is the case here[17]—one can get easily carried away with deriving ever more complex extensions based on the underlying theory, as exemplified by the model of cued TOJs in Manuscript C. This, of course, is just the purpose of a formal model based on simpler and better-understood processes. However, it also carries the dangers of leaving behind assumptions made in the core model that may need further investigation. Therefore, at this point, I highlight the most important assumptions, discuss their plausibility and point out possible alternatives.

The most important assumptions made by the model are that the order is determined by the VSTM entry time, and that the encoding into VSTM follows an exponential race model. The latter is a direct consequence of using TVA as the basis for the model (see Section 3), whereas the former is inherited from the ICM framework (see Section 4.3). Assuming the VSTM entry time as a basis for TOJs essentially means equating VSTM with the simple decision function in the ICM. In VSTM, probably more sophisticated processes could take place to generate a TOJ. The assumptions that it is a simple comparator for the entry times, and how the comparison could actually take place, will be discussed in the next section. Then follows the discussion of an alternative view in which the encoding order does not play a role for the TOJ. Presentation time stamps are evaluated instead. Discussing the VSTM as the place of order comparison is followed by a discussion of TVA's exponential race toward VSTM and a possible alternative.

6.2.1 *The "VSTM Comparator" Assumption*

No other theories of prior entry (see Section 4) make any assumptions about where the order comparison takes place, or in which structure, buffer, or memory a "prior entry" happens. The TVA-based approach

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[17] I was quite intrigued when after the first simulations of a TOJ based on TVA, with rates of the typical size, indeed psychometric functions characteristic for TOJs emerged. In retrospect, especially considering the similar model suggested by Alcalá-Quintana and García-Pérez (2013), this resemblance appears rather natural now.

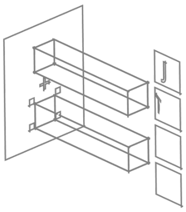
of this thesis suggests VSTM, as formalized by TVA, as the memory structure of interest. It is on the agenda for future work to test empirically whether it really is VSTM as understood by TVA where the order comparison takes place. Probably, VSTM could be filled up with other elements to see how much the TOJ is affected. If it is unaffected, a different short-term storage could be involved (the existence of many short-term storages was suggested, e.g., by Pashler, 1998, p. 329), or the mechanism could work on an entirely different basis. If it turns out that it is a different structure than TVA's VSTM at which TOJs are generated, the model would fall not much behind the other theories, because they make no assumption at all. However, it would invalidate the direct correspondence between the usual TVA processing speed parameters and TOJ-based estimates. At least at this point, there is little reason to doubt that TVA's VSTM is involved, especially because the estimated processing rates from the TOJ presented here and TVA-based studies that used letter reports are rather similar (see Tables 2 and 3 in Appendix B). The purpose of this section is not to suggest different loci or mechanisms for the order comparison, but to provide VSTM-based mechanisms of how the comparison could be conducted by the visual system.

Entry Time Stamps

A straightforward idea is the involvement of entry time stamps. Whenever a stimulus is successfully encoded into VSTM, it could be connected to an entry time stamp. This does not necessarily have to be an actual time stamp, it could also be any type of id that identifies the entry order. These time stamps could then be compared between VSTM representations when the order judgment is generated. Note that this concept is based on the VSTM *entry time* stamps and, therefore, the order judgment is connected to the encoding latencies. In Section 6.2.2 an alternative concept based on *presentation time* stamps is outlined, in which the information about the encoding latency is not reflected in its time stamp. Admittedly, the use of time stamps or ids appears overly symbolic. The VSTM is often conceptualized as an array of slots. Of course, this is a simplification of the assumed distributed neural structure. In the neural interpretation, the "VSTM system is conceived as a (*K*-winners-take-all) feedback mechanism that sustains activity in the neurons that have won the attentional competition" (Bundesen et al., 2005, p. 291). Therefore, further possible mechanisms that are less symbolic should be pointed out as well.

Triggered Sequential Recoding

It was proposed that after being encoded into VSTM, representations are recoded into another form of representation, such as auditory, motor, or amodal (A. Petersen et al., 2012). In the TOJ task, recoding the



VSTM content into a verbal representation, or some form of mentalese (Pinker, 1995), in which sequentiality carries meaning, seems useful.

Triggered sequential recoding is the idea that a finished VSTM representation (possibly after a consolidation process as suggested by W. X. Schneider, 2013) is transferred to a buffer in which sequentiality carries meaning. After the two targets are transcoded, the information "*X* appeared before *Y*" is available consciously. It can then be verbalized or transformed in any other form of report that is required.

Periodic Sequential Recoding

The concept of periodic sequential recoding is similar to that of triggered recoding. The difference is that the mere conclusion of a VSTM encoding process does not trigger the recoding. Instead, a periodic process samples VSTM and transcodes the representations found. This mechanism is a version of Sternberg and Knoll's (1973) periodic sampling proposal. Importantly, it can lead to non-deterministic decision functions. Suppose the periods are longer than the arrival time differences. Then, in one period VSTM would be empty and in the next already contain both targets, without information about their order. Whether this would happen depends on the sampling speed.

Turning VSTM Arrivals in TOJs: Deterministic vs. Non-Deterministic, Second-Order Attentional Facilitation

The first two proposals presented above represent a purely deterministic decision function. The third one can produce a non-deterministic decision function if sampling takes longer than the shortest arrival time differences. The former two versions can be augmented with non-determinacy, too: If for example entry time stamps have a certain minimal resolution, this would result in uncertainty and order reversals for smaller arrival time differences. Similarly, if sequentially triggered recodings have variance in their finishing times, non-determinacy would arise. Sometimes central distortions in psychometric functions of TOJs have been taken as evidence for non-deterministic decision function, and some degree of imprecision seems highly reasonable for a distributed systems such as the human brain. However, as demonstrated in Experiments 8 and 9, the patterns in the data are not necessarily produced by strong non-determinacy. They can also result from interactions between the targets before their encoding starts.

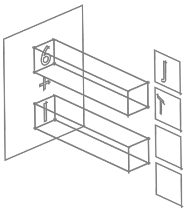
As the last point in the discussion of the possible mechanisms to turn VSTM entry times into TOJs, it should be noted that the recoding proposals generate room for what could be called second-level attentional influences on the order report.¸W. X. Schneider (2013) argued that only task relevant stimuli can benefit from protective maintenance for consolidation. It does not appear too much of a stretch that there could be gradual differences of the resources involved in recoding. Targets that attract more attention could be recoded faster than those receiving less attention. This would constitute a further influence that makes TOJs a less direct measure of the VSTM encoding latencies. It would distort the relation between rates estimated by TOJs and letter reports or other tasks. Therefore, it could potentially account for dissociations between TOJs and other tasks (such as known from simple reaction times), by imposing recoding to other representation forms for them that can occur at varying speeds.

In this section, I speculated about different forms of how the entry order to VSTM could be turned into TOJs and their implications. Most likely it would be difficult to distinguish between them empirically with TOJ experiments. For the time being, any of the mechanisms is acceptable. A question which seems of greater importance at this point is whether—and not how—VSTM entry time is the basis of TOJs.

6.2.2 *The "Time Attribute" Decision Mechanism Alternative*

One interesting alternative to generating TOJs on the basis of arrival times at a central comparator is the "time attribute" decision mechanism. Pashler (1998), for instance, mentions an alternative how observers generate their report on the timing of visual events (p. 261). The main idea is that stimulus representations could be marked with a time stamp that refers to the presentation time. Even though a target may not be identified very early in processing, the presentation time stamp could be carried through to the later stages and used in order judgments. This alternative mechanism is interesting because it can be cast into the framework of TVA. If it is the true mechanism by which TOJs are performed, it undermines the entire TVA-based TOJ model. In this alternative, the order judgment is not produced by comparing VSTM arrival times, but by comparing time stamp attributes encoded for the stimuli.

To demonstrate the concept of such a comparison, a quick TVA-based thought experiment in a somewhat different situation is helpful. Suppose we are not interested in the order of two stimuli, but in their color. The stimuli all have a similar purple hue in the range where red an blue meet on the color wheel. Now instead of judging which stimulus appeared first as in a TOJ, the observer performs the task of judging which stimulus is closer to a true red color. The shades of purple are all quite similar, and it is not known in advance which two levels are shown. Therefore simply tuning the selection criterion to a narrow color range does not seem to solve the problem. To compare the color, it is most likely required to encode candidates into VSTM for closer scrutinizing of their color, probably by linking the different color shades to color names. After some deliberation, the color response is generated.



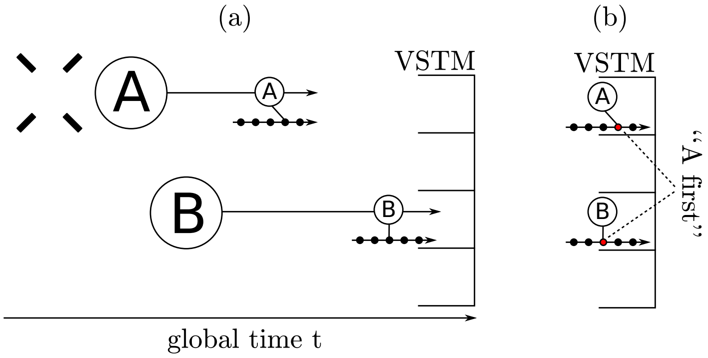


Figure 18: Visualization of the time attribute hypothesis of TOJs. (a) A hypothetical cue biases the evidence for "A" categorizations with a time attribute at an earlier time. Stimulus "B" has an unbiased time attribute and arrives earlier than "A". (b) If the TOJ is now formed on the basis of the encoded time attributes instead of the arrival order, prior entry appears in the report, even though the VSTM arrivals agree with the presentation order.

The time attribute hypothesize is simply the "time" version of this thought experiment. The selection criterion is adjusted to select stimuli with presentation times in the relevant range. The stimuli are then encoded into VSTM, where their time attributes are compared to produce the TOJ.

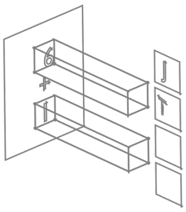
At this point, it is useful to recall that in TVA all possible stimulus categorizations race for VSTM entry. Typically, however, only the relevant stimuli have practically non-zero rates. If now attention alters the sensory evidence in favor of an earlier time attribute, the corresponding categorization is more likely to win the race. The situation is illustrated in Figure 18. Especially for a direct cue, it seems plausible that it could provide sensory evidence for an earlier point in time.

The time attribute hypothesis provides an alternative explanation for the dissociation between letter report and TOJ, and for the low TOJ performance reported in Manuscript *A*. Considering the low performance first, it could be caused by the masks whose presentation onset is varied independently of the SOA. It may smear out the evidence over multiple time points. Effectively the resources assigned to the correct time attribute categorization would be lowered. Moreover, several time attribute categorizations would have some resources. Therefore, processes would finish later and false time attributes would win the race more often. The dissociation was that letter report results were only moderately affected by a cue and to a similar degree at all COAs. In the time attribute view, for a TOJ the cue would increase the certainty of a particular time attribute, it would be more likely for it to win the race. Earlier cues may increase the evidence for earlier points in time, explaining the scaling. However, for the letter report task, the time attribute is irrelevant. An "*A* at time *X*" categorization is reported just as an "A", as is an "A at time Y" categorization. Consequently, the obscuring of the time attribute by the cue has no effect on the letter reports.

In this view, it would have to be explained how attention would modulate the evidence for something with a particular time attribute. As already mentioned, for a peripheral cue its onset signal could provide such evidence which is integrated with the subsequent target. For other attention manipulations, it is not as clear how the mechanism could work. Temporal effects of attention are usually thought to arise from increasing the attentional weight at specific locations and specific moments in time. This is on par with the view taken in the remainder of this thesis that attention leads to a relative speed advantage of the attended stimulus.

In the time attribute view, attention also leads to a relative speed advantage, but not of the probe compared to the reference. Instead, it provides an advantage for a particular categorization of the probe stimulus (see Figure 18). Whether and to which degree it could provide an additional boost relative to the reference is unclear. It is possible that genuine speedups relative to the reference increase the probability of encoding a particular categorization and that additionally this representation has a biased time stamp. That means that in TOJs performed by comparing time attributes in VSTM, both mechanisms could contribute to the effect. Investigating this is an important topic for future research because it determines the degree to which TOJs reflect the actual timing. In a TVA-based setting, a possible approach would be to treat time as other attributes. In a PR task, participants could be asked to report early but not late letters (or vice versa), just as they report red among blue ones in typical studies. If the α parameter behaves similarly for time attributes as for other attributes, for example when comparing different observers, this could be interpreted as support for a time attribute mechanism.

With the experiments presented in this thesis, it does not seem required to prefer the time attribute mechanism over the mechanism based on recognizing the VSTM entry order. However, the alternative should be kept in mind. Before closing this section, I would like to point out one more thought. For motivating the time attribute idea, I used a color-based thought experiment, because it seems more natural that an attribute such as color would be evaluated by comparison among VSTM representations. However, in this thought experiment, the task could be solved using prior entry, too. By setting the selection criterion to the highest degree of red, attentional weights would increase with the degree of redness, and so would the processing speed. Consequently, there would be a prior entry for objects which are redder. The task could then be solved by judging which stimulus entered VSTM first. Possibly in future experiments, promoting the



use of one or the other strategy—VSTM entry time or within-VSTM comparison—by instruction could help to shed light on the issue.

6.2.3 *Stimulus Encoding: Exponential Race vs. Drift Diffusion*

In addition to the assumption that the order comparison is based on the VSTM entry, the TVA-based TOJ includes the assumption that the arrival times at the VSTM follow a shifted exponential distribution. This follows directly from TVA's stimulus encoding model (see Section 4.6). Even though I am not aware of any formal challenge of TVA's encoding model in the literature, occasionally concerns are raised by anonymous reviewers and in discussions at conferences and other meetings. The essence of these concerns is the memoryless probabilistic nature of TVA's stimulus encoding. At constant hazard rates, stimuli can instantaneously be encoded into VSTM. This is in contrast with a common view that the visual system incrementally accumulates evidence until a threshold is passed and the corresponding mental event or action is triggered.

First, in defense of TVA's assumptions, it should be noted that the model enjoys great empirical support. It fits data from many paradigms. Especially impressive are the fits of WR and PR data. It can fit complex patterns from various different conditions with a minimum of parameters, all of them psychologically meaningful (Shibuya & Bundesen, 1988). Furthermore, NTVA shows how such arrival times can be generated by processes which plausibly model neurons as Poisson generators (Bundesen et al., 2005). Such neurons fire independently in exponentially distributed intervals and the collection of neurons, again, constitutes a Poisson process. TVA models can then be based on counting the Poisson events to describe the accrual of evidence for a certain categorization (e.g., see Kyllingsbæk et al., 2012). This indeed constitutes a form of incremental information accumulation and allows to model varying decision thresholds (see also the discussion of Experiment 2 in Tünnermann et al., 2015). An explorative study by Andersen and Kyllingsbæk (2012), which considered various alternative psychometric functions for the encoding processes, came to the conclusion that there is not much support for exchanging the current model for one of the alternatives in general.

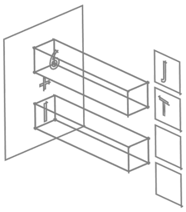
The main concept of this thesis was to enhance the traditional independent-channels model (see Section 4.3) with TVA as a formal model of the individual encoding processes. As mentioned above, exponentially distributed arrival times at the order comparator were imported. Even though occasionally challenged, the enjoy broad support. However, considering an alternative model for encoding processes that is hinged on the incremental accrual of information can be revealing as an alternative analysis of TOJs. Furthermore, investigating the similarities and differences between such a model and TVA's exponential model can possibly inform advances of TVA.

A full-fledged analysis of the two alternative views cannot be conducted in the scope of the discussion here. However, a brief sketch of how a variant of a DDM could be used as the basis for a TOJ model with incremental evidence accumulation is already very insightful (A DDM was already used successfully to resolve the dissociation between TOJ and RT by J. Miller & Schwarz, 2006).

DDMs are typically used in the analysis of reaction times and errors in two-alternative forced choice (2AFC) tasks (Ratcliff & Rouder, 1998; Wagenmakers, 2009). Even though reaction times play no central role in TOJs, a DDM is an interesting candidate for a model of stimulus encoding in the present framework. This is the case because, similar to TVA, it is a popular model applicable to various research questions. Further similarities are the psychologically meaningful parameters. In the form that is proposed here, the meanings of the parameters parallel the meanings of corresponding TVA parameters.

Usually, a DDM can be understood as a continuous version of a random walk which starts between two decision boundaries. The distance to the boundaries reflects the decision criterion, α. The starting point between the boundaries can be biased toward either boundary (parameter z). If the starting point is centered exactly between the decision boundaries, the observer has no apriori bias to either decision. The information accumulation is then represented by a drift rate v which models the average slope toward a decision boundaries. It is subject to random noise. Depending on the rate of drift relative to the noise and in relation to decision boundaries, the walk can reach the correct response boundary or the erroneous one. The process does not only determine the outcome, correct or wrong, but also the reaction time. Because of the drift and randomness, the boundaries can be reached at different times. Typically, a further parameter t_0, the no-decision time, is included in the model. It models additional additive components of the reaction time, such as ineffective exposure duration (as t_0 in TVA, see Section 3) or delays from motor components.

The model investigated here is illustrated in Figure 19. In contrast to the usual 2AFC DDM, only the upper boundary is checked, and drift rates are considered to be always positive. Random noise could lead to drift in the other direction, where the process would hit the lower boundary or even surpass it, but it will meet the upper boundary eventually. In unmasked and unspeeded TOJs, as used in this thesis, there is virtually no criterion to terminate the process other than with correct target encoding. Notably, each of the two stimuli is encoded by an independent diffusion process with a diffusion rate determined before the first process starts. In this sense, the model is a version of an independent-channels model. The influence of attention is assumed to alter the drift rates in advance. That is, even though a DDM allows



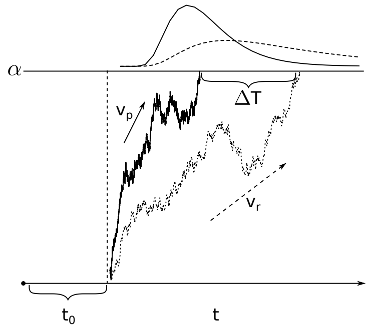


Figure 19: Two single-boundary drift diffusion processes for an SOA of zero, with equal non-decision times t_0. The processes evolve in time t. The solid trajectory represents the process associated with the attended stimulus. It progresses with the drift rate v_p. The dotted one describes the unattended stimulus, which progresses with v_r. The ΔT is the delay between the arrival times at the decision boundary α. The plotted curves above the decision boundary illustrate the arrival time distributions of the two diffusion processes.

for different decision thresholds, a starting point bias, and additional additive delays, these components are assumed to be unaffected, just as the analogous components in the TVA-based TOJ-model proposed in this thesis.

Another similarity to the TVA-based TOJ-model is that the actual order decision is deterministic, based on which of the two diffusion processes finishes first. Therefore, the role of exponential arrival time distribution in the TVA model is taken by DDM-based arrival time distributions in this model (see the distribution curves on top of Figure 19).

As a first approach to investigate similarities between the DDM- and TVA-based models, data was simulated with the diffusion model described above and subsequently fitted with the simple TVA-based TOJ model (see Section 4.6.3. The DDM arrival distributions were obtained via the *R* package *rtdists* (Brown, Gretton, Heathcote, & Singmann, 2014). The t_0 parameter was set to zero for both processes. The decision boundary α was set to one and the starting point z to 0.5. Because only the upper boundary was checked, z does not have the meaning of a bias here and only defines a starting point relative to α. Simulations were performed with different combinations of probe and reference drift rates, v_p^{DDM} and v_r^{DDM}, respectively. They were between 4 and 12 and either equal (neutral condition), or the rate of the probe was higher (attention condition), as shown in the lower left corners of the top-row panels in Figure 20. For each combination, 10000 trials were simulated at each of 80 SOAs over the relevant range. The simple TVA-based TOJ model was fitted to the data via maximum likelihood estimation.

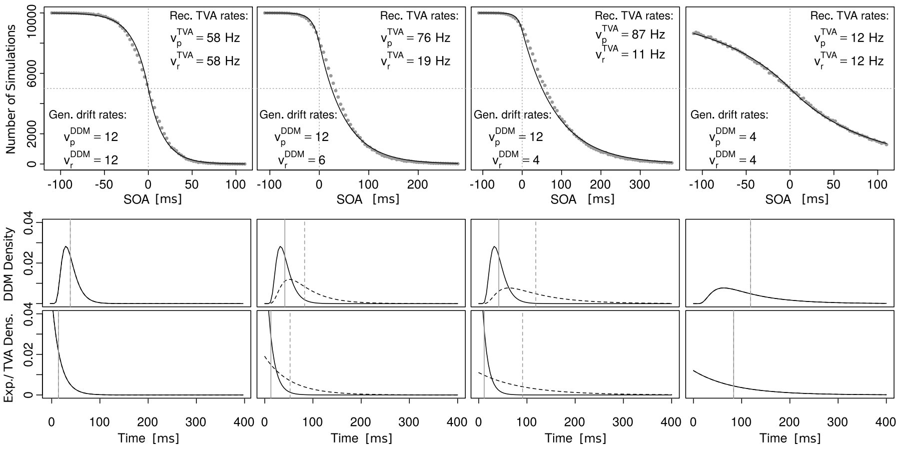
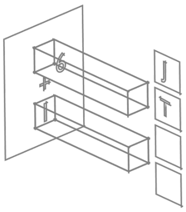


Figure 20: Simulations of TOJs based on a DDM fitted with the TVA-based approach. The top row shows simulated "probe first" counts and the TVA-based fit. The lower left corners of the panels contain the generating drift rates of probe, v_p^{DDM}, and reference, v_r^{DDM}. The upper right corners contain the fitted TVA processing rates of probe, v_p^{TVA}, and reference, v_r^{TVA}. The second row contain the DDM-based arrival time probability densities (probe = solid, reference = dashed). Vertical lines indicated the expected values. The bottom row contains the densities of TVA's exponential arrival time distributions.

The results of this computational experiment are interesting. Qualitatively, the DDM- and TVA-based approaches are very similar. The DDM version also produces asymmetric psychometric functions with shifts of the PSS resulting from differences in the two processing rates (see Figure 20, second and third panel). Differences in the diffusion rates were approximated by a similar (but not proportional) pattern of changes in TVA processing rates. The TVA-based TOJ model closely fitted DDM simulations. Small deviations are visible in conditions where the probe rate was higher than the reference rate. If these are real differences, that is, if they are not an artifact of the approximation procedure, they are probably so small that they would be hidden in noise in real data. The two lower rows of Figure 20 show arrival time distributions for both models with the corresponding parameters. The distance between their expected values (vertical lines) for probe and reference is highly similar, as is expected when the "probe first" probability is similar at SOA zero. Despite the fact that the diffusion rates were chosen rather arbitrarily (only making sure that they produce some S-shaped curve over a usual SOA range), the absolute positions of expected values on stimulus encoding time scales of both distributions are rather similar. The obtained TVA-based processing rates are, too, plausible with regard to typical rates in real data (see Table 3 in Appendix B).

Of course, simulating data with one model and closely fitting it with another one does not provide conclusive evidence that the mod-



els are the same. Neither do the slight deviations provide strong evidence that the models are not practically highly similar within certain parameter boundaries. It does also not provide any insight into which of the two models better describes actual experimental data, not to speak of the true underlying mechanisms. However, it is quite revealing that the models appear to behave very similar qualitatively, and that parameters have very similar interpretations. It would even be possible to apply the DDM-based model to address the question "does attention speed up the attended or slowdown the unattended stimulus?", a question central to this thesis. Most likely, the conclusion from drift rates would be the same as the one obtained consulting TVA parameters.

One conclusion about the similarity between both approaches that can be drawn at this point is that the models probably cannot be easily distinguished with moderate attention manipulations. Probably, the strong influence of peripheral cues, which is challenging at least for the TVA-based TOJ-model (see Manuscript C) could provide a suitable test case. Another possibility could be the use of masks and speeded responses in TOJs. This should introduce errors that should alter the shape of the DDM arrival times. The TVA-based TOJ model could then be extended to model such conditions, and both models could be compared.

To conclude this section, an alternative stimulus encoding model on the bases of a DDM seems possible. It remains unclear for now whether it would be an improvement in terms of creating a model close to the underlying processes. It seems, however, likely that both models make similar predictions about how attention leads to alteration in the perception of temporal order. On a final note, it is interesting that the arrival time distributions (see second row of Figure 20) look quite similar to Stelmach and Herdman's (1991) TIRFs in their TPM (see Section 4.4). A DDM could provide a formal basis to derive a consistent version of the TPM, avoiding the difficulties in the interpretation of the TIRFs.

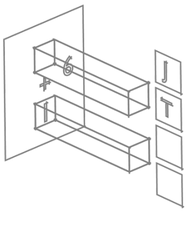
6.3 TVA IN SEQUENTIAL DISPLAYS: THE DYNAMICS OF RESOURCE DISTRIBUTION

The experiments presented in this thesis used different methods to manipulate attention in TOJs. Some (Experiments 1, 2, 5, 6, 7, 8) contained direct peripheral cues, whereas others included salience (Experiment 3, and experiments by Krüger et al., 2016, in preparation, which are not part of this thesis but use an extended version of the TVA-based TOJ model) and natural-scene layout manipulations (Experiment 4). Even though it may look as if direct cues and salience can be modeled similarly because of their exogenous nature, the same simple model was used for salience and natural-scene layout. The peripheral cueing experiments required a more complicated model, which was developed in Manuscript C. Its necessity originates from the fact that with a cue present, different encoding sequences can lead to "probe first" judgments. However, the influence of potentially different resource distributions in these sequences has only been considered crudely. For instance, it was modeled so that a stimulus which is shown before the cue can not already be influenced by it. It was assumed that as soon as an attention manipulation is present, the attentional weights are calculated. This means, the weights are determined in advance to the target presentation, whereas TVA usually assumes that the targets trigger the weight estimation. The in-advance weight estimation assumed here is briefly described in the next section. Subsequently, a novel approach for investigating the resource distribution by estimating many parameters from highly accurate data is described.

6.3.1 *In-Advance Weight Estimation*

The need for an assumption concerning the resource distribution originates from the fact that usually in TVA all stimuli are equipped with resources at the same time according to their attentional weights. This conception fits well for the usual experimental paradigms, WR and PR, which are typically used to obtain data for TVA-based analysis. The distribution of processing resources in paradigms with temporally distributed stimuli was discussed only recently by a few studies (e.g., A. Petersen et al., 2013; W. X. Schneider, 2013; Tünnermann et al., 2015) and cannot be considered fully understood.

Therefore, in this thesis, in the experiments in which the influence of attention is available before the targets are presented, in-advance weight estimation was assumed. Following TVA strictly—not making this assumption—would mean that when the first target is shown, all resources are assigned to it. Processing starts after t_0. No resources are then available for the second target. In a weaker form, such a mechanism explains the attentional dwell time phenomenon, where the presentation of the first target impairs the report of the second one (A. Petersen et al., 2013). According to the idea of in-advance weight estimation, the attentional weights are estimated as soon as the attention manipulation is present. For example, in the salience displays, the salient pattern was present before the targets flickered. Similarly, in the experiment with natural images, the scene layout which was expected to influence attention was visible before the targets appeared. So in this view, at the time point when the first target is shown, its processing resources are already determined and restricted—it will not grab all available resources—and it starts to race. From a formal perspective, this means that the weights are determined and normalized first and are not normalized before the race with respect to all



visible stimuli as usually assumed. Possibly, the weights would be modified if required by target attributes, for example, by the degree the sensory evidence matches the selection criterion.

For the types of attention manipulation mentioned above, the assumption of in-advance weight estimation seems reasonable, and the model provides good fits. When the displays become more complex with additional stimuli guiding attention, the assumption becomes unreasonable. If in a trial the COA is 50 ms, for example, and the SOA, is 100 ms, the cue is shown halfway between the reference and probe. That is, the reference, which is shown first, could not get its resources increased by the cue whereas the probe, which comes after both stimuli, could.

6.3.2 *Assessing the Dynamics of Resource Distribution*

For most of the experiments in this thesis that were fitted with the TVA-based TOJ-model, an in-advance weight estimation as described above was assumed. In some models, further reasonable assumptions have been made, for example in the model for cued TOJs, the reference stimulus cannot already be influenced by the cue when it is shown before the cue.

However, up to now, the distribution of processing resources in complex settings is not fully understood in TVA. In TOJs, the cue alters the processing rates of the targets (see Manuscript *C*). However, does the first target also act like a cue, dragging resources away from the second target? It could even remove resources from processing the cue. Will the cue get less effective then (as, e.g., suggested by Weiß et al., 2013)?

One approach for studying these difficult questions in the future might be to fit TVA-based TOJ models with many free parameters. The processing rates under different circumstances (e.g., reference preceding the cue, reference in between cue and target, etc.) could be estimated and compared.

Here I show an analysis of this kind for the two participants from Experiment 9 for whom the most repetitions are available, LS and JG (see Table 1 in Appendix B). The model is a version of the TVA-based model of cued TOJs described in Section 4.6.3. The equations are in the appendix of Tünnermann and Scharlau (in review), Manuscript *C*. As can be seen in the upper part of Figure 21, all rate parameters are now free to obtain individual values.

Importantly, before I discuss the outcome, a warning is in order. The complex model has 18 parameters which were fitted from 21 data points. It is highly under-determined, especially for the third case, $\text{SOA} > 0 \wedge \text{COA} < \text{SOA}$, in which six parameters are estimated from two data points. Especially in these parts, much of the rate estimates may originate from the prior information. For the main rate parameters, v_p and v_r, diffuse normal priors with a mean of 40 Hz and a standard deviation of 100 Hz were used. For the cue encoding rates, v_{cc} and v_{cp}, the priors had a mean of 5 Hz and a standard deviation of 10 Hz.

Another warning is needed because the model does not allow for the possibility of varying t_0 (see Manuscript C) or its suspected reset mechanism which was discussed in Sections 5.3 and Section 6.1.1 as a potential mechanism involved in the distribution of resources. Hence, despite its complexity, it is still a simplification.

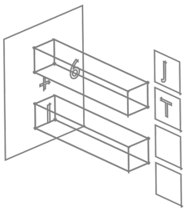
The model was fitted with the Stan package (Stan Development Team, 2016). The results are shown in Figure 21 and Figure 22. Many posterior distributions have wide 95 % HDIs indicated by the black bars in the figures which express the uncertainty. As warned above, inferences should be made with caution.

Probably the most prominent pattern concerning resource distributions is that the rates of the reference stimulus are rather low whenever it comes after the probe. Only if it precedes the probe, in the rightmost case, its rate is comparable to the probe.

The most intriguing feature of this tentative analysis can be seen in the psychometric function of JG shown at the bottom of Figure 22. The model predicts discontinuous jumps at the SOAs of 0 ms and 140 ms that separate the three cases. These discontinuities coincide with a very similar pattern in the data. The remainder of the predicted psychometric function and the data points is rather smooth. A similar pattern may be present in participant LS (see Figure 22). However, because of the high performance of this participant (steep psychometric function), it is difficult to see.

The smoothness within the sections and the jumps between them may provide a first clue where different resource distributions are present. It speaks for the case that the resources are not redistributed during the ongoing races. This is in accordance with the usual TVA assumptions. However, the resource distribution appears to depend on the relative order of the stimuli. That is, it makes a difference whether the reference appears at the end of the sequence, between cue and target, or as the first stimulus.

Future investigation of the resource distribution in sequential displays could proceed similarly to the approach presented here. It may be advisable to look at a simpler case first, for example, with no cue but a salience manipulation (e.g., see Experiment 3). Then only two cases need to be distinguished, but it would be still possible to determine whether the reference can interfere with the attention manipulation when it appears first (see Weiß et al., 2013). Moreover, the precision in the data should be improved by performing more repetitions and possibly reduce the SOA steps to 5 ms. The high precision experiments in this thesis aggregated raw data from many sessions. To account for changes in the psychometric function shapes caused by



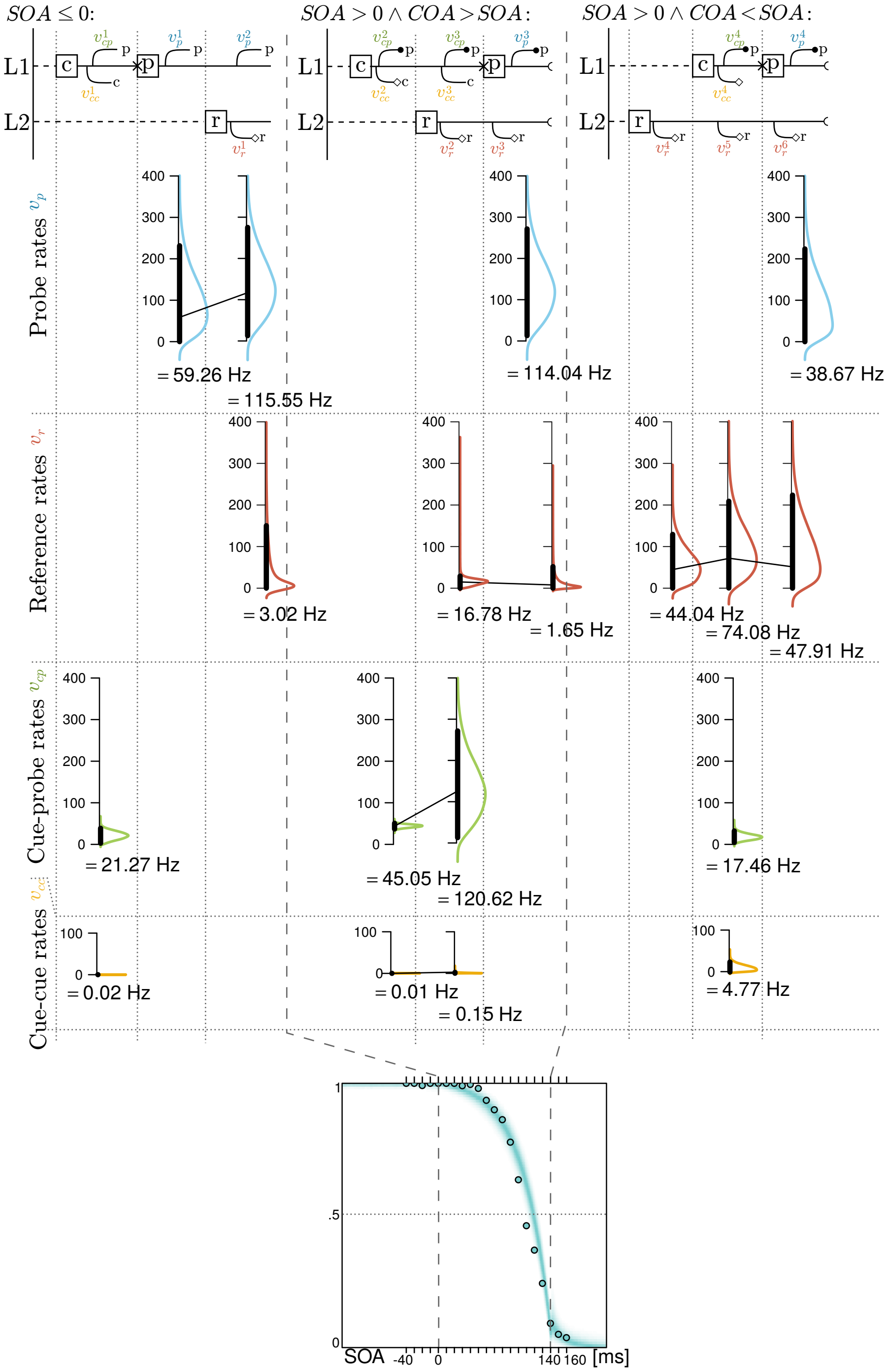


Figure 21: Fit with a TVA-based TOJ model with 18 free rate parameters of data set LS from Experiment 9. Black bars represent 95 % HDIs.

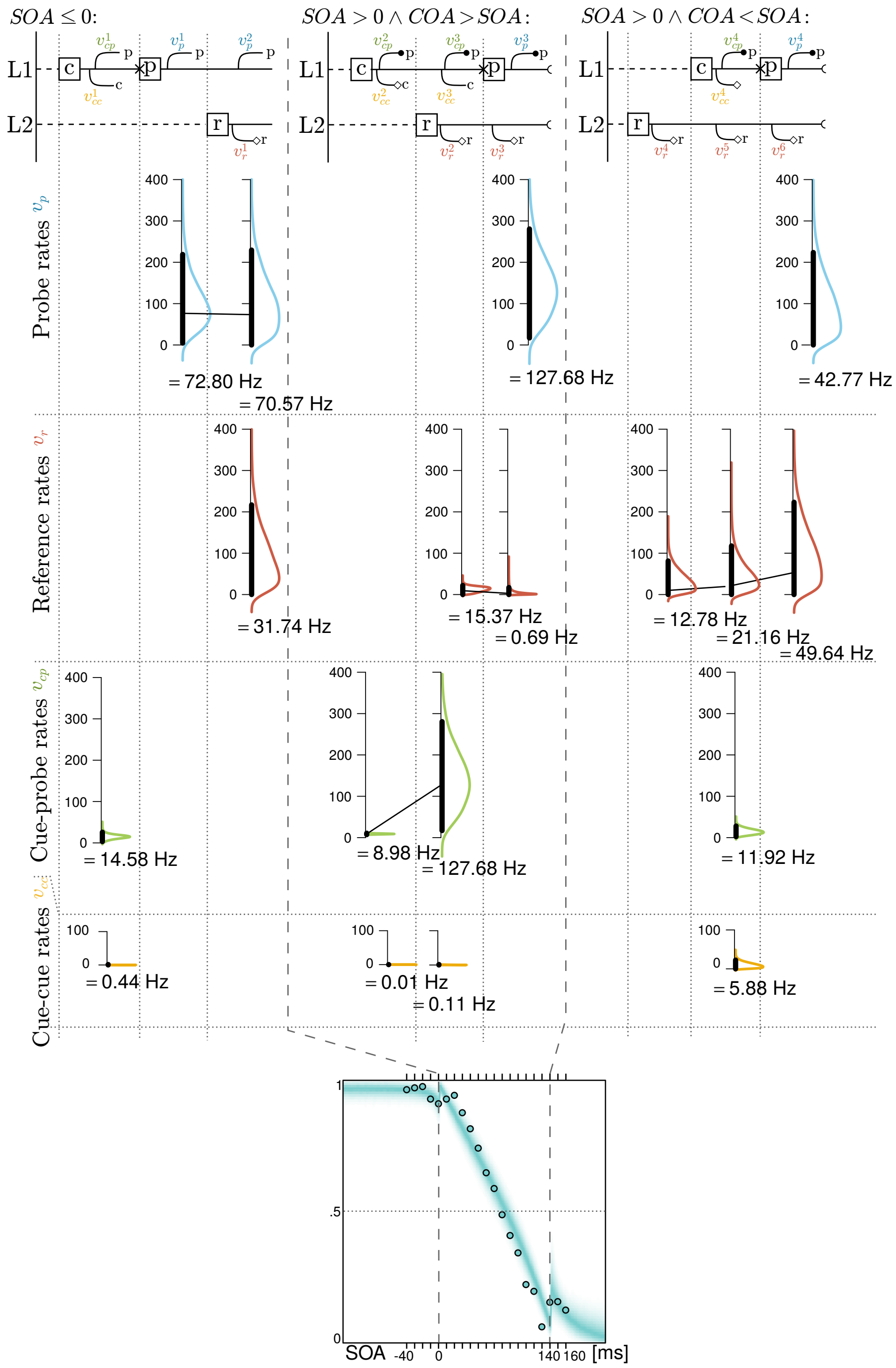
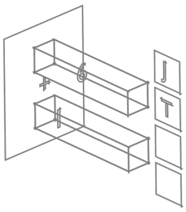


Figure 22: Fit with a TVA-based TOJ model with 18 free rate parameters of data set JG from Experiment 9. Black bars represent 95 % HDIs.



learning over sessions, a hierarchical approach could lead to further improvements in precision.

6.4 APPLICATIONS OF TOJS TO ESTIMATE TVA PARAMETERS

6.4.1 *TVA Parameters for Almost Arbitrary Stimuli*

As mentioned in Section 3.0.2, TVA is used in a wide range of clinical and fundamental research areas to estimate discrete components of the visual attention system. The prevailing tasks which are presented to observers are letter-report paradigms. WR and PR, as well as the *CombiTVA* paradigm (Vangkilde et al., 2011) are employed. These use letters or digits as targets and distractors. Any other stimulus material is practically impossible with these tasks. To establish a TVA-based item report paradigm with other stimulus material, one would need to make sure that (1) sufficient alternatives can be presented to counter the influence of guessing, and (2) that the stimuli can be masked effectively. Furthermore, (3) observers need to be able to report the identities and, (4) they need to do so efficiently so that a sufficient amount of trials can be presented. Requirements one and two impose constraints on the stimulus material. Three and four can only be achieved by extensive training of stimulus–response–key mappings. In short, using stimulus material different from letters or digits is not feasible with the usual item report methods.

In certain situations, it may be very useful to estimate TVA-parameters for stimuli other than letters and digits. For example, if one needs to measure how efficiently a certain type of stimulus is processed, TVA's processing rates would be highly useful. Additionally, for observers who cannot read and report letters or digits, such as children, animals, or patients with certain impairments of mental conditions, it may be helpful to work with other stimulus material.

The TVA-based TOJ model provides just this possibility. Because of the nature of the task with only two stimuli, TVA parameter K, the VSTM capacity, cannot be estimated. Similarly, with the simple TVA-based TOJ model, the perceptual threshold t_0 cannot be estimated.[18] Fortunately, the important processing speed parameter C and two attentional weights w_p and w_r can be estimated for almost arbitrary stimulus material with the TVA-based TOJ model developed in this thesis. It is neither necessary to train participants with stimulus–response-key mappings, nor to mask the targets after presentations.

Estimating these TVA parameters for very different stimulus types was exemplified in Experiments 3 and 4 of this thesis. In short, TOJs constitute a very simple task to estimate TVA parameters for almost arbitrary visual stimulus material. All targets are possible for which

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[18] However, see Experiments 8 and 9 for how this may be possible, given the model used there is correct.

the order can be judged. This method has already provided a framework for a new method to investigate visual salience (see Krüger et al., 2016, in preparation; Tünnermann et al., in review).

The simplicity of the TOJ task also enables its use it in animal perception research to conduct TVA-based analyses in this domain. This is demonstrated in the next section.

6.4.2 *TVA-Based TOJ Analysis in Animal Perception Studies*

Wada, Moizumi, and Kitazawa (2005) showed that it is possible to train mice to perform TOJs (see Wada, Higo, Moizumi, & Kitazawa, 2010, for an investigation of neural mechanisms involved in temporal-order perception based on this method). They trained mice to perform tactile TOJs, in which short air puffs were delivered to the left or right whiskers. The mice moved their heads after an additional go signal to indicate which air puff, left or right, was delivered first.

Wada et al. (2005) analyzed the results by fitting a psychometric function to collapsed data from all mice and estimated summary parameters. They found that mice perform at a weaker temporal resolution than humans in comparable tasks. Furthermore, the asymptotes of the psychometric functions reached neither zero or one, respectively. The PSS was strongly shifted by 133 ms, indicating that mice have a bias for judging "left first". They suggested that the weaker performance reflected in the lower asymptotes might result from underdeveloped—compared to humans—cognitive processes involved with the task execution. Alternatively, different signal convergence in the mouse primary sensory cortex could explain the lower asymptotes.

To explain the leftward bias in the responses, Wada et al. (2005) suggested lateralization of TOJs to the right hemisphere, where the majority of left-whisker signals converge. The shifted PSS could be explained interhemispheric conduction delays. Shifts consistent with such an explanation would, however, be as small as approximately 10 ms, so that they cannot explain the large 133 ms shift of the PSS (Wada et al., 2005).

A TVA-Based Analysis of Mouse Data TOJs

Can analysis based on a model which considers the encoding processes provide further insights? Wada et al. (2005) kindly provided their raw data so that I could fit it with the TVA-based TOJ model. TVA is a theory of visual attention. For the time being, I ignore this fact and use it as TWA, a theory of whiskers' attention. This is maybe not too far-fetched. The only assumption required is that the categorization latencies are exponentially distributed. This arrival time distribution was already used to model modalities other than vision, for example for auditory signals (Alcalá-Quintana & García-Pérez, 2013).

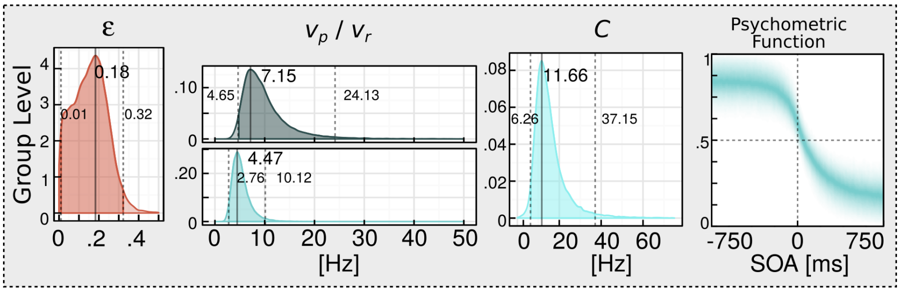


Figure 23: Group-level attention parameter estimates for mice TOJs from Wada et al. (2005). Lapse–error parameter ϵ; probe processing rate, v_p (dark shaded curves), and reference v_r (bright shaded curves); and overall processing rate C. Psychometric functions are posterior predictive simulations at fine grained SOAs with 100 repetitions.

I fitted the raw data with the simple TVA-based TOJ model described in Section 4.6.3. The model was extended to include an ϵ parameter for response errors (e.g., errors caused by lapses or in the response execution). This was done because, as already mentioned, Wada et al. (2005) observed that the psychometric functions in their analysis did not reach their usual asymptotes. García-Pérez and Alcalá-Quintana (2012b) suggest to include error parameters in such cases. Importantly, this parameter models the mismatch between the internal order perceptions and the observed judgments. Therefore, the processing rate estimates are still conform with TVA.

The estimation was performed in a hierarchical Bayesian procedure (see Kruschke & Vanpaemel, 2015), which yields subject-level and group-level estimates of the individual processing rates v_p and v_r, the overall processing rate C, and the error parameter ϵ.

The group-level estimates are shown in Figure 23. Note that for consistency with the other TOJs reported in this thesis, the raw data was converted to "probe first" judgments as defined in Chapter 4, with the left air puff being the probe stimulus.

On the group level, the TVA-based estimates show a processing speed advantage for the left stimulus ($v_p = 7.15\,\text{Hz}$) compared to the right stimulus ($v_r = 4.47\,\text{Hz}$; the lower boundary of the 95 % HDI on $v_p - v_r$ is at 0.35 Hz). This is in agreement with Wada et al.'s (2005) finding that mice have a leftward bias when performing TOJs. Also, the low discrimination performance is reflected in the TVA estimates. An estimate of $C = 11.16\,\text{Hz}$ corresponds to a performance roughly five to eight times lower than human performance in simple visual TOJs (see Table 3 in Appendix B). The group-level error parameter was estimated at 0.18.

Considering the expected values of the signal arrival times (see Equation 5) for the calculation of a potential interhemispheric conduction delay, this delay turns out to be 84 ms. It is smaller than Wada et al.'s (2005) PSS-based estimate of 133 ms, but still large compared

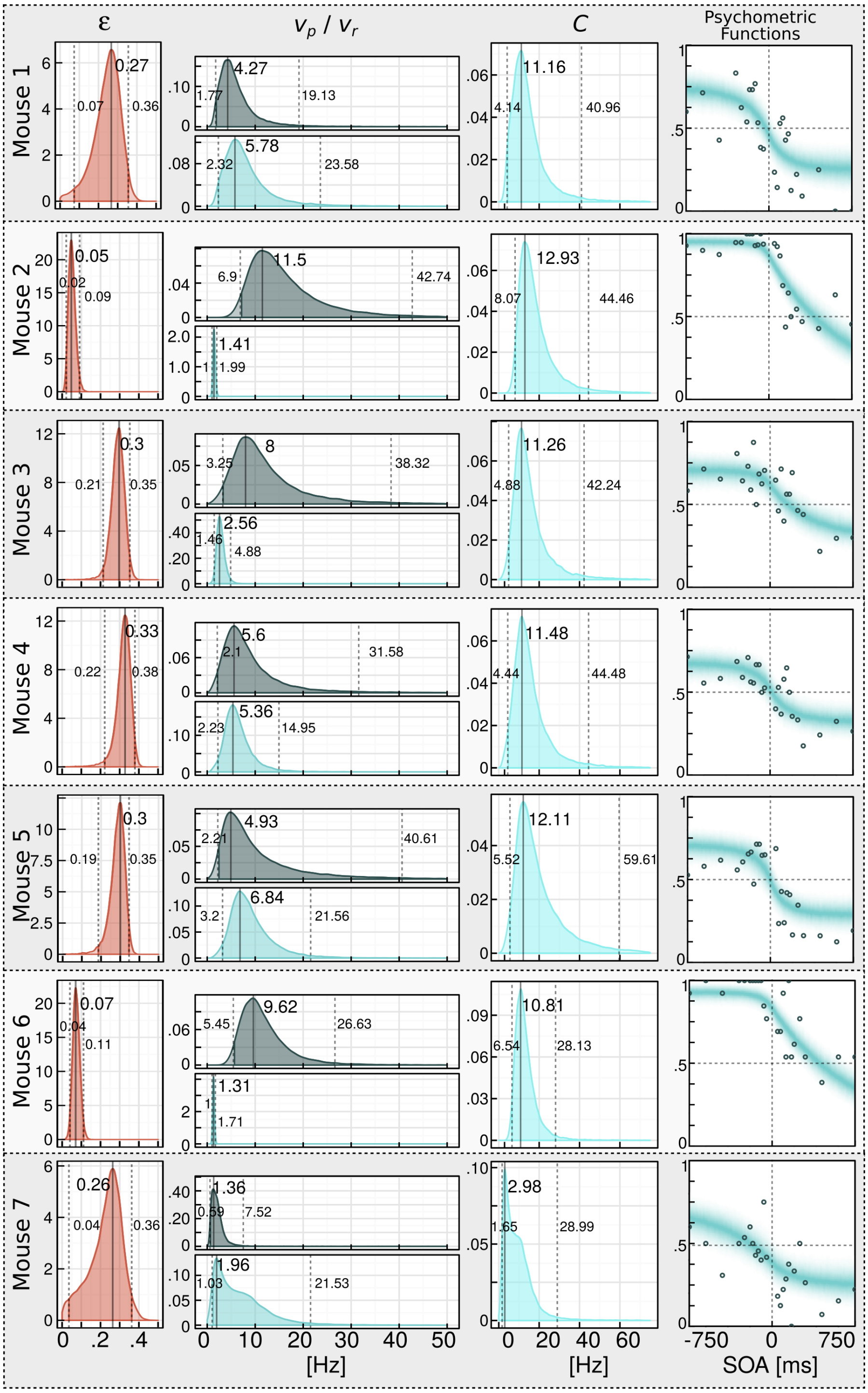
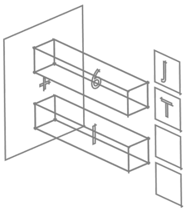


Figure 24: Subject-level attention parameter estimates for mice TOJs from Wada et al. (2005). Lapse–error parameter ϵ; probe processing rate, v_p (dark shaded curves), and reference v_r (bright shaded curves); and overall processing rate C. Psychometric functions are posterior predictive simulations at fine grained SOAs with 100 repetitions.



to the expected 10 ms. Furthermore, considering the subject-level estimates, it would be even larger than 400 ms for some mice that show a strong leftward bias (see Figure 24).

The subject-level analysis shows two interesting features. Strikingly, the overall processing rate C of approximately 12 Hz is highly similar in all mice (except for mouse 7, which shows strong peaks at very low values in the posterior density). This is true even when comparing mice that show a strong leftward bias of the processing rate (e.g., mouse 2) and mice with no bias (e.g., mouse 5).

The second interesting feature is the strong leftward biases in some mice (mice 2,3, and 6). These drive the smaller bias observed on the group-level.

Taken together, these observations provide a possible explanation for the leftward bias which is too large to be accounted for by interhemispheric conduction delay (Wada et al., 2005). The overall amount of available processing resources, captured in TVA parameter C, is similar in all mice. Some mice, however, may have learned a strategy, in which they devote as many resources as possible to the left stimulus. Normally, for instance in typical TOJs in humans, such a strategy is disadvantageous, and in principle it is disadvantageous for the mice, too. However, they already have a rather low performance which renders the disadvantage rather unimportant. Consider mouse 3 (see Figure 24) that employs the leftward-bias strategy. With these attentional parameters, it only gives the correct response in 57 % of the trials. If the mouse would distribute its processing resources equally (the optimal strategy), the performance would only increase to 61 %. If now the biasing strategy leads to a reduction of lapses or response errors, it would even be beneficial. Reducing ϵ to 0.05 for mouse 3 would increase its performance to 77 % correct. At least two of the three biased mice (2 and 6) show extremely low error parameters, hinting that this strategy may indeed decrease lapses or response errors.

This attentional bias strategy may explain the large size of the PSS shift. However, it remains unclear why the bias is toward the left side. It must be kept in mind that only three mice in the seven mice sample drive this effect. They could have assumed the leftward bias by chance because the explanation above works equally well with a rightward bias.

Alternatively, the small interhemispheric conduction delay discussed by Wada et al. (2005), which leads to a small leftward bias, could be the reason. This small bias could tip the system away from the neutral resource distribution, a local maximum, toward the leftward bias strategy, which is another local maximum because of the reduction of response errors. This theory could be tested by experimentally inducing an opposite PSS shift that is strong enough to counteract the interhemispheric delay and tip the system to the local maximum associated with a strong rightward bias strategy. In general, this theory predicts that gradual attention manipulations of different strengths will not lead to gradual changes in processing rates (or the PSSs). Instead, the system would be pushed into one of the strategic local maxima.

Conclusion of the TWA-Based Analysis

The interpretations above are speculative, mainly because they are based on a theory of visual attention in humans. Furthermore, I have not brought them into relation with the literature of attention in rodents. Nevertheless, as a proof-of-concept, the analysis shows that TVA-based TOJ analysis is possible for data from animal experiments. Because mice can perform other simple tasks that assess visual attention (e.g., see Bushnell & Strupp, 2009), it should be possible to train them to perform visual TOJs, similarly to how Wada et al. (2005) trained mice for whisker-based tactile TOJs. Then, their visual attention parameters could be directly compared to those obtained for humans or other animals able to perform TOJs.

Only recently, a typical animal paradigm for assessing rodent attention (i.e., the five-choice continuous performance task) has been discussed in the context of TVA (Fitzpatrick, in preparation). In the future, it may be interesting to compare result from this domain with TOJ-based analysis.

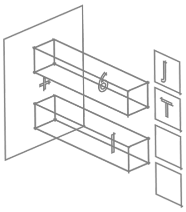
Finally, the analysis provided here highlights the advantage of using a hierarchical Bayesian framework. On the one hand, subject-level estimates inform each other via shrinkage toward the group-level estimates (e.g., Kruschke & Vanpaemel, 2015). This enables consistent subject-level fits even for such highly noisy data. On the other hand, the subject-level estimates revealed two different types of response strategies, which would have been obscured when fitting data averaged over subjects.

6.4.3 *TOJs in Dynamic Environments*

As mentioned above and demonstrated by the use in animal attention research, the TOJ task is rather simple. A further advantage of this simplicity is that the task can be integrated into dynamic environments, such as computer games.

In an interdisciplinary games engineering and psychology seminar at Paderborn University in 2015 and 2016, computer science students developed different games that integrated a TOJ task. One example is discussed here, and a resulting data set is analyzed with the TVA-based TOJ model.

Figure 25a shows a screenshot of a game implemented by Ngoc Chi Banh and Kyrill Uljanow. The space ship approaches rows of rocks which drift in space. At a certain distance, the intensity of one rock is



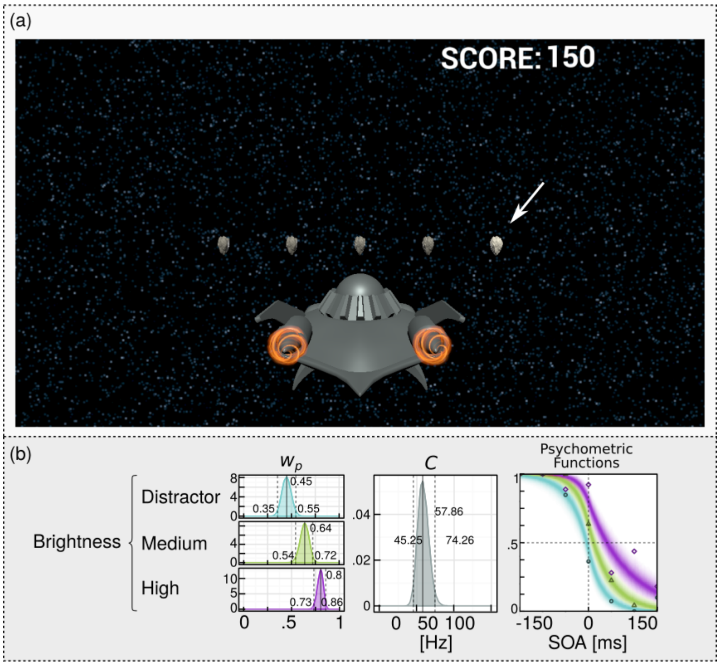


Figure 25: (a) Screenshot from the computer game. The white arrow highlights a high-intensity target. (b) Estimates of TVA-parameters and posterior predictive psychometric functions obtained with the TVA-based TOJ model.

increased, as shown in the screenshot (white arrow). Then, two rocks, probe (the brighter one) and reference, flicker with varying SOAs as in the salience experiment, Experiment 3. The SOAs −150, 100, 50, 0, 50, 100, and 150 ms were used.

The player's task is to maneuver the ship to collect the rock which flickered first. This provides a TOJ response. The intensity of the probe rock was varied over three levels: same intensity as the distractors, intermediate intensity, and high intensity (as shown in the image).

TVA parameter estimates are shown in Figure 25b. The estimates were obtained for a single player. The probe first responses from the 432 trials were fitted with a non-hierarchical version of the Bayesian model described in Manuscript *B*. Here, a common *C* parameter was used for all three intensity conditions. This was done because all conditions were highly similar so that no difference in *C* was expected and a more parsimonious model could be fitted to the relatively low number of trials.

The overall processing rate *C* was estimated at 57.26 Hz, a value in agreement with rates estimated in the other experiments (see Table 3 in Appendix B). The attentional weights increased with the stimulus intensity from 0.45 over 0.64 to 0.8. The neutral weight 0.5 is only included in the 95 % HDI of the neutral condition, in which the probe had the same intensity as the distractors.

It should be noted that in this experiment the weight increase is quite strong, compared to the one induced by color salience in Experiment 3. Most likely, this is because not only salience, the relative contrast, but also the absolute intensity was increased here.

The successful integration of a TOJ in a computer game, and the successful estimation of TVA-based processing speed parameters further highlights the high usability of TOJs in attention parameter estimation. Implementing TOJs in games could be a tool for increasing the motivation of participants in attention experiments.

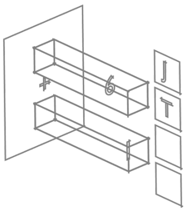
6.5 CONCLUSION

Section 6.1 summarized the results of this thesis. In short, it was found that attention indeed speeds up processing of attended stimuli and slows down unattended ones. This, and how the effects combine to varying degrees, was measured by a novel TVA-based model. Moreover, the complex mechanisms behind peripheral cues and how they affect TOJs have been uncovered using a refined version of this model in which the cue is considered a full stimulus and not just an influence. These advances became possible because the new model was built on a mathematical theory of visual attention, TVA. This allows to quantitatively describe the encoding of the individual stimuli of a TOJ display. Furthermore, the obtained parameters are meaningful in the TVA framework. They constitute processing rates in "items per second", which allows to compare them with estimates from other paradigms. The rates estimated in TOJs throughout the thesis are in agreement with those estimated in usual TVA (see Tables 2 and 3 in Appendix B). Therefore, the TOJ-based measurement of TVA parameters constitutes a promising tool for future research.

In the discussion that followed the summary at the start of this chapter, several aspects were discussed in detail, and many of these details lead to interesting questions for future research. VSTM as the location of the order comparison is not implausible, but far from proven, and interesting alternatives exist. Furthermore, the new model provides an alternative to the usual view that indeterminacy at the decision level leads to patterns typically observed in TOJ data.

Furthermore, TVA's exponential race as a basis for the encoding processes was contrasted with a view that information is accumulated incrementally as conceptualized with a DDM. These provide an interesting basis a for comparison of their concept of information uptake with TVA's. Possibly, they can also help link TVA, TOJs, and reaction times.

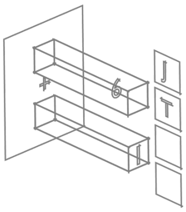
It was also discussed how the resource distribution for stimuli in TOJs is assumed to take place. An approach was suggested with which the resource distribution could be investigated in spatiotemporally



complex displays in future work. This has the potential to substantially advance TVA in this aspect.

Finally, the application in animal research and dynamic environments to estimate TVA processing speed parameters is a great advantage that follows from the simplicity of TOJs. With the method developed in this thesis, the domain in which TVA-based assessment can be applied was greatly enhanced.

LIST OF FIGURES

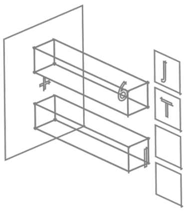


LIST OF TABLES

ACRONYMS

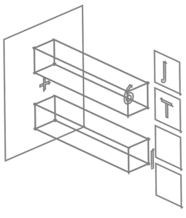
2AFC	two-alternative forced choice
AUM	asynchronous updating model
BIC	Bayesian information criterion
CLD	cue location displacement
COA	cue onset asynchrony
CPP	controlled parallel processing
DDM	drift diffusion model
DL	difference limen
GPS	global positioning system
HDI	highest density interval
ICM	independent-channels model
IOR	inhibition of return
LTM	long-term memory
NTVA	Neural Theory of Visual Attention
OC	order comparator
PR	partial report
PRM	Perceptual Retouch Model
PSS	point of subjective simultaneity
RT	reaction time

SC	simultaneity comparator
SJ	simultaneity judgment
SOA	stimulus onset asynchrony
STM	short-term memory
T1	target shown first
T2	target shown second
TIRF	temporal impulse response function
TOJ	temporal-order judgment
TPM	Temporal Profile Model
TRAM	Task-Driven Visual Attention and Working Memory
TTVA	Temporal Theory of Visual Attention
TVA	Theory of Visual Attention
TWA	Theory of Whiskers' Attention
VSTM	visual short-term memory
VWM	visual working memory
WR	whole report



Part II

APPENDIX TO THE SYNOPSIS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CONVERTING ARRIVAL LATENCIES TO TVA RATES

Hypothetical TVA processing rates can be calculated for data from paradigms that report perceptual latency increases ($L_{\text{inc.}}$) and reductions $L_{\text{red.}}$). This procedure can be handy when comparing TVA-based results with results from other studies, as in the discussion in Section 5.1 of this thesis. The necessary assumptions are that processing follows the exponential encoding model of TVA and that the overall processing capacity C is preserved under the attentional manipulation.

The relative prior entry $PE_{\text{rel.}}$ is the difference between the expected values of the reference and probe stimulus encoding times $E_{reference}$ and E_{probe}, which can be expressed as expected values of a neutral target encoding time and a latency increase $L_{inc.}$ or reduction $L_{red.}$, respectively:

$$\begin{aligned} PE_{\text{rel.}} &= E_{\text{reference}} - E_{\text{probe}} \\ E_{\text{probe}} &= E_{\text{neutral}} - L_{\text{red.}} \\ E_{\text{reference}} &= E_{\text{neutral}} + L_{\text{inc.}} \end{aligned} \tag{24}$$

The expected values E are inverses of the processing rates v, $1/v$ (see section 3).[19] Hence, combining the equations and replacing the E variables with $1/v$ yields

$$\begin{aligned} \frac{1}{v_{\text{neutral}}} - L_{\text{red.}} &= \frac{1}{v_{\text{neutral}} + v_{\text{ch}}} \\ \frac{1}{v_{\text{neutral}}} + L_{\text{inc.}} &= \frac{1}{v_{\text{neutral}} - v_{\text{ch}}}. \end{aligned} \tag{25}$$

This set of equations can be solved for v_{neutral} and the processing rate change $v_{\text{ch.}}$:

$$v_{\text{neutral}} = \frac{L_{\text{inc.}} - L_{\text{red.}}}{2 \cdot L_{\text{inc.}} \cdot L_{\text{red.}}}, \tag{26}$$

and

$$v_{\text{ch.}} = \frac{(L_{\text{inc.}} - L_{\text{red.}})^2}{2 \cdot L_{\text{inc.}} \cdot L_{\text{red.}} \cdot (L_{\text{inc.}} + L_{\text{red.}})}. \tag{27}$$

Based on these, $v_{\text{probe}} = v_{\text{neutral}} + v_{\text{ch.}}$ and $v_{\text{reference}} = v_{\text{neutral}} - v_{\text{ch.}}$ can be calculated.

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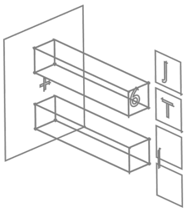
[19] Note that t_0 is ignored because typically adds an equal term to the expected values of the probe and reference stimuli in the neutral and the attention condition, which therefore cancels out.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LARGE TABLES

Table 1: SOA distribution and repetitions used in Experiment 9. SOA values in milliseconds.

SOAs(N):	-100	-90	-80	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
SOAs(A):	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160
LS	80	100	120	140	160	180	200	220	240	260	280	260	240	220	200	180	160	140	120	100	80
JG	56	70	84	98	112	126	140	154	168	182	196	182	168	154	140	126	112	98	84	70	56
HM	40	50	60	70	80	90	100	110	120	130	140	130	120	110	100	90	80	70	60	50	40
MG	40	50	60	70	80	90	100	110	120	130	140	130	120	110	100	90	80	70	60	50	40

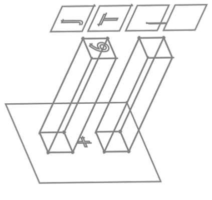
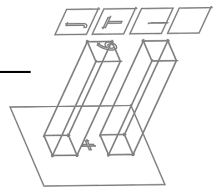


Table 2: TVA parameters estimated under different influences with common TVA tasks, WR, PR (WR+PR = intermixed), and *CombiTVA*. Models used in the estimations are labeled as "TVA-G" the generalized model by Dyrholm et al. (2011), "TVA" the earlier version as in Kyllingsbæk (2006). "TVA-?" indicates that the article did not identify which of the two models was used. †: C was estimated separately for the left and right part of the visual field. The values were averaged here. *: The values from this study have been approximated visually from their Figure 3 as integers (C and t_0) in 0.1 increments (K) and 0.05 increments (α), respectively.

Reported in	Tested Influence	Group (Condition)	Model	C (Hz)	t_0 (ms)	K	α
Ásgeirsson et al. (2015)	Grapheme-Color Synesthesia	Synesthetes (Congr.)	TVA-G	103.6	11.8	3.78	0.57
		Synesthetes (Incongr.)		83.8	12.7	3.55	0.53
		Control (Congr.)		91.69	9.35	2.23	0.45
		Control (Incongr.)		82.67	9.45	3.22	0.53
McAvinue et al. (2015)	Children with ADHD	ADHD	TVA-?	32.06	19.74	3.2	0.85
		Control		40.35	15.46	2.85	0.69
Caspersen and Habekost (2013)†	Children with Spina Bifida Myelomeningocele	SBM	TVA-G	36.9	25.7	2.4	0.82
		Control		43.85	17.2	3.1	0.42
Wilms et al. (2013)	Video Gaming	Experienced	TVA-G	70.2	19.1	3.73	0.59
		Causual		60.5	21.2	3.95	0.6
		Non-players		53.9	22	3.44	0.54
McAvinue et al. (2012)*	Change Across Lifespan	Children	TVA-?	46	20	2.8	0.75
		Teens		64	15	3.7	0.7
		20s		61	16	3.6	0.6
		30s		57	18	3.5	0.8
		40s		51	17	3.2	0.85
		50s		38	21	2.8	0.9
		60s		38	18	2.8	0.85
		70s		29	28	2.1	0.9
Vangkilde et al. (2011)	Nicotine Consumption	NS Placebo	TVA-?	70	15	3.3	0.47
		NS Nicotine		55	12	3.2	0.5
		Smokers		51	10	3.2	0.49
Finke et al. (2005)	Healthy Subjects	(Long Version)	TVA	24.48	NA	3.94	0.56
		(Short Version)		23.44	NA	3.85	0.64

Table 3: Estimates of TVA parameters in TOJs. "Facil." and "Inhib." are the facilitative and inhibitory contribution to prior entry, respectively. Negative values represent effects opposite the usual directions (attended facilitated, unattended inhibited). "PE" = prior entry. "*C* cons." indicates whether *C* remained constant with respect to the neutral condition, using a lenient 10 % allowed change threshold. †: In this estimate, 53.06 ms originate from the τ parameter, whereas the rate-based contribution was negative (-8.11). *: This cue was spatially displaced but still overlapping with the target. **: This cue was completely next to the target. Note that some values have been calculated on the basis of others, if they were not directly measured (e.g., calculating C as $v_p + v_r$) and that some parameters may have been fixed (e.g., when only a single neutral rate was estimated, it is listed here as two identical rates v_p and v_r.). For these details and uncertainties of the estimates refer to the original studies.

Reported in	Experiment	Stimuli	Task	Condition	Cue	Model	C (Hz)	v_p (Hz)	v_r (Hz)	w_p	PE (ms)	Facil.	Inhib.	C cons.
Tünnermann et al. (2015)	Exp. 1	Masked Letters	LR	Attention	100	TVA	57.36	34.7	22.66	0.60	15.31	4.87	10.44	Yes
				Neutral			59.36	29.68	29.68	0.50	0			
	Exp. 2 B. 1	Masked Letters	LR	Attention	50	TVA	63.77	32.86	30.91	0.52	1.92	1.85	0.07	Yes
				Neutral			61.96	30.98	30.98	0.5	0			
	Exp. 2 B. 2	Masked Letters	LR	Attention	100	TVA	58.53	35.58	22.95	0.61	15.47	3.61	11.86	Yes
				Neutral			63.06	31.53	31.53	0.5	0			
	Exp. 2 B. 3	Masked Letters	LR	Attention	200	TVA	58.16	34.33	23.83	0.59	12.83	4.35	8.49	Yes
				Neutral			59.74	29.87	29.87	0.5	0			
Tünnermann et al. (in review)	Exp. 1	Col. Salience Flicker	TOJ	Attention		simple	67.11	41.06	27.16	0.59	12.46	-1.12	13.69	Yes
				Neutral			85.79	43.04	43.23	0.5	-0.1			
	Exp. 2	Natural Images	TOJ	Action		simple	64.94	33.54	30.96	0.52	2.48	0.12	-2.34	No
				(Neutral)			62.32	33.4	28.87	0.54	4.7			
	Exp. 3	Cued Letters	TOJ	Attention	110	simple+τ	65.07	28.32	36.76	0.42	44.95†	-2.37	-5.73	Yes
				Neutral			60.79	30.36	30.36	0.5	0			
Krüger et al. (2016)	Exp. 1	Ori. Salience Onset	TOJ	Attention		simple	49.7	25.1	24.6	0.49	0.81	1.14	-2.45	Yes
				Neutral			47.6	24.4	23.2	0.51	2.12			
	Exp. 2	Ori. Salience Offset	TOJ	Attention		simple	55.2	23.4	31.8	0.39	-11.29	-11.09	-3.4	Yes
				Neutral			60.3	31.6	28.7	0.52	3.2			
	Exp. 3	Ori. Salience Flicker	TOJ	Attention		simple	40.7	27.5	13.2	0.64	39.39	12.18	20.48	Yes
				Neutral			38.69	20.6	18.09	0.53	6.74			
	Exp. 4	Lum. Salience Flicker	TOJ	Attention		simple	32	18.7	13.3	0.58	21.71	1.17	16.71	Yes
				Neutral			35.4	18.3	17.1	0.52	3.83			
Tünnermann and Scharlau (in review)	Exp. 1	Letters	TOJ	Attention	40	cp-cc	72.39	36.97	35.42	0.51	1.18	8.61	-7.43	No
				Attention	80		83.95	56.29	27.66	0.67	18.39	17.90	0.49	
				Attention	140		132.43	32.54	99.89	0.25	-20.72	4.93	-25.65	
				Neutral			56.08	28.04	28.04	0.5	0.00			
	Exp. 2	Letters	TOJ	Attention	80	cp-cc	128.75	99.76	28.99	0.77	24.47	23.23	1.24	No
				Attention	80 *		92.95	59.59	33.36	0.64	13.19	16.47	-3.28	
				Attention	80 **		72.26	36.11	36.15	0.5	-0.03	5.56	-5.59	
				Neutral			60.14	30.07	30.07	0.5	0.00			



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ZUSAMMENFASSUNG AUF DEUTSCH (GERMAN SUMMARY)

ÜBER DIE ENTSTEHUNG WAHRGENOMMENER ZEITLICHER REIHENFOLGE

Die Wahrnehmung zeitlicher Reihenfolge ist ein ausgesprochen interessantes Thema. In der Wahrnehmungspsychologie wird sie bereits seit weit über hundert Jahren experimentell untersucht. Dennoch sind wichtige Fragen noch immer unbeantwortet. Die vorliegende Arbeit beantwortet einige von diesen mit einer neuen Methode, die auf einem quantitativen Aufmerksamkeitsmodell beruht. Zunächst soll die Frage zeitlicher Reihenfolgen jedoch allgemein in den Blick genommen werden. Warum ist dieses Thema, das doch von allereinfachster Art zu sein scheint, so interessant?

Zeitliche Reihenfolge kann auf drei Ebenen betrachtet werden, die der externen, internen und konsensuellen Realität (Tegmark, 2014). Die externe Realität, eine mathematisch und ultimativ physikalische Wirklichkeit, existiert unabhängig jeglicher Beobachtung. Die interne Realität ist die subjektive Wahrnehmung der externen Wirklichkeit und die konsensuelle Realität eine gemeinsam anerkannte Beschreibung dieser.

Laut Tegmark (2014) besteht die Herausforderung für die Physik darin, eine konsensuelle Realität aus der externen abzuleiten. In der Psychologie und den Neurowissenschaften besteht sie hingegen darin, von konsensueller Realität auf interne zu schließen. Im Zusammenhang mit zeitlicher Reihenfolge kann gesagt werden, dass diese beiden Herausforderungen, so simpel sie zunächst erscheinen mögen, verblüffende Parallelen aufweisen.

Normalerweise bezweifeln wir nicht, dass zwei Personen dieselbe zeitliche Reihenfolge wahrnehmen. Es erscheint inhärent klar, dass es für zwei zeitlich getrennte Ereignisse eine eindeutig definierte zeitliche Reihenfolge gibt, die jeder Person durch einfache Beobachtung zugänglich ist und über welche sich alle Beobachtenden einig sind. Werden jedoch extreme Fälle betrachtet, kann gezeigt werden, dass dies nicht so ist. Für zwei Individuen, die sich mit substantiellen Bruchteilen der Lichtgeschwindigkeit relativ zueinander bewegen, können sich zwei Ereignisse in unterschiedlicher Reihenfolge ereignen. Es bedarf Einsteins spezieller Relativitätstheorie, um nun eine konsensuelle Realität zu finden.

Ein ähnlicher Extremfall in der Wahrnehmung zeitlicher Reihenfolge ist der “Prior-Entry”-Effekt. Der “frühere Eintritt”, dem der Effekt seinen Namen verdankt, bezieht sich auf das Bewusstsein des Betrachters. Der Effekt tritt zum Beispiel dann auf, wenn einem Reiz selektiv Aufmerksamkeit zugewendet wird. Er wird dann früher bewusst als ein unbeachteter Reiz (Titchener, 1908). Theorien selektiver Aufmerksamkeit werden benötigt, um eine konsensuelle Realität zu etablieren. Vorherrschende Theorien hierzu sind interessanterweise meist quantitativ unpräzise. Sie treffen eher qualitative Vorhersagen, welche dann im Zusammenhang mit Messungen diskutiert werden. Ziel der vorliegenden Arbeit ist es, eine präzise Theorie zu entwickeln, die wesentliche offene Fragen zur Wahrnehmung zeitlicher Reihenfolge beantwortet.

Die Arbeit ist zweifelsfrei der Grundlagenforschung zuzuordnen. Wie später gezeigt wird, gibt es zwar einige direkte praktische Anwendungen in der Messung visueller Aufmerksamkeit, jedoch steht der Ausbau einer prospektiv umfassenden Aufmerksamkeitstheorie im Vordergrund. Warum diese Entwicklung wichtig ist, wird deutlich, wenn wir uns wieder dem Beispiel der physikalischen Reihenfolge zuwenden. Die Fortschritte der relativistischen Physik, die großteils in der ersten Hälfte des letzten Jahrhunderts erreicht wurden, schienen zunächst von rein theoretischer Bedeutung zu sein. In der zweiten Hälfte des Jahrhunderts zeigte sich jedoch ihre enorme Bedeutung für praktische Anwendungen. Ein Beispiel ist das Global Positioning System (GPS), welches ohne die Korrekturen relativistischer Effekte in den Signallaufzeiten unmöglich wäre.

Ähnlich kann man sich vorstellen, dass ein akkurates Verständnis selektiver Aufmerksamkeit und ihres Einflusses auf die Wahrnehmung zeitlicher Reihenfolge in Zukunft praktisch relevant wird, obwohl die Effekte sich im Millisekundenbereich abspielen. Zum Beispiel könnten komplexe Fahrerassistenzsysteme die Anzeige virtueller Warnsymbole genau so koordinieren, dass diese hilfreich und nicht ablenkend wirken, was in einer kritischen Situation von größter Bedeutung sein könnte.

wahrnehmung zeitlicher reihenfolge: ein ergebnis von selektion durch aufmerksamkeit?

Der Titel dieser Arbeit ist ein Wortspiel mit dem Titel von Charles Darwins Buch über die Entstehung der Arten. Jedoch geht es hier um die Entstehung eines Wahrnehmungseindrucks der zeitlichen Reihenfolge von visuellen Reizen. Der Titel impliziert, dass ein solcher Eindruck durch Selektion, die wiederum durch Aufmerksamkeit bedingt ist, entsteht. Inwieweit ist diese Implikation gerechtfertigt? Im Alltag gibt es viele Situationen, zum Beispiel die Ankunftszeiten von zwei Bussen, deren wahrgenommene Reihenfolge nicht von der Aufmerksamkeitsausrichtung abhängt. Auch im Millisekundenbereich kann die Reihenfolge eindeutig sein. Ein Reiz, der 400 ms vor einem anderen in der selben Modalität dargeboten wird, wird von normalen Personen zweifelsfrei als "zuerst" berichtet. Der im vorherigen Abschnitt angesprochene Prior-Entry-Effekt verändert den Wahrnehmungseindruck nur bei noch kleineren Zeitabständen (200 ms und kleiner).

Das in dieser Arbeit entwickelte Modell der Wahrnehmung zeitlicher Reihenfolge basiert auf einer mathematischen Theorie der basalen Informationsverarbeitungsprozesse und der Art, wie diese von Aufmerksamkeit beeinflusst werden. Im Gegensatz zu anderen Ansätzen (z. B. sogenannte Spotlight- und Zoom-Lens-Modelle, siehe C. W. Eriksen & St James, 1986) versteht diese Theorie Aufmerksamkeit nicht als einen von einem Homunculus gelenkten Suchscheinwerfer. Vielmehr sind die Effekte, die wir beobachten und mit dem Begriff Aufmerksamkeit bezeichnen, in diesem Ansatz emergente Phänomene, die sich aus dem Zusammenspiel der Verteilung von Verarbeitungsressourcen und dem Wettbewerb der Reize um einen Platz im visuellen Kurzzeitgedächtnis ergeben. Das Modell ist jedoch nicht auf die spezielle Situation kurzer Zeitabstände zwischen zwei Ereignissen bei gleichzeitiger Aufmerksamkeitsverlagerung beschränkt. Somit kann gesagt werden, dass diese Aufmerksamkeitstheorie die Wahrnehmung von zeitlicher Reihenfolge im Allgemeinen beschreibt, inklusive der wenig interessanten Fälle mit großen Zeitabständen und ohne Aufmerksamkeitsverlagerungen.

Im Folgenden wird auf bislang unbeantwortete Fragen zu Prior Entry eingegangen. Die Fragen und ihre Wichtigkeit sollen kurz erläutert werden, um die Erforderlichkeit der weiteren Forschung zu Prior Entry und der Wahrnehmung zeitlicher Reihenfolge zu verdeutlichen, obwohl das Thema schon seit weit über 100 Jahren erforscht wird.

PRIOR ENTRY UND NOCH OFFENE FRAGEN

Prior Entry, TOJs und deren Relativität

Das bereits oben erwähnte Prior-Entry-Phänomen ist von zentraler Bedeutung für die vorliegende Arbeit. Während die Erforschung von Prior Entry ihren Ursprung im audiovisuellen Bereich hat, wo beispielsweise gemessen wurde (und wird), wie viel früher ein visueller Reiz gezeigt werden muss, damit er als gleichzeitig zu einem auditiven wahrgenommen wird (Titchener, 1908; Zampini et al., 2005), geht es in der vorliegenden Arbeit um Prior Entry in der visuellen Modalität und seine Messung durch Beurteilung der zeitlichen Reihenfolge von zwei kurz aufeinanderfolgenden Reizen (Temporal Order Judgment, TOJ). In diesem Paradigma werden typischerweise zwei Reize dargeboten, deren Zeitabstand von Durchgang zu Durchgang variiert. Die Probanden beurteilen, welcher der Reize als erstes (oder als zweites) gezeigt wurde. Wird nun Aufmerksamkeit auf einen der

Reize, im Folgenden "Sondierreiz", gelenkt, wird dieser als früher wahrgenommen und die Verteilung der Urteile verschiebt sich zu seinem Gunsten (Shore et al., 2001). Ohne Aufmerksamkeitsmanipulation werden zur Hälfte "Sondierreiz zuerst"-Urteile abgegeben, wenn der Zeitabstand zwischen den Reizen (Stimulus Onset Asynchrony, SOA) null ist. Dieses SOA, an dem beide möglichen Urteile gleich häufig sind, wird als Punkt subjektiver Gleichzeitigkeit (Point of Subjective Simultaneity, PSS) bezeichnet. Unter dem Einfluss einer Aufmerksamkeitsverlagerung verschiebt sich der PSS. Diese Verschiebung gilt als Maß von Prior Entry.

Häufig wird Prior Entry durch die, meist implizite und, wie die vorliegende Arbeit zeigt, nicht immer gerechtfertigte Annahme, dass Aufmerksamkeit die Verarbeitung des beachteten Reizes beschleunigt erklärt. Wie oben beschrieben bilden TOJs die experimentelle Grundlage fast der gesamten Prior-Entry-Forschung. Sie erlauben jedoch nur Aussagen über relative Geschwindigkeiten. Das heißt, Prior Entry im TOJ könnte durch Beschleunigung des beachteten, Verlangsamung des unbeachteten Reizes oder durch eine Kombination von beidem entstehen ohne dass in der Verschiebung des PSS erkennbar wäre, welche diese Alternativen zutrifft.

Die Frage nach der Verarbeitungsgeschwindigkeit

Wie im vorherigen Abschnitt schon angedeutet, ist zu klären, ob Prior Entry durch beschleunigte Verarbeitung des beachteten Reizes entsteht. Alternativen, die bis vor kurzem weitgehend ignoriert wurden, sind die Verlangsamung des unbeachteten Reizes oder eine Kombination aus Beschleunigung und Verlangsamung (Weiß et al., 2013). Diese Frage wird in dieser Arbeit hauptsächlich in Manuskript *A* und Manuskript *B* adressiert.

Die Frage nach dem peripheren Hinweisreiz

Periphere Hinweisreize werden direkt am Ort eines Zielreizes vor dessen Präsentation eingeblendet. In TOJs führen sie zu robusten und oft großen Verschiebungen des PSS (Scharlau & Neumann, 2003a; Shore et al., 2001). Fraglich ist, ob allein Aufmerksamkeit an diesen Verschiebungen beteiligt ist (Spence & Parise, 2010). Vermuten lässt sich zum Beispiel auch, dass von Aufmerksamkeit unabhängige Komponenten am Effekt beteiligt sind, wie zum Beispiel die Verwechslung von Hinweis- und Zielreizeigenschaften (K. A. Schneider, 2001). Der grundsätzlichen Frage, wie sich ein peripherer Hinweisreiz auswirkt auf verschiedene Prozesse und wie diese zu (vermeintlichen) Aufmerksamkeitseffekten beitragen, widmet sich Manuskript *C*.

Entscheidungsregeln

Eine weitere Frage, die geklärt werden muss, um das Phänomen des Prior Entry zu verstehen, betrifft Entscheidungsregeln in TOJs. Solche Entscheidungsregeln bilden ein Modell der Prozesse, die die Ankunftszeiten der verarbeiteten Reize in einem zentralen Vergleichssystem auswerten und daraus das dann tatsächlich geäußerte Reihenfolgeurteil bilden. Deterministische Entscheidungsregeln generieren Reihenfolgeurteile, die direkt mit den Ankunftszeiten übereinstimmen. Nicht-deterministische Regeln erlauben einen Bereich, in dem die zeitliche Reihenfolge nicht weiter aufgelöst werden kann und ein zufälliges Urteil oder ein "gleichzeitig"-Urteil generiert wird (wenn die Aufgabe dies zulässt). Solche Entscheidungsregeln werden mit bestimmten Merkmalen im Verlauf der Reihenfolgeurteile über die SOAs in Verbindung gebracht. Die vorliegende Arbeit demonstriert, dass die selben Merkmale auch aus deterministischen Entscheidungsregeln folgen können.

Können mit TOJs bedeutungsvolle Aufmerksamkeitsparameter gemessen werden?

Wie oben beschrieben, ist der PSS als zentraler Aufmerksamkeitsparameter üblicher TOJ-Analysen nicht unproblematisch. In dieser Arbeit werden TOJs mit der mathematischen Aufmerksamkeitstheorie TVA (Theory of Visual Attention, Bundesen, 1990) modelliert. Die TVA umfasst gut interpretierbare Parameter des Aufmerksamkeitssystems, wie zum Beispiel die Verarbeitungsgeschwindigkeit und die Aufmerksamkeitsgewichte sowie die VSTM-Kapazität. Daher stellt sich die Frage, ob diese mithilfe von TOJs bestimmt werden können. Diese Frage wird in der allgemeinen Diskussion im späteren Teil der Arbeit behandelt.

AUFMERKSAMKEIT UND DIE WAHRNEHMUNG ZEITLICHER REIHENFOLGE

Unter anderem werden im zweiten Kapitel der vorliegenden Arbeit klassische Theorien und Befunde zum Thema Aufmerksamkeit vorgestellt. Ein Schwerpunkt ist die Diskussion der Fragen, wann die Selektion beachteter Reize stattfindet und wie weit unbeachtete Reize verarbeitet werden. Erste Theorien nahmen an dass Selektion sehr früh auf Basis einfacher Reizeigenschaften stattfindet (Broadbent, 1958), oder dass sie sehr spät nach inhaltlicher Analyse der Reize stattfindet (Deutsch & Deutsch, 1963). Später wurden weniger extreme Theorien entwickelt, die eine teilweise frühe Selektion und anschließende parallele Verarbeitung beinhalten (Pashler, 1998, pp. 217). Diesen Theorien fehlt jedoch eine genaue Beschreibung, welche Mechanismen den

Selektionsprozessen und der parallelen Verarbeitung zugrunde liegen.

TVA - EINE MATHEMATISCHE AUFMERKSAMKEITSTHEORIE

Wie bereits erwähnt, wird in dieser Arbeit Bundesens 1990 TVA verwendet. Diese Theorie beschreibt mathematisch die Enkodierung visueller Reize. Werden Reize präsentiert, nehmen sie der TVA zufolge an einem Wettlauf um einen Platz im VSTM teil. Die Ankunftszeiten der Reize im VSTM sind exponentialverteilt. Üblicherweise finden im VSTM drei bis vier Reize Platz (TVA-Parameter K).

Die Wahrscheinlichkeit $F(t)$, dass ein einzelner Reiz bis zu einem bestimmten Zeitpunkt t im VSTM ankommt ist durch die folgende Gleichung gegeben:

$$F(t) = \begin{cases} 1 - e^{-v(x,i)(t-t_0)} & \text{wenn } t > t_0 \\ 0 & \text{sonst.} \end{cases}$$

Die Verarbeitungsraten werden durch die v-Parameter repräsentiert und t_0 ist eine Wahrnehmungsschwelle. Reize, die kürzer als t_0 gezeigt werden, werden überhaupt nicht verarbeitet. Die weiteren TVA-Gleichungen, die im Folgenden genannt werden, sind in Kapitel 3 zu finden.

Die Verarbeitungsraten v werden aus den Aufmerksamkeitsgewichten w nach Gleichung 3 bestimmt. Auch diese Aufmerksamkeitsgewichte können weiter aufgeschlüsselt werden, wie Gleichung 4 beschreibt. Die Gesamtkapazität C ist in der Regel die Summe der Raten v aller gezeigten Reize.

Wenn mehr als nur ein Reiz gezeigt wird, ist die Wahrscheinlichkeit, dass ein Reiz bis zu einer gewissen Zeit enkodiert wird und dass nicht schon alle Plätze belegt sind, durch Gleichung 2 gegeben. In dieser spielt zusätzlich der Parameter K eine Rolle, welcher die VSTM-Kapazität beschreibt.

Typische TVA-Versuche verwenden sogenannte Whole- oder Partial-Report-Aufgaben (Sperling, 1960). Die Versuchspersonen berichten Buchstaben oder Zahlen, die nach einer variablen Dauer maskiert werden (siehe Abbildung 1). In Versuchen dieser Art wurden mit der TVA zahlreiche theoretische, aber auch klinische Aspekte von Aufmerksamkeit untersucht (Bundesen et al., 2015).

Da in dieser Arbeit TOJs mit TVA modelliert werden und diese nur zwei (oder drei, falls es einen Hinweisreiz gibt) Reize verwenden, spielt die Begrenzung des VSTMs auf K Reize keine Rolle und die einfachere Gleichung oben kann verwendet werden, um davon konkrete TOJ Modelle abzuleiten.

Im Rahmen dieser Arbeit werden hauptsächlich die Parameter C und w mit einer neuen Methode geschätzt. Dafür musste eigens ein

TVA-basiertes TOJ-Modell entwickelt werden, welches am Ende des nächsten Abschnitts erläutert wird.

MODELLIERUNG VON URTEILEN ZEITLICHER REIHENFOLGE

Im TOJ-Paradigma beurteilen Versuchspersonen, welcher von zwei Reizen zuerst (oder als zweites) präsentiert wurde. Während manche Studien auch Gleichzeitigkeit als Urteil erlauben (siehe Weiß, 2012), werden in dieser Arbeit binäre TOJs verwendet. In Experimentalbedingungen wird Aufmerksamkeit auf einen der beiden Reize, den Sondierreiz, gelenkt. Der andere Reiz ist der Referenzreiz.

Zeitliche Reihenfolgeurteile ergeben in der Regel sigmoide Verteilungen. Diese werden mit mathematischen Funktionen approximiert. In der Regel sind dies in der Psychophysik übliche Funktionen, etwa die logistische oder die kumulative Verteilungsfunktion der Weibull-Verteilung (Fründ et al., 2011). Allerdings geben die Parameter dieser Funktionen keine Auskunft über die zugrundeliegenden Prozesse eines Reihenfolgeurteils. Sie erlauben lediglich, die Daten mit einem kontinuierlichen Verlauf zu beschreiben, um die in Abbildung 3 erwähnten zusammenfassenden Parameter der Urteile zu bestimmen. Häufig werden die TOJ-Analysen dann mit qualitativen Vorhersagen von Aufmerksamkeitstheorien in Zusammenhang gebracht, zum Beispiel bezüglich der Zeitverläufe von Prior Entry (siehe, z. B. Scharlau et al., 2006). Diese Herangehensweise erlaubt jedoch nicht, das einleitend erwähnte Problem der TOJ Relativität zu lösen. Somit können die in der Einleitung beschriebenen offenen Fragen zu Prior Entry auf diese Weise nicht untersucht werden.

Anstelle eines Abgleichs qualitativer Vorhersagen mit Veränderungen in den zusammenfassenden Parametern sind konkrete Modelle der basalen Verarbeitungsprozesse erforderlich. Frühere Ansätze gehen mit der Modellierung dieser Prozesse unterschiedlich weit. Sternberg und Knolls (1973) Modell unabhängiger Verarbeitungskanäle (Independent-Channels Model; ICM) bietet einen abstrakten Rahmen für TOJ-Modelle und der Analyse statistischer Eigenschaften. Es enthält jedoch keine Beschreibung der eigentlichen Verarbeitungsprozesse. Stelmach and Herdman (1991) hingegen beschreiben die internen Prozesse, leiten jedoch kein mathematisches Modell ab, mit dem für TOJ-Daten tatsächlich Parameter geschätzt werden könnten. Die vorliegende Arbeit zeigt in Abschnitt 4.4, dass dies auch nicht möglich ist. Modelle, mit denen dies möglich wird, wurden von K. A. Schneider and Bavelier (2003) und Alcalá-Quintana and García-Pérez (2013) vorgeschlagen. Diese nehmen normalverteilte oder exponentialverteilte Enkodierungszeiten an. Damit können Parameter geschätzt werden; jedoch ist deren Bedeutung für Fragestellungen zur Aufmerksamkeit nicht ganz klar. Zum Beispiel haben die beiden Modelle Komponenten, die wie der PSS nur eine relative Verschiebung modellieren.

Aufgrund der Unzulänglichkeiten der bestehenden Ansätze musste ein gänzlich neues Modell für Aufmerksamkeit in TOJs entwickelt werden. Dieses basiert auf er bereits erwähnten TVA, einer fundamentalen Aufmerksamkeitstheorie.

Das in dieser Arbeit entwickelte TVA-basierte TOJ Modell

Im Folgenden wird das Modell in seiner einfachsten Form mathematisch beschrieben. In dieser Variante nehmen wir an, dass t_0 für beide Reize gleich ist, so dass es in den folgenden Formeln vernachlässigt werden kann.

Dieses TVA-basierte TOJ Modell lierfert eine Funktion der TVA Raten v_p (Sondierreiz), v_r (Referenzreiz) und des SOAs, welche die Wahrscheinlichkeit liefert, dass die Versuchsperson "Sondierreiz zuerst" urteilt. Wenn das SOA größer als null ist, gilt,

$$P_{p^{1st}}(v_p, v_r, SOA) = 1 - e^{-v_p|SOA|} + e^{-v_p|SOA|}\left(\frac{v_p}{v_p + v_r}\right).$$

Dabei ist $1 - e^{-v_p|SOA|}$ die Wahrscheinlichkeit, dass der Sondierreiz enkodiert wird, bevor der Enkodierungsprozess des Referenzreizes startet. Wenn dies nicht (mit der Wahrscheinlichkeit $e^{-v_p|SOA|}$) geschieht, laufen die Enkodierungen parallel und der Sondierreiz wird mit der Wahrscheinlichkeit $v_p/(v_p + v_r)$ zuerst enkodiert.
Bei positivem SOA ist die Wahrscheinlichkeit für das Urteil "Sondierreiz zuerst"

$$P_{p^{1st}}(v_p, v_r, SOA) = e^{-v_r|SOA|}\left(\frac{v_p}{v_p + v_r}\right).$$

Mit der Wahrscheinlichkeit $e^{-v_r|SOA|}$ wird der Referenzreiz noch nicht vor dem Start der Enkodierung des Sondierreizes enkodiert. Unter dieser Bedingung gewinnt der Sondierreiz wie oben den Wettbewerb mit einer Wahrscheinlichkeit von $v_p/(v_p + v_r)$.

Der wichtigste Aspekt dieses Modells ist, dass es für jeden der Reize eine Rate beinhaltet. Im Vergleich zu neutralen Bedingungen kann dann überprüft werden, ob eine etwaige Verschiebungen des PSS durch eine Beschleunigung des beachteten Reizes oder einer Verlangsamung für den unbeachteten verursacht wird. Diese Form der Modellierung wird in Manuskript *A* beispielhaft vorgestellt. In den Manuskripten *B* und *C* wurden auf diese Weise Modelle aufgestellt, welche dann mit hierarchischen Bayes'schen Verfahren zur Analyse von Experimentaldaten eingesetzt wurden.

In Abschnitt 4.6.3 der Synopse werden die konkreten Modelle beschrieben. Abschnitt 4.6.2 enthält eine Anleitung für ein generalisiertes Vorgehen bei der Entwicklung konkreter Modelle.

ERGEBNISSE

Die Ergebnisse dieser Arbeit wurden in den drei publizierten bzw. zur Publikation eingereichten Artikeln, Manuskript *A*, *B* und *C*, sowie in weiteren Abschnitten in dieser Synopse (siehe Abschnitt 5.3) detailliert beschrieben und diskutiert. Hier sollen sie nun kurz im Zusammenhang mit den einleitend dargestellten offenen Fragen zu Prior Entry diskutiert werden.

In der vorliegenden Arbeit konnten einige offene, grundlegende Frage zu Prior Entry beantwortet werden. Die in der Literatur weitgehend ignorierte, jedoch fundamentale Frage, ob die Verlagerung von Aufmerksamkeit den beachteten Reiz beschleunigt oder den unbeachteten Reiz verlangsamt oder beides, wurde mithilfe der TVA untersucht. In verschiedenen Experimenten, hauptsächlich solchen mit TOJs, wurden beschleunigte Verarbeitungsraten der beachteten Reize, aber auch verlangsamte Raten der unbeachteten gefunden. In den Experimenten mit Buchstabendetektion in Manuskript *A* sowie in Versuchen von Krüger et al. (2016), ergab sich das Bild, dass dieselben vorhandenen Ressourcen gleichmäßig umverteilt wurden. Das heißt, dass die Beschleunigung des beachteten Reizes zulasten des unbeachteten geschieht. In einigen Versuchen (Experiment 3 mit dem Farb-Pop-Out aus Manuskript *B*) fand sich lediglich eine Verlangsamung.

Definitiv lässt sich schlussfolgern, dass entgegen der gängigen Interpretation, nach der Aufmerksamkeit eine ausschließlich beschleunigende Natur hat, auch eine Verlangsamung des nicht beachteten Reizes stattfindet. Dass dabei die Verzögerung numerisch größer ist, folgt aus dem exponentiellen Race-Modell der TVA. Somit haben Weiß et al. (2013) in gewisser Weise recht, dass Prior Entry mehr ein Posterior Entry—also ein verspäteter Eintritt—ist, da die Verzögerung oft überwiegt. Jedoch geschieht dies nicht, weil Verlangsamung oder Inhibition stärker ist, sondern es folgt aus den Eigenschaften des exponentiellen Race.

Unter welchen Bedingungen bestimmte Verhältnisse von Beschleunigung und Verlangsamung auftreten, ist eine noch offene Frage. Insbesondere ist zu klären, wann die Gesamtressourcen gleich bleiben und wann eine Aufmerksamkeitsmanipulation zusätzliche Ressourcen mobilisieren kann oder zu einer absoluten Unterdrückung führt. Das in dieser Arbeit entwickelte quantitative Modell für Aufmerksamkeit in TOJs bietet eine gute Grundlage für solche Untersuchungen.

Eine zweite wesentliche Frage der vorliegenden Arbeit war die nach der aufmerksamkeitsbezogenen Wirkung eines peripheren Hinweisreizes. Die Experimente aus Manuskript *C* zeigen, dass der Hinweisreiz mit drei unterschiedlichen Effekten verbunden ist, die gemeinsam die in TOJs mit Hinweisreiz häufig beobachtete Verschiebung des PSS erwirken.

Der erste Effekt ist ein Muster aus Beschleunigung und Verlangsamung der Verarbeitungsraten der einzelnen Reize, wie es oben diskutiert wurde. Zu beachten ist jedoch, dass diese Verlagerung nur bei kleineren COAs (Cue Onset Asynchrony, Intervall zwischen Hinweis- und Zielreiz) zugunsten des Sondierreizes ausfällt, der am Ort des Hinweisreizes erscheint. Bei größeren Intervallen schlägt dieser Effekt zum Nachteil des beachteten Sondierreizes um. Dies ist konsistent mit dem IOR-Effekt, der die Rückkehr von Aufmerksamkeit an einen zuvor untersuchten Bereich der Szene unterdrückt. Was dabei genau mit "klein" und "groß" gemeint ist, kann nur grob eingegrenzt werden. Bei einem COA von 80 ms hat der Effekt noch den Sondierreiz stark begünstigt. Ein Intervall von 140 ms bedeutet bereits einen starken Vorteil für den Referenzreiz. Hier ist noch anzumerken, dass 140 ms eher früh für IOR sind. Üblicherweise tritt der Effekt erst nach mehreren hundert Millisekunden auf, wird gelegentlich jedoch sogar noch früher gefunden (Danziger & Kingstone, 1999).

Der zweite mit dem Hinweisreiz verbundene Effekt ist, dass dieser gelegentlich mit dem Zielreiz verwechselt wird. Dies geschieht nicht unbedingt bewusst, sondern auf einer perzeptuellen Ebene. Im TVA-basierten Modell wurde dies durch eine Kategorisierung "Hinweisreiz als Sondierreiz" erfasst. Bisherige Ansätze hingegen betrachten den Hinweisreiz nicht als einen vollwertigen Reiz, sondern lediglich als einen Aufmerksamkeitseinfluss. Laut TVA finden Enkodierungsprozesse jedoch für alle möglichen Kategorisierungen statt. Die meisten von ihnen erhalten Aufmerksamkeitsgewichte, die praktisch null sind. Das TOJ einer Versuchsperson wird also nicht dadurch beeinflusst, dass prinzipiell auch eine Kategorisierung des Reizes als Junggeselle im Besitz eines ansehnlichen Vermögens möglich ist, für die sowohl die sensorische Evidenz als auch die Filter- und Kategorisierungsparameter des visuellen Systems (im Sinne der TVA) praktisch null sind. Der Hinweisreiz hingegen besitzt Zielreizeigenschaften, wie zum Beispiel eine ähnliche Größe oder Farbe, aber insbesondere auch ein zeitliches Onset-Signal, ein Attribut, welches im TOJ von Bedeutung ist. So gesehen schreibt die TVA sogar vor, dass es einen gewissen Anteil an Enkodierungen des Hinweisreizes als Sondierreiz gibt. Die Experimente in Manuskript *C* zeigen, dass solche Kodierungen tatsächlich zur Verschiebung des PSS beitragen. Sie sind zwar nicht der alleinige Grund für die Verschiebung (ein gelegentlicher Verdacht und die Hypothese von Manuskript *C*), sie sind jedoch zwingend erforderlich. Eine Veränderung der Verarbeitungsraten durch Aufmerksamkeit allein kann die Verschiebung also nicht erklären.

Schließlich existiert ein dritter Effekt des Hinweisreizes. Durch ihn wird eine COA-abhängige Modulation der insgesamt verfügbaren Ressourcen ausgelöst. Solche Effekte schlagen sich im TVA-Parameter C nieder und wurden bereits zuvor beobachtet. Dass weitere Ressourcen aktiviert werden, lässt sich damit erklären, dass diese zuvor mit der Verarbeitung von Rauschen gebunden waren (siehe z. B. A. Petersen et al., 2012, für einen solchen Mechanismus in einem anderen TVA Modell).

Das Zusammenspiel dieser drei Mechanismen erklärt, wie der Hinweisreiz funktioniert und wie er insbesondere starke Verschiebungen des PSS bewirken kann. Zusätzlich wird auch erklärt, warum IOR im typischen Zeitprofil von TOJs mit Hinweisreiz bislang nicht gefunden wurde, obwohl der Effekt eigentlich zu erwarten ist: Der IOR-Effekt auf die Raten wird vom starken Einfluss der Kategorisierungen des Hinweisreizes als Sondierreiz verdeckt.

Weiterhin wurde in der Arbeit gezeigt, dass das TVA-basierte Modell für TOJs gewisse Datenmuster in TOJ-Daten ohne die Annahme eines nicht-deterministischen Entscheidungsmechanismus erklären kann. In zukünftigen Arbeiten muss überprüft werden, ob diese Alternative gegenüber der traditionellen Annahme bevorzugt werden sollte bzw. wie weit die beiden Mechanismen den tatsächlichen Prozessen zugrunde liegen.

Es wurde in der Arbeit auch gezeigt, dass, anders als in der klassischen TVA, mit der neuen Methode TVA-Parameter für sehr unterschiedliche Reize geschätzt werden können. In den Experimenten aus Manuskript *B* zum Beispiel wurden Pop-Out-Muster, natürliche Bilder und Buchstaben als Reize verwendet. Insbesondere in der Erforschung von Salienz mit Pop-Out-Mustern erweist sich der neue Ansatz schon jetzt als nützlich. Von Krüger et al. (2016, in preparation) wurde dass Konzept TVA-basierter TOJ-Auswertungen bereits erweitert und in diesem Bereich angewandt.

Die weite Anwendbarkeit der TVA-basierten TOJ Methode wurde fernerhin dadurch belegt, dass behaviorale Daten von Mäusen (bereitgestellt von Wada et al., 2005), die taktile TOJs mithilfe ihrer Schnurrhaare absolvierten, mit ihr analysiert werden konnten (siehe Abschnitt 6.4.2). Weiterhin war es möglich, TVA-Parameter für ein TOJ, das in ein Computerspiel eingebettet wurden, zu schätzen (siehe Abschnitt 6.4.3).

An dieser Stelle sollen noch einmal die Annahme des Modells erwähnt werden, dass das VSTM der Ort ist, an dem die Reihenfolgeurteile gebildet werden. Weiterhin wird in der vorliegenden Arbeit davon ausgegangen, dass die Ankunftszeiten im VSTM ausschlaggebend sind und dass diese deterministisch in ein Reihenfolgeurteil übersetzt werden. Im sechsten Kapitel der Arbeit werden jedoch auch einige Alternativen vorgestellt wie zum Beispiel, dass Reize ein Zeitattribut tragen, welches zur Urteilsbildung herangezogen wird. In zukünftigen Arbeiten muss der genaue Mechanismus ermittelt werden.

Kritisch diskutiert werden muss auch die probabilistische Modellierung der Ankunftszeiten mit der Exponentialverteilung in der TVA, bei der es eine konstante Hazardrate gibt, mit der zu jedem Zeitpunkt

Enkodierungen geschehen können. Eine mögliche Alternative mit einem Prozess, der Informationen kontinuierlich akkumuliert, bis eine Entscheidungsgrenze erreicht ist, bieten Drift-Diffusionsmodelle (DDMs). In der Synopse wurden ein auf einem DDM basierendes Modell entwickelt und mit diesem simulierte Daten diskutiert. Es zeigte sich, dass trotz des grundsätzlich verschiedenen Verständnis der Enkodierung—Hazardrate vs. kontinuierliche Akkumulation–eine große Ähnlichkeit zwischen den Modellen besteht. In zukünftigen Arbeiten muss der noch offene Zusammenhang zwischen TVA und DDM bzw. die Frage, welches dieser Modelle TOJ-Daten besser erklärt, untersucht werden.

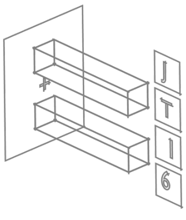
Schließlich wurde ein neuer Ansatz vorgestellt, um das schwierige Problem zu untersuchen, wie TVA Verarbeitungsressourcen in komplexen Situationen verteilt werden. In ersten Analysen von Daten aus Experiment 9, welche eine relativ hohe Genauigkeit aufweisen, wurde eine Variante des Modells aus Manuskript C verwendet. In dieser Variante wurden 18 freie Ratenparameter unter den unterschiedlichen möglichen Präsentations- und Enkodierungsreihenfolgen geschätzt. Die Ergebnisse geben erste Hinweise, dass Interferenz zwischen den Reizen durchaus zu unterschiedlicher Ressourcenverteilung für die verschiedenen Darbietungsreihenfolgen führt, dass jedoch bereits laufende Enkodierungen hiervon nicht betroffen sind. Konkret heißt dies zum Beispiel, dass der Referenzreiz mehr Ressourcen bekommt, wenn er zuerst gezeigt wird, und nur sehr wenige erhält, wenn andere Reize zuerst kommen. Das deutet darauf hin, dass gewissermaßen jeder Reiz die Fähigkeit eines Hinweisreizes hat Aufmerksamkeit zu lenken. Um dies in zukünftigen Arbeiten genauer zu untersuchen, wäre es vorteilhaft, zunächst das Paradigma zu vereinfachen, zum Beispiel durch Verwendung einer Salienzmanipulation anstelle des Hinweisreizes. Dabei sollte auch die Genauigkeit der Daten weiter erhöht werden, etwa durch die Verwendung von mehr Wiederholungen und noch kleineren SOA-Abständen.

SCHLUSSFOLGERUNG

Diese Arbeit hat den Zusammenhang zwischen Aufmerksamkeit und der Wahrnehmung zeitlicher Reihenfolge in der visuellen Domäne untersucht. Es wurde gezeigt, dass sowohl Beschleunigung in der Verarbeitung beachteter Reize als auch die Verlangsamung der Verarbeitung von nicht beachteten Reizen zu Prior Entry führen, der relativ früheren Wahrnehmung beachteter Informationen.

Weiterhin wurde die Funktionsweise peripherer Hinweisreize untersucht. Dabei hat sich gezeigt, dass der hier verwendete modellbasierte Ansatz Unstimmigkeiten im Zeitverlauf der Effekte aufklärt, die in vorherigen Arbeiten gefunden wurden.

Einerseits hat sich TVA als theoretischer Rahmen für diese Untersuchungen bewährt, andererseits sind die daraus abgeleiteten Modelle auch für die Weiterentwicklung von TVA nützlich. Dies ist insbesondere der Fall, weil die neue TOJ-basierte Methode den Anwendungsraum TVA-basierter Untersuchungen stark erweitert. Die Verwendung nahezu beliebiger Reize ist nun möglich. Weiterhin kann die einfache TOJ-Aufgabe für Untersuchungen mit Tieren herangezogen werden, wie in dieser Arbeit demonstriert wurde. Zudem kann die Aufgabe in dynamische Umgebungen wie Computerspiele integriert werden, um die Motivation der Teilnehmenden zu erhöhen.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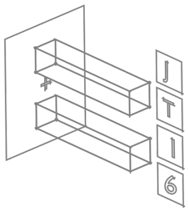
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Part III

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MANUSCRIPTS

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