Spatiotemporal biases in manual interception – effects of visual and auditory information processing

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Abbreviations

ATOM	A Theory of Magnitude
CMT	Conceptual Metaphor Theory
CrI	Credibility Interval
ISI	Interstimulus Interval

Abstract

From a purely cognitive perspective, psychological processes are mostly assessed on the level of perception or information processing. Embodied cognition research has broadened this point of view by acknowledging that input from the sensorimotor system might impact such mental processes. Basing on this approach, this thesis assesses interrelations between spatial and temporal processing by investigating early psychophysical phenomena and implementing new empirical approaches on spatiotemporal processing in the context of movements. It consequently provides new perspectives to current theoretical debates on spatiotemporal processing.

The processing of space and time is prone to distortions. For example, spatial length and temporal duration can impact the perception of each other (reciprocally). Longer lines are perceived to be presented for longer temporal intervals and (potentially) vice versa. Here it is argued that such spatiotemporal interrelations depend on the type of sensory input (e.g., visual or auditory), because the precision of spatial and temporal representations differs between sensory modalities (Chapter 1.2). It is explained why this account of modality appropriateness or specificity can be most suitably investigated in situations in which combined processing of space and time is key – that is in movements. For this reason, this thesis focusses on interception reactions towards moving stimuli, as when catching a ball. This extends most previous research on spatiotemporal interrelations which was mainly concentrated on perceptual judgements. Initially, this thesis introduces a method to disentangle a spatial and a temporal part from the combined spatiotemporal interception response and shows that both are susceptible to perturbations of visual input (blur) in Chapter 2. Next, initial support for the important role of sensory input for spatiotemporal interrelations is provided by showing biases of temporal manipulations on spatial interception for auditory but not visual stimuli (Chapter 3). Interestingly, it appears that eye movements might be more sensitive for such interrelations as various effects on timing and endpoints of saccades across modalities were found. In the final part of this thesis, the visual effects were addressed in an adapted online version of the experiment, showing that small adaptations of the paradigm towards increasing task difficulty can largely impact the results. This supports the notion that not the type of sensory input per se but rather the acuity of the signal is relevant for such effects (Chapter 4). Furthermore, this study compared the effect of spatial manipulations on temporal interception to the effect on pure temporal prediction thereby adding to the debate about action vs. perception.

In summary, this thesis shows that i) spatiotemporal biases can transfer from perceptual judgements to motoric responses (i.e., interception and eye movements), that ii) the type of sensory input impacts these interrelations, and that iii) this effect of sensory modality might derive from differences in the acuity of the signal (and consequently representational noise). Thereby, the results indicate that seemingly contradictory theoretical predictions and related empirical findings might be explained by the involved sensory modalities, shed light on the potential impact of spatiotemporal biases on everyday tasks and add towards the debate on the perception-action dissociation, and more concretely on the discussions about visual illusions transferring to action.

Zusammenfassung

Psychologische Prozesse werden, wenn sie aus einer rein kognitiven Perspektive betrachtet werden, häufig auf einer perzeptuellen Ebene untersucht. Diese Art der Betrachtung wurde durch Forschung im Bereich Embodied Cognition erweitert, welche berücksichtigt, dass psychologische Prozesse auch durch Informationen aus dem sensomotorischen System beeinflussen werden könnten. In dieser Arbeit wurden, aufbauend auf diesem Ansatz, Wechselwirkungen zwischen räumlicher und zeitlicher Verarbeitung erforscht. Hierzu wurden psychophysikalische Phänomene untersucht und neue empirische Ansätze zu räumlich-zeitlicher Verarbeitung im Zusammenhang mit Bewegungen implementiert und so eine neue Perspektive auf aktuelle theoretische Debatten zu räumlich-zeitlicher Verarbeitung geschaffen. Die Verarbeitung von Raum und Zeit ist anfällig gegenüber Verzerrungen. Beispielsweise können sich die Wahrnehmung von räumlicher Länge und zeitlicher Dauer (gegenseitig) beeinflussen. Längere Linien werden wahrgenommen als würden sie für längere Zeit präsentiert und (möglicherweise) existiert auch der inverse Effekt. In dieser Arbeit wird argumentiert, dass diese räumlich-zeitlichen Zusammenhänge von der Art des sensorischen Inputs (z.B. visuell oder auditiv) abhängen, da sich die Genauigkeit von räumlichen und zeitlichen Repräsentationen zwischen sensorischen Modalitäten unterscheidet (Kapitel 1.2). Dieser Modalitätsspezifitätsansatz lässt sich besonders gut in Situationen untersuchen, in denen eine gemeinsame Verarbeitung von Raum und Zeit elementar ist – nämlich in Bewegungen. Aus diesem Grund werden in dieser Arbeit vor allem Interzeptionsreaktionen auf bewegte Stimuli untersucht, wie beispielsweise beim Fangen eines Balles. Diese Vorgehensweise erweitert die Forschung zu räumlich-zeitlichen Wechselwirkungen, welche sich bisher insbesondere mit perzeptuellen Urteilen beschäftigt hat. Zu Beginn wird eine Methode eingeführt, um den räumlichen und zeitlichen Anteil der kombinierten räumlich-zeitlichen Interzeptionsreaktion unterscheidbar zu machen. Es zeigt sich, dass beide Anteile anfällig für Störungen im visuellen Input (Unschärfe) sind (Kapitel 2). In Kapitel 3 dieser Arbeit zeigen sich Verzerrungseffekte (Biases) für auditive, aber nicht für visuelle Stimuli. Dies liefert erste Hinweise darauf, dass der sensorische Input tatsächlich eine wichtige Rolle für räumlich-zeitliche Wechselwirkungen spielt. Augenbewegungen scheinen interessanterweise sogar sensitiver für solche Wechselwirkungen zu sein, da eine Reihe von Effekten auf das Timing und den Endpunkt von Sakkaden sowohl visuell als auch auditiv gefunden wurde. Schließlich wurden die visuellen Effekte in einem angepassten Online-Experiment neu betrachtet. Es zeigte sich, dass kleine Anpassungen des Paradigmas in Richtung einer schwierigeren Aufgabe starke Effekte auf die Ergebnisse haben können. Dieser Befund unterstützt den Schluss, dass nicht die Art des sensorischen Inputs per se, sondern eher die Genauigkeit des Signals relevant für die Größe der Effekte ist (Kapitel 4). Außerdem wurden in dieser Studie Effekte von räumlichen Manipulationen auf den zeitlichen Teil von Interzeption mit Effekten auf reine zeitliche Prädiktion verglichen, womit zur Debatte über das Verhältnis von Wahrnehmung und Handlung beigetragen wird. Zusammengefasst wird in dieser Arbeit gezeigt, dass i) sich räumlich-zeitliche Verzerrungen von perzeptuellen Urteilen auf motorische Reaktionen (Interzeption und Augenbewegungen) übertragen können, dass ii) die Art des sensorischen Inputs diese Wechselwirkungen beeinflussen kann, und dass iii) dieser Effekt der sensorischen Modalität auf unterschiedlichen Genauigkeiten im Signal (bzw. dem daraus resultierenden repräsentationalen Rauschen) basieren könnte. Die Ergebnisse deuten somit darauf hin, dass sich scheinbar widersprüchliche theoretische Vorhersagen und die zugehörigen, empirischen Befunde durch die involvierten sensorischen Modalitäten erklären lassen. Sie geben Aufschluss über potentielle Einflüsse von räumlich-zeitlichen Verzerrungen in alltagsnahen Aufgaben und Tragen zur Debatte über die Dissoziierung von Wahrnehmung und Handlung beziehungsweise zur Diskussion um den Transfer von perzeptuellen Illusionen auf Handlung bei.

1 Theoretical Background

Time and space are modes by which we think and not conditions in which we live.[3]

Albert Einstein

Already Albert Einstein, as a physicist, acknowledged that time and space are not just important as absolute physical entities, but also (and maybe more importantly) should be considered in the way they are processed by humans. In other words, it is the key to understanding how the human brain uses spatial and temporal information to describe, explain and predict human perception and behavior.

Spatial and temporal percepts are constant companions of one's daily life. Especially when it comes to motion, the interplay between time and space is important to adequately perceive and act in our environment. For instance, to be able to catch a ball, one needs to be in the right place at the right time. But how can this be achieved? Successfully catching a ball is not just an outcome of accurate perception of time and space, but also involves, among other processes, the prediction of target motion (e.g., Fiehler et al., 2019), distribution of attention, decision making, accurate motoric actions, and anticipation of action outcomes (see also, Hodges et al., 2021).

It is important to understand how these processes work, interact, and how they rely on the processing of time and space. One way to study these processing networks is to analyze situations in which perceived time and space differ from the physical size and duration of objects in the environment. This thesis focusses on such misjudgments that result from interrelations in the processing of time and space. I will initially introduce literature on temporal and spatial processing in the visual and auditory modality, highlight situations in which correct spatial and/or temporal perception systematically fails (biases and illusions), and then introduce theories about their interrelations. By reviewing existing literature, the hypothesis of this study – namely that the interrelations between time and space depend on modality and quality of sensory input – will be presented. Before describing the experimental work, I will explain why a motoric task was chosen, highlight the necessary empirical steps to execute this task and introduce methodological challenges and decisions.

[3] Similar statements have been made by other scholars, for example, by Immanuel Kant in his 'Kritik der reinen Vernunft' (1787)

1.1 Time and space

As time and space are precise and unambiguously defined physical entities, one may have the impression that it is possible to accurately perceive spatial and temporal cues. However, are these perceptions indeed reliable? Most certainly, human perceptual systems can perceive space and time through several modalities. We are able to localize objects in our environment when seeing them, when hearing the sound they produce, or when touching them. Next to pure localization, spatial processing further includes, for example, perception of size, or recognition of spatial patterns or configurations, as used in face recognition (e.g., Freire et al., 2000; Itz et al., 2018) among others. Temporal information can be processed, for instance, auditorily, when listening to music acquiring the rhythm. Timing information indicates the start or ending of an event, together building its duration. Temporal cues are often used as indication to initiate an action, as for instance, the visual and auditory signal of the starting clapper of a sprint competition. These examples show that time and space are constantly perceived and processed across several sensory modalities in our daily lives. Similar to previous studies focusing on the processing of space and time, and investigating their interrelations, this thesis will focus on the perception of spatial and temporal magnitudes as indicated by spatial length or distance and temporal duration (Walsh, 2003).

As can be inferred from the examples above, there might be differences in the sensory input that commonly captures our processing of space and time. Whereas spatial information is predominantly processed by the visual system, auditory input can dominate the perception of time (Recanzone, 2009). In general, it can be assumed that in a multisensory context, the sensory modality providing better acuity of space or time will be prevalent for the resulting percept (see also, modality appropriateness, Welch & Warren, 1980). Spaital localization is much more accurate for visual (e.g., Cavonius & Robbins, 1973) compared to auditory signals (e.g., Recanzone et al., 1998; Stevens & Newman, 1936), and for timing information auditory signal might be more important than visual information (e.g., Recanzone, 2009; Welch & Warren, 1980). These sensory differences in spatiotemporal perception can already be identified on a purely physiological level. Paradoxically, despite the slower physical propagation of sound (auditory) compared to light (visual), auditory signals are processed significantly faster within the human body, not only at the level of distal physiological processing receptors but also regarding latencies in the respective sensory cortices (Recanzone et al., 2000; cf. Recanzone, 2009).

This modality specificity of time and space is further highlighted by multiple behavioral findings. O'Connor and Hermelin (1972), for instance, showed that humans prioritize temporal or spatial information differently across separate modalities. They presented participants with a succession of three numbers, that followed a spatial, temporal, and numerical order. They were then asked to identify the ‘middle’ one. Based on the procedure three strategies were possible: participants could either choose the spatially centered number (between the left and right), the temporally secondly presented number or the arithmetically middle number. As proposed, participants’ responses depended on the sensory modality that was chosen to present the digits: for visual presentations participants mostly chose the spatial center, whereas in an auditory condition, the temporal order was considered as the decision criterion. When simultaneously presented, participants relied on the spatial order, indicating that vision dominated their decision. However, when a simultaneous trial was preceded by auditory presentation, the temporal order became most prominent in the audiovisual condition. These results highlight the modality-specificity of spatial and temporal representations.

The processing of spatiotemporal characteristics is part of everyday tasks that may seem relatively easy. Yet, even in simple tasks, errors occur. Human perception of time and space has been shown to be prone to distortions. Some robust and illustrative examples can be found in the context of illusions. For instance, the Müller-Lyer illusion shows that lines of the same size are perceived differently depending on whether their endings are either surrounded by shafts running into an arrow (acute angles) or shafts pointing in the opposite direction (obtuse angle) (Müller-Lyer, 1889). Another spatial illusion was found for moving stimuli: the representational momentum. Initially, this effect was found for rotating stimuli, and later also for linear motions, showing that participants’ memory of the spatial orientation (rotation) of a stimulus is biased in the rotation direction (Freyd & Finke, 1984).

Temporal illusions have been reported, for example, for filled vs. empty geometric forms, with filled objects being perceived as presented longer (Hall & Jastrow, 1886). In other experiments, it was shown that a larger number of objects is perceived to be presented longer than a smaller number of objects (Dormal et al., 2006; Xuan et al., 2007), previous temporal intervals impact the perceived time of the current interval (Estel, 1885) and attention to other tasks leads to an underestimation of time (Ejner, 1889). Further examples of temporal illusions are nicely summarized in Fernandes and Garcia-Marques (2013). All these examples show that human perception of space and time is far from being perfect, or in other words, does not fully correspond to our physical operationalization of time and space in the physical world.

Often time and space are correlated with each other, which can be ascribed to their connection through motion. For example, when going on a hike, we can compare trails of different distances. While this is a purely spatial criterion, we will typically associate these judgements with a temporal duration assuming a (more or less) constant velocity. The spatially longer the trail is, the more time we will need to finish it, at least, if we do not adapt the speed. Based on such connections, humans develop heuristics or expectations about the interrelations of time and space. The close associations between time and space can, for example, be observed in speech: across languages, often similar expressions are used to describe spatial or temporal features, for example, the previously mentioned word ‘middle’ (O'Connor & Hermelin, 1972) can be allocated to a temporal or spatial (and also numerical) sequence, while asking “how long” can refer to the duration of a theater play or the spatial length of a stick, among others.

Studies on such interdependencies of temporal and spatial processing show that the subjective estimates of time and space might differ from their physical magnitudes. Casasanto and Boroditsky (2008), for instance, visually presented lines, growing over time until reaching a final size. After the presentation participants were asked to either reproduce the duration of the presentation or the size of the object. The authors showed that the final size did impact participants reproduced duration. That is, the larger the line was, the longer participants estimated the time it needed to grow. For the reproduced size, however, no (or smaller) influences of duration were found. In a conceptually similar study, Cai and Connell (2015) provided indications of both, showing effects of temporal features on spatial processing and vice versa. Participants were asked to indicate either the size of a stick, they had held between their fingers, or the duration of a sound, presented simultaneously. It was shown that, the larger the stick was, the longer the duration of the sound was estimated, and that the opposite holds true as well - the longer the sound was presented, the larger the stick size ratings. These two final examples deliver a first hint on interrelations between space and time. They form part of two seemingly contradictory theories about the nature of those interrelations. In the following sub-chapter, published as a review article, these two theories will be introduced and literature supporting either theory is reviewed.

1.2 Review: Interrelations Between Temporal and Spatial Cognition: The Role of Modality-Specific Processing

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Abstract

Temporal and spatial representations are not independent of each other. Two conflicting theories provide alternative hypotheses concerning the specific interrelations between temporal and spatial representations. The asymmetry hypothesis (based on the conceptual metaphor theory, Lakoff & Johnson, 1980a) predicts that temporal and spatial representations are asymmetrically interrelated such that spatial representations have a stronger impact on temporal representations than vice versa. In contrast, the symmetry hypothesis (based on a theory of magnitude, Walsh, 2003) predicts that temporal and spatial representations are symmetrically interrelated. Both theoretical approaches have received empirical support. From an embodied cognition perspective we argue that taking sensorimotor processes into account may be a promising steppingstone to explain the contradictory findings. Notably, different modalities are differently sensitive to the processing of time and space. For instance, auditory information processing is more sensitive to temporal than spatial information, whereas visual information processing is more sensitive to spatial than temporal information. Consequently, we hypothesized that different sensorimotor tasks addressing different modalities may account for the contradictory findings. To test this, we critically reviewed relevant literature to examine which modalities were addressed in time-space mapping studies. Results indicate that the majority of the studies supporting the asymmetry hypothesis applied visual tasks for both temporal and spatial representations. Studies supporting the symmetry hypothesis applied mainly auditory tasks for the temporal domain, but visual tasks for the spatial domain. We conclude that the use of different tasks addressing different modalities may be the primary reason for (a)symmetric effects of space on time, instead of a genuine (a)symmetric mapping.

Keywords: time-space mapping, asymmetry hypothesis, symmetry hypothesis, conceptual metaphor theory, a theory of magnitude, spatial representation, temporal representation

1.2.1 Introduction

For complex human behavior, including sensorimotor actions such as catching a ball, precise representations of time and space are of utmost importance (e.g., Rosenbaum et al., 2012). For instance, in movement-related tasks the anticipation of duration (= time) and distance (= space) influences manifold decisions about how to act such as when deciding whether to cross the street or stop walking (Zito et al., 2015), whether to accelerate or slow down when trying to catch a ball (Postma et al., 2017), or whether to wait for the elevator or take the stairs (Wittmann, 2014). In order to predict environmental demands and to plan actions, an actor has to constantly and adequately represent temporal and spatial information (Postma et al., 2017).. For example, the looming sound of an approaching car helps a pedestrian to estimate its speed and moment of passing and thus to adjust movements and avoid a collision. This is the very reason why e-cars, which typically do not generate sounds, are considered more dangerous for pedestrians than normal cars. As a consequence, a law in the US requires all newly manufactured e-cars to produce auditory noise when driving. Though it is well-known that interrelations between temporal and spatial representations are essential for human functioning, the mechanisms underlying these interrelations are far from being well understood.

When reviewing the literature that addresses the (a)symmetry of time and space, it is evident that there is no consensus about the intimate links between temporal and spatial representations (Winter et al., 2015). Two influential and currently debated hypotheses are the *asymmetry hypothesis*, which is based on the conceptual metaphor theory (= CMT, Boroditsky, 2000; Lakoff & Johnson, 1980a) and the *symmetry hypothesis*, which is based on a theory of magnitude (= ATOM, e.g., Walsh, 2003). Both assume different relationships between temporal and spatial representations and, as a consequence make divergent claims about how time-space mappings modulate movements. Notwithstanding the divergent predictions, both hypotheses received robust empirical support (Agrillo & Piffer, 2012; Boroditsky, 2000; Bottini & Casasanto, 2013; Coull et al., 2015; Hyde et al., 2013; Merritt et al., 2010; Skagerlund et al., 2016; Skagerlund & Träff, 2014; Xue et al., 2014). The question arises as to how it is possible that two contradicting hypotheses seem to both have received robust empirical support? In search of themechanisms that cause the contradictory findings, it is important to realize that the different modalities are differently sensitive to the processing of time and space. Consequently, we hypothesized that different sensorimotor tasks addressing different modalities may account for the contradictory findings. Based on this assumption, in this mini-review we critically review relevant literature to examine which modalities were addressed in time-space mapping studies.

Focusing on the role of modalities during the processing of temporal and spatial information, it should be considered that auditory information processing shows enhanced sensitivity to temporal information but lower sensitivity to spatial information (e.g., O'Connor & Hermelin, 1972; Recanzone, 2009). By contrast, visual information processing shows higher sensitivity to spatial information but lower sensitivity to temporal information (e.g., O'Connor & Hermelin, 1972; Recanzone, 2009). However, in audio-visual conditions, people tend to use the modality with the highest informational value to solve the task (e.g., Zhou et al., 2007). To illustrate, people are better in deducing spatial information regarding an approaching car when presented with information visually compared to being presented with auditory information. Therefore, when deducing temporal and spatial information from an approaching car, vision is our dominating system and thereby relatively impervious to distortion (Keshavarz et al., 2017). By contrast, in foggy environments, when the car is almost invisible, auditory information becomes more important. This relative importance of modality information depending on the informational value becomes also apparent when individual capacities are considered, as for example in blind subjects playing tennis with rattling balls. Further empirical evidence for the strong dependence on modality-related task characteristics is supported by illusion effects in which one modality dominates the perception of a multisensory object or event (Radeau & Bertelson, 1974). These illusion effects seem to be largely driven by the sensory modality that has the highest informational value for solving the task (for a review, see Recanzone, 2009).

In sum, the different sensitivities of different modalities to temporal and spatial information might moderate the empirical results. Because auditory information processing is more sensitive to temporal than spatial information and visual information processing is more sensitive to spatial than temporal information, it is reasonable to argue that different sensorimotor tasks may address auditory and visual information processing to different degrees. If true, then it can be hypothesized that different tasks addressing mainly one modality might cause the contradictory results with respect to the (a)symmetry of temporal and spatial representations. To test this, here we review the relevant literature to examine which modalities were addressed in studies that examined interrelations between temporal and spatial representations, supporting either the asymmetry or the symmetry hypothesis.

1.2.2 Theoretical background: CMT vs ATOM

According to the asymmetry hypothesis, spatial representations grounded in movement have a stronger impact on temporal representations than vice versa. The asymmetry hypothesis is based on the conceptual metaphor theory (=CMT), which assumes that the neural system characterizing concrete sensorimotor experience has more inferential connections and therefore a greater inferential capacity than the neural system characterizing abstract thoughts (Boroditsky, 2000; Lakoff & Johnson, 1980a).

It follows that the abstract representation of time tends to be asymmetrically dependent on the more concrete representation of space. This asymmetric relationship between time and space, which is at the core of the asymmetry hypothesis, was originally supported by the analysis of metaphorical language (Clark, 1973; Lakoff & Johnson, 2003): When we talk about time, we mainly use spatial terms that often include movement (e.g., "The weekend is getting closer," "The birthday is behind me"). Only rarely do we use temporal terms to talk about space ("I am five minutes from the central station", see Cai & Connell, 2015). A number of studies have provided evidence that these linguistic expressions reflect a deeper, asymmetric conceptual link between time and space (Boroditsky, 2000; Bottini & Casasanto, 2013; Coull et al., 2015; Merritt et al., 2010; Xue et al., 2014), with concurrent spatial information affecting time judgments (e.g., duration) to a greater extent than concurrent temporal information affecting spatial judgments (e.g., length). Taken together, a plethora of studies seems to support the *asymmetry hypothesis* and its assumption that spatial representations have a stronger impact on temporal representations than vice versa.

In contrast, according to the symmetry hypothesis, which is based on a theory of magnitude (= ATOM), it is assumed that time and space are processed by a shared analog magnitude system (Walsh, 2003). In keeping with ATOM, temporal and spatial representations are processed in a common neural substrate and share representational and attentional resources (e.g., Walsh, 2003).

The shared system for magnitudes of time and space (and numbers) explains compatibility effects without specifying any directionality of the effects. If space and time are both represented by the same general-purpose analog magnitude metric, there is no a-priori reason to posit that representations in one domain should depend asymmetrically on representations in the other. Empirical evidence for ATOM is provided by studies showing, for example, that expertise in temporal tasks (e.g., musicians) shows a positive transfer to spatial tasks (Agrillo & Piffer, 2012), or that overlapping neural substrates are active across temporal and spatial magnitude tasks (Skagerlund et al., 2016). By now, there is considerable empirical evidence for the *symmetry hypothesis* that space and time share the same basic spatio-temporal metrics and thereby equally influence each other (Agrillo & Piffer, 2012; Cai & Connell, 2015; Hyde et al., 2013; Skagerlund et al., 2016; Skagerlund & Träff, 2014; Walsh, 2003).

To summarize, on the one hand, there is empirical evidence for the asymmetry hypothesis and its main assumption that time and space remain two separate representational systems, with spatial representations being paramount in shaping our understanding of time, whereas temporal representations have less relevance when making spatial judgments (Boroditsky, 2000; Bottini & Casasanto, 2013; Coull et al., 2015; Merritt et al., 2010; Xue et al., 2014). On the other hand, there is empirical evidence to support the symmetry hypothesis that time and space share a common representational system, and hence, are symmetrically interrelated (Agrillo & Piffer, 2012; Cai & Connell, 2015; Hyde et al., 2013; Skagerlund et al., 2016; Skagerlund & Träff, 2014).

1.2.3 Scope of Mini-Review: Selection Criteria

The aim of this short review is to critically assess the literature supporting either the asymmetry hypothesis (CMT, Boroditsky, 2000; Lakoff & Johnson, 1980a) or the symmetry hypothesis (ATOM, Walsh, 2003) with a special focus on the question whether different tasks addressing different modalities may be the primary reason for (a)symmetric effects of space on time, instead of a genuine (a)symmetric mapping. To this end, we assessed whether the temporal and spatial tasks in the studies addressed the visual and/or auditory modality.

As both hypotheses have variants that refer to the same theory but use different wording (e.g., "*metaphorical* mapping", "*magnitude* system"), the literature search was based on the core words for each theorical background ("metaphor", "magnitude"). Therefore, the authors performed two database searches (Web of Science, 24th of March 2018) using the terms a) "metaphor*", "time" or "temporal", and "space" or "spatial", and b) "magnitude*", "time" OR "temporal", and "space" OR "spatial". Papers with these three terms in the title were included. The search resulted in a) 36 and b) 40 results. To extend and validate the search results, the authors performed an additional database search using the terms: "time-space" or "space-time" and "asymmetr* mapping," or "symmetr* mapping." The search resulted in only four hits, of which one was in favor of the symmetry hypothesis. This article was therefore added to b). Two were off-topic and the fourth article was non-empirical and therefore not included.

From the list of papers resulting from the literature search, we selected only empirical studies that focused on time as well as on space (e.g., some studies focused on temporal metaphors without addressing the time-space (a)symmetry or others were completely off-topic). Although important for the understanding of the interrelations of time and space, the following review makes no statements about accounts concerning the processing stage in which the interrelation might occur (encoding, memory interference, retrieval) or about other possible moderators or modulators (e.g., R. Wang & Cai, 2017). Furthermore, neural correlates of spatial and temporal representations are not discussed within the scope of this mini-review. In addition, based on suggestions by an anonymous reviewer, two further studies important in the context of temporal and spatial representations were added (Casasanto et al., 2010; Casasanto & Boroditsky, 2008). In the end, 16 studies were included in the analysis (see Tables 1-1 to 1-3). These 16 studies will be summarized with a special focus on the modality of the applied tasks.

Table 1-1. Studies supporting the conceptual metaphor theory and therefore an asymmetric time-space mapping

Study	**Participants**	**Temporal and spatial tasks: Modalities**	**Independent variables**	**Dependent variables**	**Main finding**
Boroditsky, 2000	Exp. 1: *N* = 98 Exp. 2: *N* = 302 Exp. 3: *N* = 53	Space: visual Time: visual	Exp. 1 – 3: Temporal and spatial prime questions to prime either an ego-moving or object-moving frame of reference	Consistent response between prime and target questions (%); confidence score	Asymmetric time-space mapping, evidence for conceptual metaphor theory
Casasanto and Boroditsky, 2008	Exp. 1-3: *N* = 9 Exp. 4: *N* = 16 Exp. 5: *N* = 10 Exp. 6: *N* = 19	Space: visual Time: visual and auditive	Duration/ spatial displacement of stimuli (growing lines/ moving dot) presented on a computer screen	Temporal or spatial judgment (Cross-dimensional interference effects; effect of distance on time estimation/effect of time on distance estimation)	Behavioral asymmetry: we rely on spatial information to make temporal estimates (particularly when space and time are conflicted in motion); not vice versa -> not only linguistic, here also nonlinguistic (representations for estimation)
Casasanto et al., 2010	*N* = 99 native Greek-speaking children	Space: visual Time: visual	Presentation of "racing snails" with congruent/incongruent traveled distance (spatial) and duration (temporal), duration/distance tasks without spatial/temporal interference	Temporal or spatial judgement (cross-dimensional interference tasks), distance or duration judgment (non-interference tasks)	Space and time related asymmetrically, evidence for conceptual metaphor theory (children can ignore irrelevant temporal information when making judgments about space, but have difficulty ignoring spatial information when making judgments about time)

Merritt et al., 2010	2 rhesus monkeys, 16 adult humans	Space: visual Time: visual	Presentation of lines with congruent/ incongruent length (spatial) and duration (temporal)	Temporal or spatial judgments, influence of irrelevant dimension (space or time) on relevant dimension (space or time)	In humans: Asymmetrical time-space interactions predicted by conceptual metaphor theory; In monkeys: Symmetrical time-space interactions
Bottini & Casasanto, 2013	*N* = 56 children (4-10 years old)	Space: visual Time: visual	Presentation of 'racing snails' with congruent/ incongruent travelled distance (spatial) and duration (temporal), duration/distance tasks without spatial/temporal interference	Temporal or spatial judgment (cross-dimensional interference tasks), distance or duration judgment (non-interference tasks)	Space and time related asymmetrically, evidence for conceptual metaphor theory (children can ignore irrelevant temporal information when making judgments about space, but have difficulty ignoring spatial information when making judgments about time)
Xue et al., 2014	*N* = 24 (Chinese)	Space: visual Time: visual	Chinese and English sentences, (correct/ incorrect) containing temporal ordering and spatial sequencing	Acceptability ratios, ERPs	Neural representations during temporal sequencing and spatial ordering in both languages different, time-spatial relationship is asymmetric, evidence for conceptual metaphor theory
Coull et al., 2015	*N* = 16	Space: visual Time: visual	Duration or distance of dynamic trajectory of a moving dot (or static line stimulus, control condition)	fMRI (comparison of the accumulation of information in temporal versus spatial domains)	Shared magnitude system, but time-space asymmetry
Zito et al., 2015	*N=36 (18 old and 18 young participants)*	Space: visual Time: visual	Virtual reality with slow traffic condition (cars driving 30km/h) vs. a fast traffic condition (cars driving 50 km/h)	Street crossing behavior (temporal or spatial judgement), eye and head movements, non-parametric tests	Both groups paid more attention to space (distance of oncoming cars) than to time (speed of the cars) -> asymmetric; younger pedestrians behaved in a more secure manner while crossing a street (as compared to old people)

1.2.4 Asymmetry vs. symmetry hypothesis: A modality-specific analysis

Results indicate thatmost studies in favor of an *asymmetric* time-space mapping (Table 1-1) used visual tasks for both temporal and spatial representations (Boroditsky, 2000; Bottini & Casasanto, 2013; Casasanto et al., 2010; Coull et al., 2015; Merritt et al., 2010; Xue et al., 2014; Zito et al., 2015). Only one study (Casasanto & Boroditsky, 2008) included an audiovisual task but only for temporal judgments. Tasks applied were, for example, duration and distance judgments (Bottini & Casasanto, 2013) or ambiguous temporal and spatial questions (Boroditsky, 2000).

All reviewed studies in favor of a *symmetric* time-space mapping (Table 1-2, Agrillo & Piffer, 2012; Hyde et al., 2013; Skagerlund et al., 2016; Skagerlund & Träff, 2014) used visual tasks for the spatial domain only (except for one study that applied haptic tasks, Cai & Connell, 2015). With respect to the temporal domain, most of the studies in favor of the symmetry hypothesis applied an auditory task to measure temporal representations. Tasks included, for instance, temporal (e.g., which of two tones lasted longer) and spatial (e.g., which of two lines was longer) discrimination tasks (Hyde et al., 2013), or incongruent vs. congruent audio-visual length-time pairings (Agrillo & Piffer, 2012). One study (Skagerlund & Träff, 2014) used a visual task for measuring temporal performance.

The results of three studies support neither a symmetric nor asymmetric time-space mapping (Table 1-3; Cai & Connell, 2016; Rousselle et al., 2013; Yates et al., 2012). These reviewed studies applied visual tasks (except one study that applied an auditory task for the temporal domain, Rousselle et al., 2013), consisting of, for example, temporal and spatial distance judgments tasks (Cai & Connell, 2016) or temporal and spatial discrimination tasks (Rousselle et al., 2013).

Importantly, Yates et al. (2012) investigated whether the found interrelations between time and space are due to affected representations or whether they are influenced by a decisional bias. As they found a reversed effect of space on time when changing the comparative task to an equality judgement they concluded that the given response requirements might affect the interaction between space and time as well. These findings neither support ATOM nor CMT. Therefore, the study was categorized to Table 1-3.

Furthermore, we decided not to list (Cai & Connell, 2016) in Table 1-2, supporting the symmetry hypothesis based on ATOM, but in Table 1-3 as the authors did not investigate the bidirectionality of the relationship between temporal and spatial representations. Only the influence of space on time was examined and therefore no conclusion concerning the (a)symmetry was drawn. Note though that Cai and Connell (2016) interpreted their results as being favorable toward the internal clock model (Gibbon et al., 1984) which is based on ATOM.

Finally, Rousselle et al. (2013) failed to support the symmetry hypothesis in their study. They showed a relationship between the magnitude perception of numbers and space but no association to time perception. Hence, their results support neither of the two theories and were also included in Table 1-3.

Table 1-2. Studies supporting the theory of magnitude, and therefore a symmetric time-space mapping

Study	Participants	Temporal and spatial tasks: Modalities	Independent variables	Dependent variables	Main finding
Agrillo and Piffer, 2012	*N* = 27 (13 professional musicians, 14 non-musicians)	Space: visual Time: auditory	Temporal (which of two tones lasted longer), spatial (which line was longer), numerical discrimination (which group of dots was more numerous) tasks	Judgment ratio, accuracy	Musicians (= experts in temporal discrimination) were not only better in temporal discrimination, but also in spatial discrimination, evidence for a shared magnitude system
Hyde et al., 2013	*N* = 32 (five-month old infants)	Space: visual Time: auditory	Relationally congruent/incongruent audio-visual length-time pairings	ERPs	Preverbal infants show incongruent effects when temporal and spatial magnitude do not match, evidence for a shared magnitude system
Skagerlund and Träff, 2014	*N* = 82	Space: visual Time: visual	Magnitude processing tasks: Space, time and number processing, screening tests, domain-general cognitive abilities	Response times	Children with dyscalculia displayed difficulties across time, space, and number magnitude processing tasks, evidence for a shared magnitude system
Cai and Connell, 2015	*N* = 32	Space: haptic Time: auditory	Touching (without seeing) physical sticks while listening to a congruent/incongruent auditory note	Reproducing length and duration of the presented stick/auditory note	Space-time mapping depends on the perceptual acuity of the modality used to perceive space, evidence for a shared magnitude system
Skagerlund et al., 2016	*N* = 24	Space: visual Time: visual	Time, space, and number discrimination tasks	Accuracy, response times, fMRI	Overlapping neural substrates across multiple magnitude dimensions, evidence for a shared magnitude system

1.2.5 Discussion and conclusions

Based on the evaluation of 16 studies that were included in this short review, the results seem to provide initial support for the assumption that the use of different tasks addressing different modalities may account for (a)symmetric effects of space on time. In fact, the studies supporting the symmetry hypothesis predominantly used auditory tasks (and not visual tasks) when compared to studies supporting the asymmetry hypothesis. Given the discrepancy in the theoretical interpretation of the corresponding findings we suggest that (task-dependent) modality-specific processing plays a significant role for interrelations between temporal and spatial representations. Therefore, taking modality-specific processing into account when putting the conflicting hypotheses to test seems mandatory in order to shed light on the mechanisms underlying the interrelation between temporal and spatial representations.

Table 1-3. Studies examining temporal and spatial representations, but suggesting neither an asymmetric or symmetric time-space mapping.

Study	Participants	Temporal and spatial tasks: Modalities	Independent variables	Dependent variables	Main finding
Yates et al., 2012	Exp. 1: *N* = 16 Exp. 2: *N* = 16	Space: visual Time: visual	Small and large squares differing in duration	Exp. 1: Duration judgment (longer/shorter than previous stimuli) Exp. 2: Duration judgment (same/different than previous stimuli)	Larger stimuli were judged—though not necessarily perceived—as *shorter* in duration
Rousselle et al., 2013	20 patients with Williams Syndrome 40 typically developing children	Space: visual Time: auditory	Temporal (which of two tones lasted longer), spatial (which line was longer), and numerical (which group of dots was more numerous) discrimination tasks, visuo-spatial task	Working memory of space, judgment ratio of time and space	The number processing difficulty of patients with Williams Syndrome was related to difficulties in visuo-spatial magnitude processing; auditory processing was not related to number processing difficulty
Cai and Connell, 2016	Exp. 1: *N* = 26 Exp. 2: *N* = 18	Space: visual Time: visual	Exp. 1: Visual flicker and spatial distance at either encoding (Exp. 1a) or reproduction (Exp. 1b) stage Exp. 2: Replication of Exp. 1, but with a within-subject design	Exp. 1a: Participants reproduced the stimulus duration while a neutral visual stimulus appeared onscreen Exp. 1b: Participants reproduced the stimulus duration while the visual flicker or spatial distance stimulus appeared onscreen. Exp. 2: Same as in Exp. 1	Exp. 1: Visual flicker affected time perception at both encoding and reproduction stages, whereas spatial distance affected time perception at the encoding stage only Exp. 2: Replication of Exp. 1

Based on our assessment, it seems justified to argue that the studies in favor for either asymmetry or symmetry could easily be re-interpreted. For example, in Coull et al. (2015) asymmetry experiment it is apparent that the spatial and the temporal information were both provided by visual information. If we consider that visual information processing shows higher sensitivity to spatial information yet lower sensitivity to temporal information (e.g., Recanzone, 2009), the observed asymmetry could be based on the different informational values of vision and audition with respect to spatial and temporal information. In other words, when only visual information (but no auditory information) was provided, the reported asymmetry between space and time may hinge on that fact that the task was purely visual, and hence had a higher informational value for space than for time. In this context, R. Wang and Cai (2017), for instance, suggest that the cross-dimensional magnitude interaction depends on the amount of representational noise. If the rated construct is noisier and thus less reliable, it is more likely to be influenced by other magnitudes. Cai et al. (2018) therefore provide a Bayesian interference model to explain the findings.

Although the literature indicates that modality-specificity might matter when examining temporal and spatial representations, results were not distinctly clear: Some studies showed evidence for a symmetric time-space mapping, even though they applied a visual task to measure temporal representations. This pattern might be caused by the fact that modality-sensitivity is not the only factor influencing time-space mappings. Sticking with the assumption that there may be no genuine time-space (a)symmetry, there are some other factors — besides modality-specificity — that likely have an impact on the (a)symmetry of time and space. Other potential moderators could be, for example, the task automaticity/familiarity and response propert (encoding, memory interference, retrieval, e.g., Cai et al., 2018)ies that cause decisional bias (Yates et al., 2012). In addition, the participant's age could be a moderator given that temporal vision matures more rapidly than spatial vision during childhood (Ellemberg et al., 1999). Furthermore, it is still under debate at which stage of processing the interference between time and space occurs (encoding, memory interference, retrieval, e.g., Cai et al., 2018). Cross-dimensional relations might differ depending on the different stages of processing and provide avenues for future research.

Although it seems challenging to dissociate cross-dimensional interactions, future studiesmight benefit from applying tasks that genuinely require both a balanced representation of time and space. Potential tasks resembling a more balanced representation of time and space include movement tasks such as catching a ball, as temporal and spatial representations play an analogous role for the execution of such movements. Further, recent evidence shows the importance of auditory information, additional to visual information, in anticipation tasks of moving stimuli (e.g., the landing location of a tennis ball, Cañal-Bruland et al., 2018). A crucial role of movements in interrelations of temporal and spatial representations is additionally supported by the fact that the processing of such quantities overlaps in parietal brain regions associated with action control (Bueti & Walsh, 2009). It is assumed that we learn associations occurring across different magnitude domains by moving in our environment. For example, catching a ball that was thrown from far away requires slower running speed than catching a ball that was thrown from a nearer distance (assuming that the balls were thrown with the same speeds and one was trying to catch at the same interception location). Therefore, in future studies, a task that genuinely contains movement (i.e., catching a ball), and provides visual as well as auditory information, might be beneficial to investigate the mechanisms that drive time-space mappings. Surely, future empirical research including movement in the task and taking potential moderators (e.g., modality-specificity, task automaticity, age) into account is needed to confirm or reject our assumptions.

A potential limitation of our short review is that it is quite likely that not all studies scrutinizing time-space mappings were covered by our literature search. One evident reason is that different terms and wording have been used in different studies. We cannot rule out that some studies, for example, provide evidence for symmetric time-space mappings without naming it time-space mapping or mentioning ATOM.

In summary, our literature review highlighted that seemingly contradictory claims could be bridged if cross-dimensional magnitude interactions between temporal and spatial representations were considered. It follows that previous experiments that examined only one modality may have limited success to specify the (a)symmetry of temporal and spatial representations and hence do not provide a proper test to tease the conflicting hypotheses apart. Consequently, a systematic manipulation of the relative contributions of different modalities to executing task-appropriate solutions in both the space-sensitive visual domain and the time-sensitive auditory domain seems necessary. Taking a task such as catching a ball as a testbed might be a promising approach to draw conclusions about the (a)symmetry of temporal and spatial representations.

END OF PUBLICATION

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1.3 Measurement of spatiotemporal interrelations: Action vs. Perception Tasks

The previous chapter summarized studies on spatiotemporal interrelations. As highlighted, nearly all studies focused specifically on perceptual tasks, like comparative judgements (e.g., Yates et al., 2012), or on immediate reproduction of spatial extent or temporal duration (e.g., Cai & Connell, 2015). However, just because such interrelations have been found for perception, that does not mean, they necessarily impact how humans (inter)act with their environment. For instance, research on grasping movements (e.g., Aglioti et al., 1995; Haffenden & Goodale, 1998) and throwing (e.g., Cañal-Bruland et al., 2013) have shown that perceptual illusions are not consistently transferred to action tasks. Based on the notion that common spatial and temporal demands involve not only judgements or reproduction but rather movements, a more realistic setting – that is an action task – might help to investigate the relevance of such interrelations for natural human behavior.

Perceptual paradigms often produce an artificial problem. In most daily activities, it is not relevant whether people can exactly reproduce a temporal interval. Instead, it is more important, whether they can correctly adapt their behavior. This creates a more complex task where (accurate) perception needs to be accompanied by prediction of the target's motion, decision processes and movements of their own body. When observing an approaching car, we must typically predict its motion path (i.e., the future location at a certain time) rather than (only) reproducing or judging the observed movement. Based on that prediction we can decide to cross the street, adjust our speed, and so on. The perception of the observed path certainly plays a role, but more importantly, it should be addressed whether any biases can be found for the predicted path, or the resulting action.

We argue that typical tasks in which spatial and temporal interrelations become ecologically relevant and realistic are motion tasks, like catching a ball. Such a task is termed *interception*. It is defined as a situation in which a moving object is stopped by spatiotemporally approaching it within its movement path. Typical examples of interception include catching or batting a ball, puck, or other object in motion, but also whole-body movements, such as pulling up alongside a friend walking in front of us or giving a high five. An introduction on interception tasks in previous research will be given in Chapter 2.

In addition to measuring manual interception responses, another type of motor response might prove beneficial especially in the context of biases reported for perceptual tasks (cf. Schütz et al., 2011), that is, eye movements. These include smooth pursuit (slow movements of the eyes to track a target in motion; Land, 2019) and saccades (fast movements of the eyes to certain locations of interest; Land, 2019) which will be specifically addressed in Chapter 3 of this thesis.

1.4 Research Question and Outline

As a basis for experimental studies, the literature review in Chapter 1 carved out a potential factor explaining these seemingly controversial results – namely the use of different sensory input. The aim of this thesis is therefore to test spatiotemporal interrelations across different modalities to investigate the predictions of (a)symmetrical interrelation of a theory of magnitude (ATOM; Walsh, 2003) and the conceptual metaphor theory (CMT; Boroditsky, 2000; Lakoff & Johnson, 1980a) in an interception context. It is argued that for visual stimuli, in accordance with the findings of CMT, spatial features should impact the temporal response more severely than vice versa. In contrast, in an auditory setting, the impact of temporal characteristics on the spatial response is expected to be larger than the other way around (see Figure 1-1; e.g., Recanzone, 2009).

Figure 1-1. Overview of the research question. It is hypothesized that spatiotemporal interrelations depend on the sensory input. *Left*: In a visual task, human representation of space should be very accurate whilst the percept of time is expected to be noisy. Therefore, the impact of spatial characteristics on temporal reactions should be larger than vice versa, where no or only small impacts are expected. *Right*: In the case of auditory input, more precise representations of time and less precise representations of space are expected, leading to larger impacts of temporal characteristics on spatial responses.

To address these predictions, in a first step, it was necessary to find an adequate interception paradigm that allows us to *disentangle spatial from temporal contributions to the manual interception response*. The paradigm should include a task, that can be administered across at least two modalities – namely vision and audition. In Chapter 2 one example of such a paradigm is explained. Using parabolic ball flight trajectories, participants' time and horizontal location of interception on a pre-defined ground line were measured and effects of visual blur on the constant and variable errors (Tresilian & Plooy, 2006) were tested. Furthermore, a similar paradigm for auditory stimuli was tested and published in addition to this thesis (Tolentino-Castro et al., 2021).

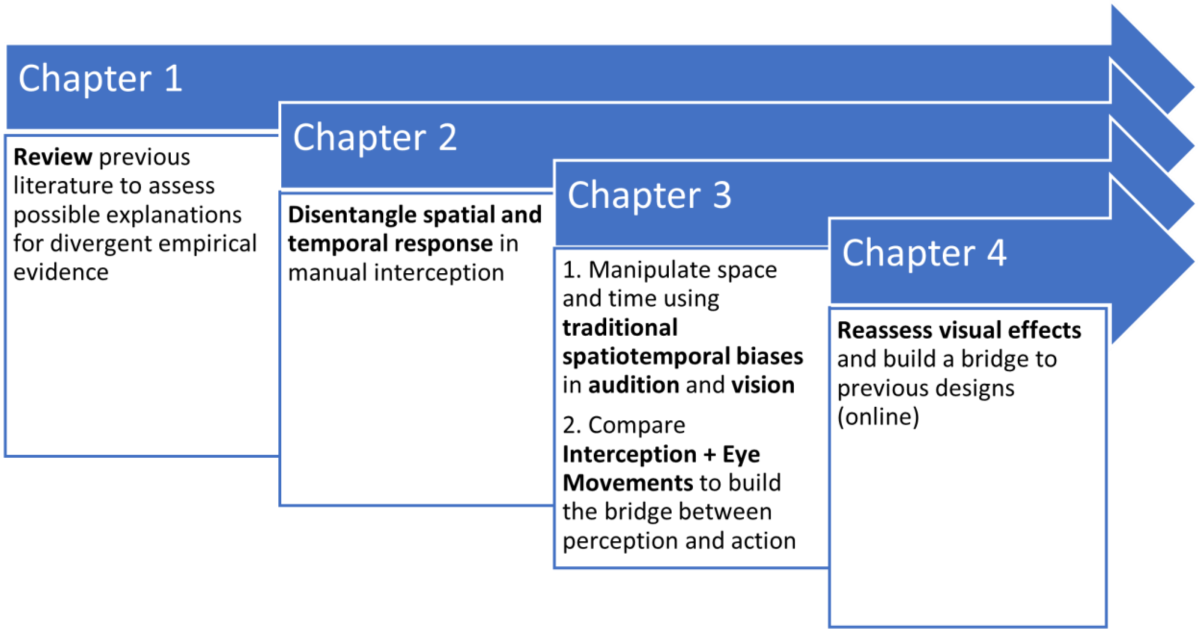

Figure 1-2. Overview of the steps to address the research question.

Despite being able to dissociate a spatial and temporal response, the chosen parabolic trajectories of flying balls showed some limitations: Time-space interdependencies in the presentation on the one hand, and difficulties of auditory localization in the vertical dimension on the other hand, forced adaptations to this task. In a second step, a new paradigm was developed based on two prominent, psychophysiological phenomena that allow the *independent manipulation of spatial and temporal features* of a 'motion' trajectory for *auditory and visual stimuli*. This study directly addresses the predicted differences in spatiotemporal interrelations. In step three, the *gap between* the focus of previous studies on *perception of spatiotemporal interrelations and action (as assessed in interception)* is addressed, by investigating eye movements. Given that eye movements depend on perceived target motion, and perceptual biases can also be found in tracking movements (cf. Schütz et al., 2011), tracking gaze may reveal whether the spatiotemporal biases are present on a perceptual level in the new paradigm, even when they are absent or weak in manual interception. Both steps are reported in Chapter 3.

As a final step, the *visual kappa effec*t – that is the effect of spatial intervals on the temporal response (introduced in Chapter 1.5) – was *reassessed* in two online experiments. Surprisingly, and in contrast to most perceptual studies on this effect, the study in Chapter 3 revealed no or even a small, reversed kappa effect for visual stimuli. To address possible explanations for this discrepancy, such as task difficulty or the simultaneous execution of the spatial and temporal response (dual task), two similar experiments with a larger sample size and small adaptations to the paradigm were run. Additionally, this study aimed at testing for interrelations not only on interception but also temporal prediction, again to address the *gap between previous perceptual paradigms and the current action task*. These two experiments are reported in Chapter 4. An overview of the steps to address the research question is provided in Figure 1.2.

1.5 Methodological considerations

To address the research questions empirically, a series of experiments, mainly in the laboratory, were planned. As already mentioned, it is an important challenge of interception to disentangle the spatial and temporal response. To do so, a first idea, further explained in Chapter 2, was to present parabolic flight trajectories (e.g., like a thrown ball) starting and ending on a ground line. A visual circle (representing a ball) moving along those trajectories, was occluded to force participants to predict the location *where* and the time *when* the ball would hit the ground line, by interception. There are different possible tasks and error definitions in the literature. For example, Kreyenmeier et al. (2017) administered a manual interception task and defined an orthogonal (spatial) error as the smallest distance from the interception location to the target trajectory, and the temporal error as the difference between this closest location and the location where the target was at the moment of interception. In a study using dart throws to intercept a moving target, the exact interception location was predefined (in one condition) and various measures of temporal and spatial accuracy were analyzed. Using a spatial constraint by predefining the targeted interception location, for instance, the deviation of the dart impact from this location, or the deviation of the dart impact from the current position of the target were taken as spatial errors. The temporal errors were calculated by dividing the distance between dart impact and target location or between target and predefined interception point by the speed of the target. The temporal error was measured as the time difference of the dart hitting the board and the target passing the defined location (Lim, 2015). Similar to the latter study, we also selected a spatial constraint to dissociate temporal from spatial interception errors, by requiring participants to intercept the location on the ground line at the moment when they predicted the target to cross this line. In contrast to the restriction in Lim (2015), only the height of interception was predefined, leaving a horizontal spatial error resembling the orthogonal error in Kreyenmeier et al. (2017), and leading to a similar definition of the timing error. The temporal error was defined as the difference between predicted and actual crossing of the line.

Similarly, the spatial error was defined as the horizontal distance between intercepted and actual point of crossing the line.

Second, as introduced above, the paradigm was further adapted based on two perceptual spatiotemporal biases – namely the tau and kappa effects. When comparing the distance between stimuli that are successively presented, our judgements have been found to depend on the temporal intervals between presentations. The more time passes between presenting two objects, the more distant they are perceived – a phenomenon called tau effect (Benussi, 1913; Helson & King, 1931). Vice versa, the influence of distance between stimuli on judgments related to their temporal succession, is called kappa effect (or initially S-effect Abe, 1935; Cohen et al., 1953). These two biases, tau and kappa, enable us to either manipulate the spatial or temporal intervals without effects on the respective other dimension.

A third methodological aspect introduced here is the method of eye-tracking. As explained above, eye movements as a correlate of perceptual processes were chosen to fill the gap between the perceptual studies on ATOM/CMT and kappa/tau on the one hand and the new interceptive action paradigm on the other hand. Predictive saccades typically move the gaze to informative locations (e.g., interception location of the hand, bounce locations of a ball) before the event of interest happens (de la Malla et al., 2017; Fiehler et al., 2019; Fooken et al., 2021; Land & McLeod, 2000; Taya et al., 2013). Therefore, analyses of the timing and the location of the final saccades before stimulus presentation or interception might serve as dependent measures to investigate spatiotemporal interrelations.

Various types of eye-trackers with different possible applications are available. To allow for a wider range of movement (interception), a mobile head-mounted eye-tracker was chosen to be most appropriate. This, however, entails additional challenges: How to extract the exact location of participant's gaze on the presentation screen at each time. Typically, such eye-tracking goggles, record a video of the viewed scene and deliver the gaze location in reference to the scene video. If participants move their head, the scene changes, but this is not expressed in changes to the gaze coordinates. As this might happen for each frame of the video, the gaze location has to be reassociated with locations in the relevant space (in this case the presentation screen). One way to extract this actual location is the manual coding of the gaze position using a standardized reference image. With a high number of recorded frames and participants, this method becomes increasingly time-consuming and is prone to human errors. This might be especially relevant in this context, where biases on spatial perception might also impact the performance of the experimenter in manually assigning the locations. Therefore, we opted to develop a novel automatic gaze extraction algorithm, which was based on automated object detection (Bradski, 2000) and implemented in Python (van Rossum & Drake Jr, 1995). To achieve this, it was necessary to present reference objects on the screen that were later used to identify the captured scene. Those objects were simple geometric forms (triangles and rectangles) presented in a certain order. For each frame these geometric forms were extracted by object detection (through several steps, including filtering out skin colors, transformation to grey colors, blurring etc., see Figure 1-3). With the help of the extracted locations of those objects, the recorded image was aligned with the presentation screen using a homography transformation (Bradski, 2000). In a last step, the gaze location (indicated as a red circle in each frame) was extracted - again using object detection - and saved with reference to the presentation screen. This allowed us to associate the gaze location with the presented target.

In the following Chapters the experimental studies investigating the research question (see Chapter 1.4) are reported. The main aim is to test for spatiotemporal interrelations across sensory modalities.

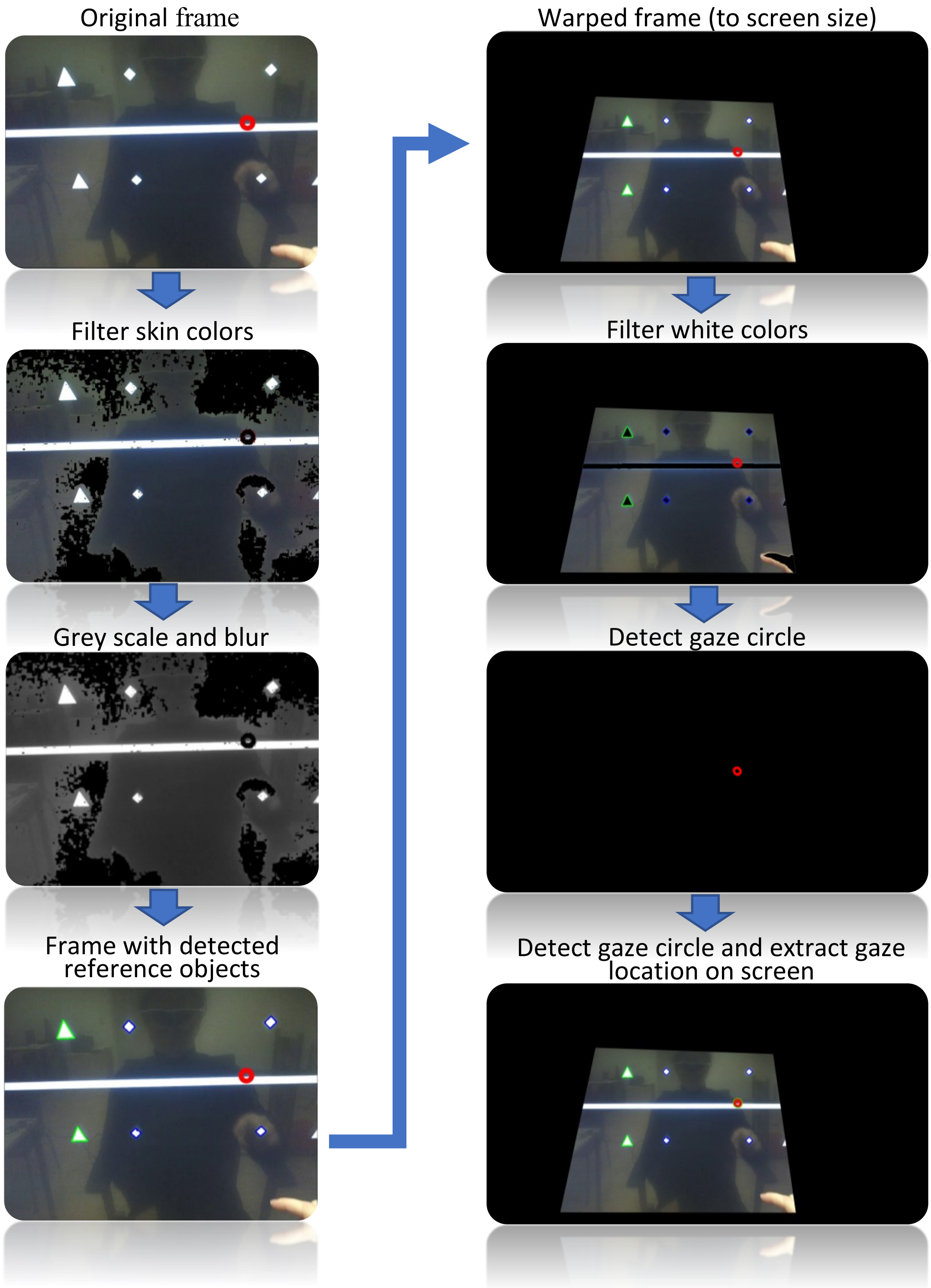

Figure 1-3. Automated gaze extraction using object detection in Python. The procedure is illustrated with one example frame. First, skin colors are removed from the original frame image, then the colors are transferred to grey scale and the image is slightly blurred to improve the following detection of the presented reference objects. In this case two triangles (green) and four rectangles (blue) were detected. Using the reference objects, the frame can then be warped to the dimensions of the touchscreen. Next, all white colors are excluded to improve the detection of the red gaze position circle. In the end, the location of the gaze is extracted and saved with reference to the current frame. This procedure is repeated for each frame of each trial.

2 Study I: Effects of visual blur and contrast on spatial and temporal precision in manual interception.

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Abstract

The visual system is said to be especially sensitive towards spatial but lesser so towards temporal information. To test this, in two experiments, we systematically reduced the acuity and contrast of a visual stimulus and examined the impact on spatial and temporal precision (and accuracy) in a manual interception task. In Experiment 1, we blurred a virtual, to-be-intercepted moving circle (ball). Participants were asked to indicate (i.e., finger tap) on a touchscreen where and when the virtual ball crossed a ground line. As a measure of spatial and temporal accuracy and precision, we analyzed the constant and variable errors, respectively. With increasing blur, the spatial and temporal variable error, as well as the spatial constant error increased, while the temporal constant error decreased. Because in the first experiment, blur was potentially confounded with contrast, in Experiment 2, we re-ran the experiment with one difference: instead of blur, we included five levels of contrast matched to the blur levels. We found no systematic effects of contrast. Our findings confirm that blurring vision decreases spatial precision and accuracy and that the effects were not mediated by concomitant changes in contrast. However, blurring vision also affected temporal precision and accuracy, thereby questioning the generalizability of the theoretical predictions to the applied interception task.

Keywords: Temporal precision, Spatial precision, Perception, Action, Interception, Spatiotemporal accuracy

2.1 Introduction

Visual perception is of utmost importance to guide our actions in daily life. For example, when aiming for a cup of coffee, vision informs us about where to grasp it so as not to tip over the cup and spill the coffee. In dynamic situations, for instance, when catching a fly ball next to spatial also temporal predictions are key (Fischman & Schneider, 1985; McBeath, 1990; Oudejans et al., 1996; Savelsbergh & Whiting, 1988). In such situations, successful actions are characterized by guiding the body or limbs to be in the right place at the right time.

To appropriately plan and control movements, the visual information picked up both in advance and during execution has been shown to make a significant contribution (see also Barany et al., 2020; Lim, 2015; Marinovic et al., 2009). Accordingly, if vision is diminished, it has been shown to result in less precise movements (e.g. H. Zhao & Warren, 2017). It was shown that manipulations of visual features such as, for instance, blur (Dehnert et al., 2011; Johnson & Casson, 1995), contrast (Hong Chen & Muhamad, 2018; Johnson & Casson, 1995), colors (Hong Chen & Muhamad, 2018), and luminance (Johnson & Casson, 1995; Tidbury et al., 2016) impact human perception by diminishing visual acuity (i.e., spatial resolution of the visual system).

Assuming that accurate visual perception is important to guide precise actions (see also Creem & Proffitt, 2001), it follows that such reductions of visual acuity should also impact spatiotemporal precision when intercepting moving objects such as when catching fly balls. In fact, Mann et al. (2007) demonstrated that high levels of myopic blur cause reductions in cricket batting performance. Players were asked to bat a ball delivered by a bowling machine under different blur conditions manipulated via differently blurred contact lenses. The highest myopic blur condition (+3 D) resulted in significantly reduced batting performance (percentage of bat-ball contacts) compared to the two smaller refractive conditions (+1 D and +2 D) whilst the other two levels did not differ significantly from normal vision. Hence, the authors concluded that optimal vision is not necessary for optimal interception, but that very high levels of myopic blur can negatively affect batting performance. The authors explain this resilience of cricket players to a wide range of blur with a good compensation of the human perceptual-motor system. They also noticed a maintenance of 'good' bat-ball contacts for high levels of blur at the cost of a less aggressive, more conservative strategy resulting in more defensive strokes which might be less efficient in a real cricket game. Similar results were obtained for aiming at stationary targets in golf putting (Bulson et al., 2008) and basketball free throws (Bulson et al., 2015) as well as for interception performance in another cricket study (Mann et al., 2010).

Bulson et al. (2008, 2015) provide several explanations of the missing effects for small blur levels: First, blur adaptation may have taken place in their experiments, as it was previously shown that participants adapt to low blur levels already after a few minutes exposure (B. Wang et al., 2006; Webster et al., 2002). Second, motor learning/motor memory might play an important role. The better a motor task is learned the stronger is the associations between sensory cues and appropriate motor responses and the less sensory input is necessary for movement execution.

H. Zhao and Warren (2017) recently investigated the effect of visual blur in a virtual interception paradigm. Participants were asked to walk in a virtual open environment towards a moving target, namely a green two-dimensional bar, to intercept it. The target was progressively blurred within each trial until reaching one of five blur levels (including no-blur) or complete disappearance. Whilst for the slowest speed condition, the constant error (mean, 'accuracy') was low for all blur levels, for targets with faster speeds, the constant interception error was increased with increasing blur, which resulted in a higher degree of undershooting. The variable interception error (intraindividual standard deviation, 'precision') increased as well with increasing blur. (H. Zhao & Warren, 2017) conclude that impairing vision by means of blur deteriorates participants' precision and accuracy (at least for faster speeds) in locomotor interception. Their results are in line with predictions of models including on-line control or continuous updating based on currently available visual information.

Together, these studies certainly show that optical defocus can deteriorate performance in interception tasks, at least for certain levels of blur. Importantly, in all these studies, the dependent measure in interception is actually an amalgam of spatial precision (being in the right place) and temporal precision (at the right time). That is, hits indicate both high spatial and temporal exactitude. Yet, whether misses (i.e., trials in which no successful bat-ball-contact was achieved) were caused by spatiotemporal imprecision or spatial imprecision or temporal imprecision alone was not disentangled.

In fact, according to Recanzone (2009), our visual system is more attuned to spatial perception whereas temporal perception is more precise in the auditory modality. Early evidence for this claim stems from work by O'Connor and Hermelin (1972) who showed that three visually presented digits were mostly analyzed for their spatial localization whilst the same but auditorily presented stimuli were merely regarded concerning their temporal succession. If true, reductions of vision by means of blur should affect spatial perception more severely than temporal perception. Consequently, it is expected that it becomes more difficult to spatially intercept a moving target resulting in a higher spatial variability of the interception response, whilst the temporal response should be less affected. If true, this leads to a more differentiated hypothesis, namely, that a reduction of vision by means of blur should result in a lower spatial precision, but not (or to a lesser extent) in a lower temporal precision. Based on this assumption, the misses observed in the highest blur condition in the study of, for instance, Mann et al. (2007) may have been mainly caused by spatial errors but not so much temporal imprecision. While other variables of interception, like movement time, have been the focus of many studies, only few studies have aimed to disentangle the interception outcome measure in a temporal and spatial ('orthogonal') response (e.g., Kreyenmeier et al., 2017; Lim, 2015). We argue that such a disentanglement would not only be practically relevant but also theoretically insightful when investigating the effect of blur.

To test whether the effect of blur on interception, indeed resulted from diminished spatial and not (or lesser so) temporal precision, in Experiments 1 and 2 participants were asked to indicate (i.e., finger tap) on a large-size touchscreen where and when a virtual ball (moving along parabolic trajectories) crossed a ground line. While in Experiment 1 vision was manipulated using five levels of Gaussian blur, in Experiment 2 we systematically manipulated five levels of contrast instead, to clarify whether coincident changes might have driven the results found for blur.

2.2 Experiment 1

To test whether the previously reported effects of (high) blur on interception performance might be caused by reduced spatial and not or lesser so temporal precision in interception, we used a manual interception task on a touchscreen. A virtual ball (white filled circle) was presented moving across the screen in a parabolic flight curve from one side towards the other until it was occluded at different times shortly before hitting a white ground line (for an illustration, see Figure 2-1). Participants were asked to intercept the ball by touching the location on the ground line *when* and *where* they expected the ball to cross it. Participants' performance was measured using the spatial constant and variable errors and the temporal constant and variable errors (Tresilian & Plooy, 2006). Similar to Brenner et al. (2014) and H. Zhao and Warren (2017), we interpreted the variable errors as indicators of the respective precision or uncertainty of the response, and the constant errors as accuracy or a general bias in the response (e.g., to overshoot or undershoot the width of the trajectory). Previous research has shown that visual perception is more attenuated towards spatial than temporal information (O'Connor & Hermelin, 1972;

Recanzone, 2009). Reducing vision by blurring the stimulus might therefore have stronger effects on spatial than temporal processing. Consequently, we hypothesized that increasing levels of Gaussian blur of the ball would lead to less precise spatial representations of the stimulus which should result in monotonically decreased spatial precision (as in H. Zhao & Warren, 2017), but would have no effect or a smaller effect on temporal precision. Additionally, the effects of blur on the spatial and temporal constant errors were examined.

2.2.1 Materials and Methods

2.2.1.1 Participants

A total of 42 participants (15 male, M_{Age} = 25.5 years, SD_{Age} = 5.2 years, 40 right-handed) took part in Experiment 1. Seven additionally recruited participants were excluded: three did not fulfil the required visual abilities and four had to be excluded due to technical problems during experimentation (for sample size justification and an a priori power analysis, see Appendix 6-1).

Participants were only included in the analysis if they had normal or corrected to normal vision and if they did not report any neurological disorders. To assess vision two subtests (Acuity C and Contrast C) of the Freiburg Vision Test (FrACT) (Bach, 1996, 2006) were conducted (and in the settings the gamma value was set prior to contrast testing). Participants had to reach a visual acuity of 0.00 log MAR or better and a contrast sensitivity of at least 1.7 log CS (Roper & Hassan, 2014). Participants received an expense allowance of 8 €. This study forms part of a research program that was approved by the local ethics committee.

2.2.1.2 Materials

We used a 43’’ touchscreen (Iiyama PROLITE TF4338MSC-B1AG, 1920 x 1080, 60Hz, 2.1 megapixel Full HD, 8 bit, Multi-Touch-Monitor) to present visual stimuli and measure participants’ responses in a manual interception task. The visual stimuli were presented using PsychoPy 3 (Peirce et al., 2019), programmed in the Coder view with a self-written Python script.

In each trial, a white circle (4,9 cm = 100 px diameter) representing a virtual ball was shown on a black screen (see Figure 2-1a). The ball moved across the screen following one of three parabola trajectories (see Figure 2-1b) mimicking the kinetics of parabolic throwing, however, neglecting air resistance. Hence, the horizontal velocity was kept constant within each trial (3, 4 or 5 px per frame = 8.82, 11.76 or 14.7 cm/s), whilst vertical velocity was varying accordingly. The three trajectories together with the three velocities resulted in nine different transit durations (ranging from 1.63 s to 4.97 s; for additional information see Appendix Table 6-1). Each trajectory started at a white ground line (0.98 x 94 cm) at a distance of 34.3 cm from the center (either on the left or the right) and moved towards the central part of the screen (see Figure 2-1b). During the final part, the ball was occluded for 300, 700 or 1100 ms before hitting the ground (Benguigui et al., 2003). The ball was presented in five different blur levels which were manipulated separately using Photoshop's ("Adobe Photoshop CS," 2004) Gaussian blur tool with radii of 0, 10, 20, 40 and 60 pixels (see Figure 2-1a upper line). The different levels of all variables were chosen based on Benguigui et al. (2003) and on pilot testing with 11 participants none of whom took part in the main experiment. Different occlusion times, velocities, sides, and trajectories were induced to create different landing positions and times (i.e., induce variability in the task), but were not the focus of analyses.

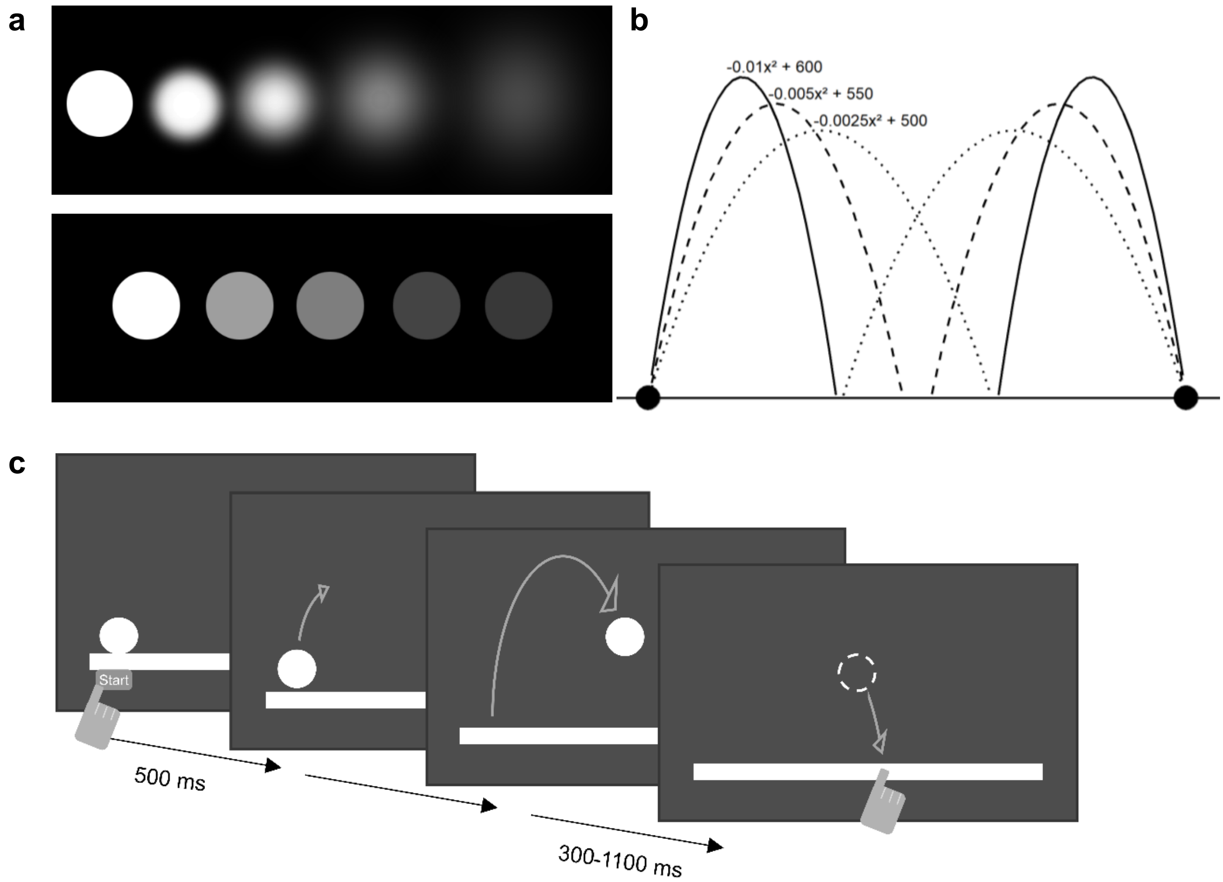

Figure 2-1. Visual Manipulation and Experimental procedure. A: Upper line: Five levels of Gaussian blur (0 px, 10 px, 20 px, 40 px, 60 px) used in Experiment 1. Lower line: Five levels of contrast (95%, 85%, 78%, 46%, 34% Michelson Contrast) used in Experiment 2. B: Parabola trajectories. C: Procedure: After pressing the start button, the ball was presented stationary for 500 ms and then began moving in a parabolic flight curve. 300-1100 ms before it would hit the ground line, it was occluded, and participants had to indicate the location and time of the hit by tapping the location at the right time. The balls horizontal velocity was kept constant per trial but altered between trials (3, 4, 5 px/frame = 8.82, 11.76 or 14.7 cm/s).

2.2.1.3 Procedure

The experiment consisted of three parts. After providing informed consent, first participants' visual acuity and contrast sensitivity were tested using the FrACT (Bach, 1996, 2006). Then, in the second and main part each individually tested participant was asked to sit at approximately 40-50 cm in front of the vertically mounted touchscreen and to perform the manual interception task (see Figure 2-1c). The participant began with a block of 12 familiarization trials (without occlusion). Each trial was initiated by the participant pressing the 'Start' button presented at the start position of the ball. Upon pressing the button, the ball was presented immediately and started its movement after a 500 ms delay. It moved in a curved trajectory (see Figure 2-1b) from the side where the 'Start' button was placed toward the central part of the screen.

As illustrated in Figure 2-1c, the participants' task was to indicate with the index finger of their dominant hand when and where they thought the center of the virtual ball (white circle) crossed the ground line (see also Brenner et al., 2013). A touch event was registered as the moment of releasing the finger from the screen. Also, this is what participants should be experienced with due to common touchscreen usage, for instance, on smartphones.[4] Subsequently, the participant performed two blocks of 12 practice trials similar to the familiarization trials but with occlusion of the ball during the final part of the trajectory. Consequently, the participant had to extrapolate the movement to correctly hit the location and time of crossing. During the familiarization and practice phase trajectories, velocities and occlusion times slightly differed from those used during the main trials of the experiment. After each trial in the familiarization and practice phase, participants received specific feedback about their temporal and spatial error (in ms and mm). Following the familiarization and practice phase, and some additional instructions, the main part of the experiment started.

The ball's trajectory (3), horizontal velocity (3), occlusion time (3), side (2), and blur levels (5) were altered randomly across the 270 trials (for levels of each variable, see Materials). Every 45 trials, a pause of at least 1 min was included. During this pause, accumulated feedback about the previous trials was presented as a percentage score of spatially and temporally correct trials (hit) for motivational reasons. A hit was defined as touching the screen at a maximum distance of 100 pixels (4.9 cm) from the *current* position of the ball's center. That means that both being

[4] It allows for spatial adjustments before the finger is released from the screen and the timing is recorded. Pilot testing showed that participants only shortly touched the screen and did not make any obvious spatial adjustments during the contact. Participants were informed about and had time to familiarize with the task demands during the initial 24 familiarization and practice trials (with immediate spatial and temporal feedback). Importantly, participants almost never used the possibility to spatially adjust and instead only shortly touched the screen.

spatially and temporally on target was required to count as a hit. In contrast, being at the correct landing position when the ball is currently at its zenith or tapping the correct position when the ball had already passed the ground line, was not counted as a hit. Different distances were tested during piloting and a distance of 4.9 cm was chosen to ensure good enough results to keep the motivation of the participants reasonably high (average hit rate between 30% and 40%).

Finally, the participant received a questionnaire collecting information about, for instance, their handedness, age, familiarity with touchscreens, electronic games, and ball sports. The whole procedure lasted about one hour.

2.2.1.4 Data preparation

To analyze the spatial error, only the horizontal deviation (on the ground line) was considered. Based on H. Zhao and Warren (2017), we took into account the flight direction of the ball (left to right and right to left) when calculating the difference between the location where the participant touched the screen and the actual landing position of the ball. This resulted in coding negative values of the *spatial deviation* as 'undershooting' and positive values as 'overshooting'[5] the width of the trajectory.

The *temporal deviation* was calculated by subtracting the actual time of the ball crossing the ground line from the time when the participant touched the screen (release of the touch event). Hence, positive values signify that the participant touched the screen too late whilst negative values stand for reactions being too early.

Outlier analysis on the level of each individual (Grubbs, 1969) indicated that for both dependent measures over 90% of the participants produced at least one outlier. Therefore, outliers defined as all values more than 1.5 times interquartile range above the 75%-quantile or below the 25%-quantile (on an individual level) were excluded. This analysis resulted in 591 of 11340 trials (5.2 %) for the spatial and 313 of 11340 trials (2.7 %) of the temporal error excluded in Experiment 1, respectively.

The dependent variables were then determined as constant (mean) and variable (standard deviation) errors by aggregating the temporal and the spatial deviation score per participant and blur level (see also Brenner et al., 2014; Tresilian et al., 2009; Tresilian & Plooy, 2006; H. Zhao & Warren, 2017). That means that the *spatial constant error* (spatial accuracy) is defined as the mean difference between the actual location where the ball crossed the ground line and the

[5] Instead of a general left/right coding. Please note that analyses for each side separately revealed similar effects.

location where the participant touched the screen, and the *spatial variable error* (spatial precision) is defined as the within-participant variability (standard deviation) in the spatial interception deviation. Similarly, regarding the temporal response, the mean of each participant (*temporal constant error* = temporal accuracy) and the within-subject variability (*temporal variable error* = temporal precision) were computed.

2.2.1.5 Data analysis

To test whether each of the errors (i.e., spatial constant and variable errors; temporal constant and variable errors) differed between blur conditions four separate multilevel models (instead of rmANOVAs, see Field et al., 2013) with error scores per blur level nested in participants were calculated. These models included random intercepts and blur levels as fixed slopes, but no random slopes. To investigate an overall effect of the factor blur, a likelihood ratio test between each model and a corresponding baseline model not including the fixed slopes for blur was calculated (see Field et al., 2013). The code for this test can be found in the Appendix 6.1.1.3 (code 1-3). Significant results were followed up by post-hoc tests (i.e., Tukey Contrasts, see Appendix 6.1.1.3 code 4-6). For significant results, we expected the error score to be monotonically increasing/decreasing with increasing blur levels (similar to the results of H. Zhao & Warren, 2017). To test this, as a second follow-up, additional likelihood ratio tests modeling a linear effect of blur vs. no effect of blur were conducted by defining blur as a numeric variable (instead of a factor).

For the interested reader (and despite not being the aim of our study), the effects of occlusion time, horizontal velocity and side and their interactions with blur on the four dependent variables, as well as associations between the error scores were examined by separate multilevel models and are reported in the Appendix 6.1 (see Figures 6-1 – 6-8).

For data analysis, R version 3.6.2 (R Core Team, 2019) and RStudio version 1.1.456 (RStudio Team, 2016) together with the following packages were used: plyr (Wickham, 2011), reshape (Wickham, 2007), ggplot2 (Wickham, 2009), nlme (Pinheiro et al., 2020), dplyr (Wickham et al., 2018), ez (Lawrence, 2016), psychReport (Mackenzie, 2020), lmerTest (Kuznetsova et al., 2017). A significance level of $\alpha = .05$ was used for all analyses.

2.2.2 Results

On average, participants hit the target in 36.9% of the trials (range: 1.5-59%). Overall, participants slightly undershot the target with a spatial constant error of -9.3 px (-4.6 mm) and reacted too late with a delay of 0.077 s. The mean spatial variable error was 37.5 px (18.4 mm) and the mean temporal variable error was 0.207 s.

2.2.2.1 Spatial accuracy and spatial precision

To test whether blur had an impact on the general bias to overshoot or undershoot the target, the effect of blur on the spatial *constant error* was evaluated. According to the model comparison, the spatial constant error was significantly affected by different blur levels [$\chi^2(4) = 29.70$, $p < .001$]. For post-hoc multiple comparisons see Table 2-1 (see also Figure 2-2a). An additional analysis revealed a significant linear effect of blur on the spatial constant error [$\chi^2(1) = 26.54$, $p < .001$], suggesting that participants undershot the target more with increasing blur level and that this relationship did not differ significantly from a linear relationship.

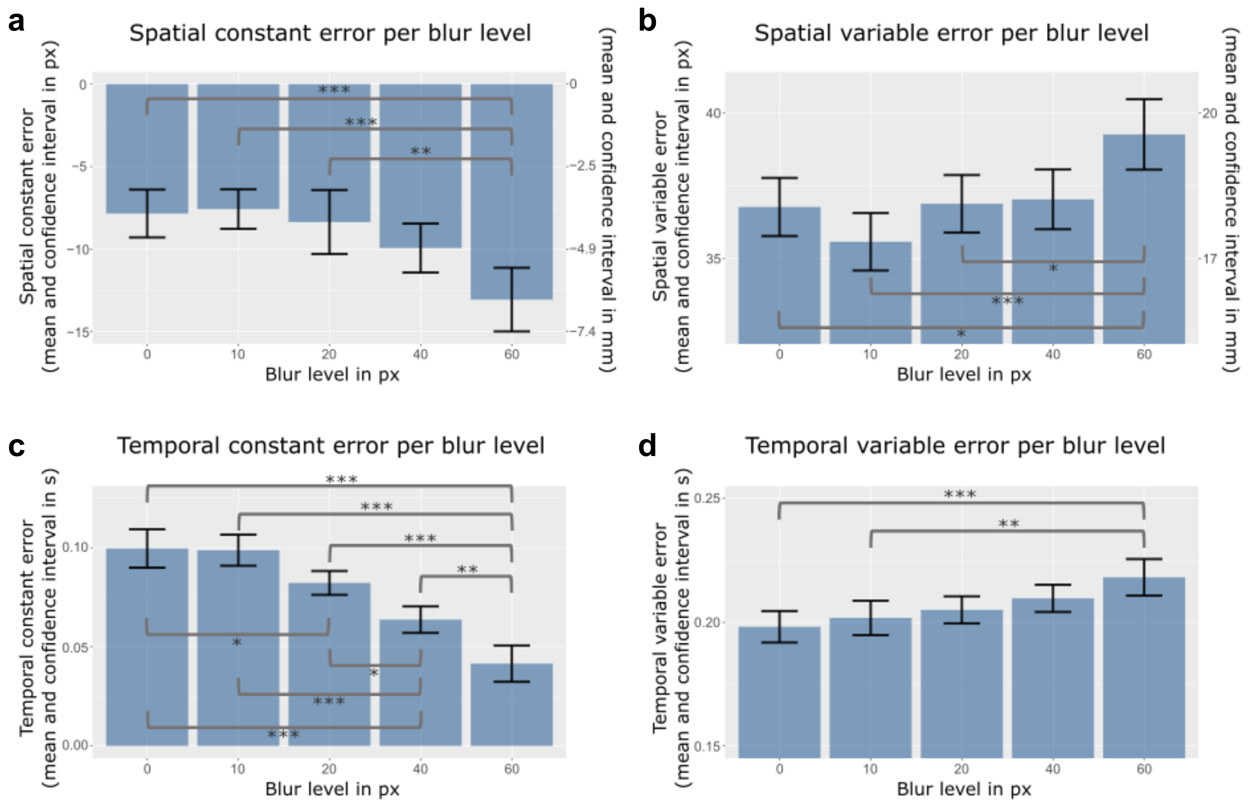

Figure 2-2. Results of the multilevel analysis: The Effect of visual blur on the spatial variable error (A) Spatial constant error (B), temporal variable error (C), and temporal constant error (D). Error bars indicate within-subject confidence intervals adjusted for the within-subject design as suggested by Loftus and Masson (1994).

Next, it was tested whether the spatial *variable error* increased with increasing levels of blur. The model comparison revealed a significant effect of blur level [$\chi^2(1) = 19.55$, $p < .001$]. As predicted, the more the ball was blurred the bigger the spatial error became (see Figure 2-2b and Table 2-1 for post-hoc analyses). The effect for the linear model comparison was significant [$\chi^2(1) = 14.93$, $p < .001$], indicating that the results did not differ significantly from a linear positive relationship between blur and the spatial variable error.

Table 2.1. Post-hoc analysis for the effect of blur on the four error scores: Multiple Comparisons of Means (Tukey Contrasts). Only trends and significant differences are reported.

Spatial errors			**Temporal errors**		
Blur conditions	*z*-value	*p*	Blur conditions	*z*-value	*p*
Spatial constant error			*Temporal constant error*		
60 - 0	-4.52	<.001 ***	20 - 0	-2.81	.040 *
60 - 10	-4.94	<.001 ***	40 - 0	-5.81	<.001 ***
60 - 20	-4.19	.002 **	60 - 0	-9.39	<.001 ***
60 - 40	-2.66	.061	20 - 10	-2.67	.059
All other		>.151	40 - 10	-5.66	<.001 ***
			60 - 10	-9.25	<.001 ***
Spatial variable error			40 - 20	-3.00	.023 *
			60 - 20	-6.58	<.001 ***
60 - 0	3.27	.010 *	60 - 40	-3.59	.003 **
60 - 10	4.33	<.001 ***			
60 - 20	3.01	.022 *	*Temporal variable error*		
60 - 40	2.57	.076			
All other		>.398	60 - 0	4.05	<.001 ***
			60 - 10	3.33	.008 **
			60 - 20	2.67	.059
			All other		>.135

2.2.2.2 Temporal accuracy and temporal precision

It was tested whether blur influenced participants in their general tendency to touch the screen too early or too late. The multilevel model comparison revealed a significant effect of blur on the temporal constant error [$\chi^2(4) = 95.08$, $p < .001$]. With increasing blur levels, the mean temporal deviation decreased (= participants reacted earlier, see Figure 2-2c). Post-hoc analyses revealed significant differences between several blur levels (see Table 2-1). Again, the linearity of the effect, was evaluated with an additional likelihood test. The effect was significant

[$\chi^2(1) = 92.64$, $p < .001$], further indicating a positive linear relationship between blur and the temporal constant error.

Finally, the temporal *variable error* was analyzed to examine whether it is affected by blur. There was a significant difference of temporal variable errors between the five blur levels [$\chi^2(4) = 18.67$, $p < .001$]. With increasing blur, the temporal variable error increased (see Figure 2-2d and Table 2-1 for post-hoc analyses). Additional multilevel analysis with blur as a continuous instead of a factorial variable revealed a significant linear effect of blur on the temporal variable error [$\chi^2(1) = 18.45$, $p < .001$].

2.2.2.3 Comparison between temporal and spatial variable error

To answer the question whether spatial precision is more severely affected by blur than temporal precision, we exploratorily compared the Multiple Comparisons effect sizes by visualizing the z-score (and 95% confidence interval) for both error types (see Figure 2-3). Visual inspection showed that there were no significant differences between the temporal and spatial variable error.

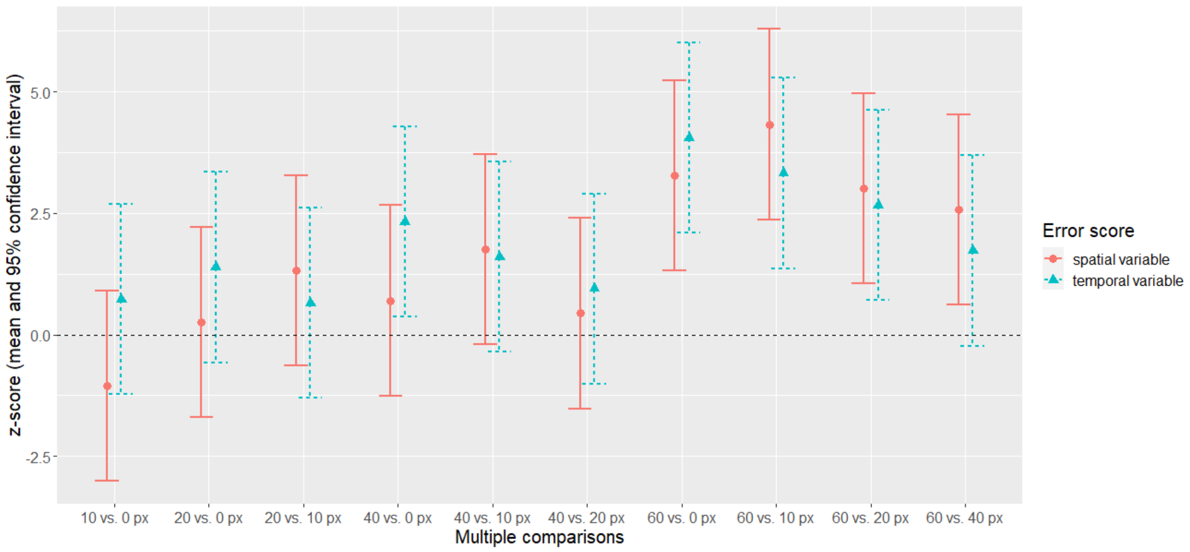

Figure 2-3. Comparison between effects of blur levels on temporal and spatial variable error. For all Multiple comparisons, z-scores were compared between the temporal and spatial precision (mean and 95%-confidence interval). On the x-axis the respective comparison is specified (e.g., '10 vs. 0 px' represents the difference between blur level 10px vs. blur level 0px)

2.2.3 Discussion

The aim of the current study was to disentangle whether the previously reported effects of blur on interception performance were merely produced by reduced spatial in contrast to temporal precision. In agreement with previous research (Mann et al., 2007; H. Zhao & Warren, 2017), we found that (especially very high levels of) blur significantly affected participants' interception performance and that the effect was negative for three out of four error scores.

First, our results showed that with increasing levels of blur participants' spatial responses became more variable (less consistent), confirming the notion that the visual system is sensitive to spatial information (O'Connor & Hermelin, 1972; Recanzone, 2009) and that hence systematic reductions of visual acuity by blurring the target result in reduced *spatial precision* (increased variable error). Second, in contrast to the hypothesis that reductions of visual acuity should not (or lesser so) affect *temporal precision* our results showed an additional systematic effect on the temporal variable error. Regarding the z-values of the multiple comparisons for all blur levels, the decreases in spatial and temporal precision are almost identical in size (see Figure 2-3). That means that participants temporal responses became less consistent (more variable) with increasing blur in a similar way as their spatial responses. We discuss this discrepancy in more depth in the general discussion and compare our results with previous literature.

There was a negative effect of blur on the *spatial accuracy*. The spatial constant error was slightly negative for all blur conditions and this general tendency to undershoot the width of the trajectory was even increased with increasing levels of blur. Unexpectedly, the *temporal accuracy* increased with increasing blur levels. Overall, participants overestimated the time the ball would need until crossing the line, but with increasing blur levels this overestimation diminished. This means that participants reacted earlier the more the ball was blurred. This effect might be mediated by coincident changes in perceived size or contrast and will be discussed more thoroughly in the general discussion.

Based on the fact that the manipulations of blur led to coincident changes in contrast (and might as well have altered perceived size), we cannot rule out that some of the results might be mediated by the concomitant changes of the blur manipulation. While there are indications that changes in size do not necessarily affect interception performance (Brenner et al., 2014; Tresilian et al., 2004; Tresilian et al., 2009), it remains an open question whether changes in contrast might. In fact, decades of research indicate an important role of contrast in vision and related tasks (e.g., Deeb et al., 2015; Johnson & Casson, 1995; Thompson et al., 2006), which is why we ran a second experiment in which we systematically manipulated contrast only.

2.3 Experiment 2

Since in Experiment 1, changes in blur were accompanied by changes in contrast, it is possible that some of the effects may have been caused by contrast rather than by blur. It has been shown that reductions of contrast have not only affected vision on the level of visual acuity (Hong Chen & Muhamad, 2018; Johnson & Casson, 1995), but also reactions towards visual stimuli, for instance, regarding reaction times in visual search tasks (Deeb et al., 2015) or driving performance (Wood et al., 2014). Contrast sensitivity testing predicts thresholds for the perception of real-world targets (Owsley & Sloane, 1987), driving performance (Wood & Owens, 2005), and rifle shooting performance (Allen et al., 2018) better than visual acuity testing. Furthermore, research using moving stimuli has shown that perceived speed can be either increased or decreased by low contrasts depending on the actual velocity (Thompson, 1982; Thompson et al., 2006; but see also Weiss et al., 2002).

Applying the same task used in Experiment 1, we tested in Experiment 2 whether the effects of blur were mediated by the concomitant changes in contrast, by presenting stimuli of the 0-blur condition but varying contrast levels.

2.3.1 Materials and Methods

2.3.1.1 Participants

A total of 42 participants (12 males, 1 not stated, M_{Age} = 21.8 years, SD_{Age} = 2.6 years, 38 right-handed, 1 not stated) took part in the experiment. None of them participated in Experiment 1. Inclusion criteria, expense allowance and ethical approval were the same as in Experiment 1. The sample size was chosen based on the aforementioned a priori power analysis (see APPENDIX).

2.3.1.2 Materials

The materials, procedure and data analysis were the same as in Experiment 1 with only one exception: instead of five levels of Gaussian blur, the ball was presented in five different contrast levels which were matched to the stimuli of Experiment 1. Therefore, the luminance values of the stimuli and the background of Experiment 1 for each blur level were measured with a luminance meter from Gossen (MAVO-SPOT 2) and the Michelson contrast was calculated: 0px blur = 95%, 10px blur = 95%, 20px blur = 93%, 40px blur = 78%, 60px blur =

46%. As the contrasts for 0px, 10px and 20px blur were very similar they were summarized as one contrast condition and two more conditions (34% and 85%) were included to keep the design (especially the duration) of the experiment comparable. To summarize, the following Michelson contrast were used: 95%, 85%, 78%, 46%, 34%, with the ball always being brighter (275 cd/m², 95 cd/m², 62 cd/m², 20 cd/m², 15 cd/m²) than the background (~8 cd/m²). The contrast stimuli for Experiment 2 were generated using GIMP (The GIMP Development Team, 2019) (see Figure 2-1a bottom line).

After outlier detection, 745 of 11340 trials (6.6%) for the spatial difference score and 336 of 11340 trials (3%) for the temporal difference score were excluded in Experiment 2, respectively.

2.3.2 Results

On average, participants hit the target in 36.2% of the trials (range: 11-55%). Across all conditions, participants slightly undershot the landing position of the ball as evidenced by a mean spatial constant error of -9.2 px (-4.5 mm). The mean temporal constant error reveals that participants reacted with a delay of 0.094 s on average. The mean spatial variable error was 35.3 px (17.3 mm) and the mean temporal error was 0.180 s.

2.3.2.1 Spatial accuracy and spatial precision

The multilevel model comparisons did not reveal any effect of contrast level on the *spatial constant error* [$p = .534$], nor on the *spatial variable error* [$p = .444$]. For an illustration, see Figure 2-4a and 2-4b.

2.3.2.2 Temporal accuracy and temporal precision

According to the multilevel model comparison, there was no effect of contrast level on the temporal constant error [$p = .741$]. Figure 2-4c illustrates these results. In contrast, results revealed a significant effect of contrast level on the temporal variable error $\chi^2(4) = 13.96$, $p = .007$ (see Figure 2-4d). Post-hoc analysis (Multiple Comparisons of Means: Tukey Contrasts) revealed a significant difference between the lowest and the second-lowest contrast level (34 vs. 46%) only [$z = 3.48$, $p = .005$]. The temporal variable error was higher in the 46% contrast condition. There were non-significant trends for the comparisons of contrasts 95% vs. 34% [$z = 2.49$, $p = .092$] and 78% vs. 46% [$z = -2.52$, $p = .086$]. All other comparisons did not reach significance (all ps $> .281$). There was no evidence of a linear effect [$\chi^2(1) = 0.93$, $p = .334$].

2.3.3 Discussion

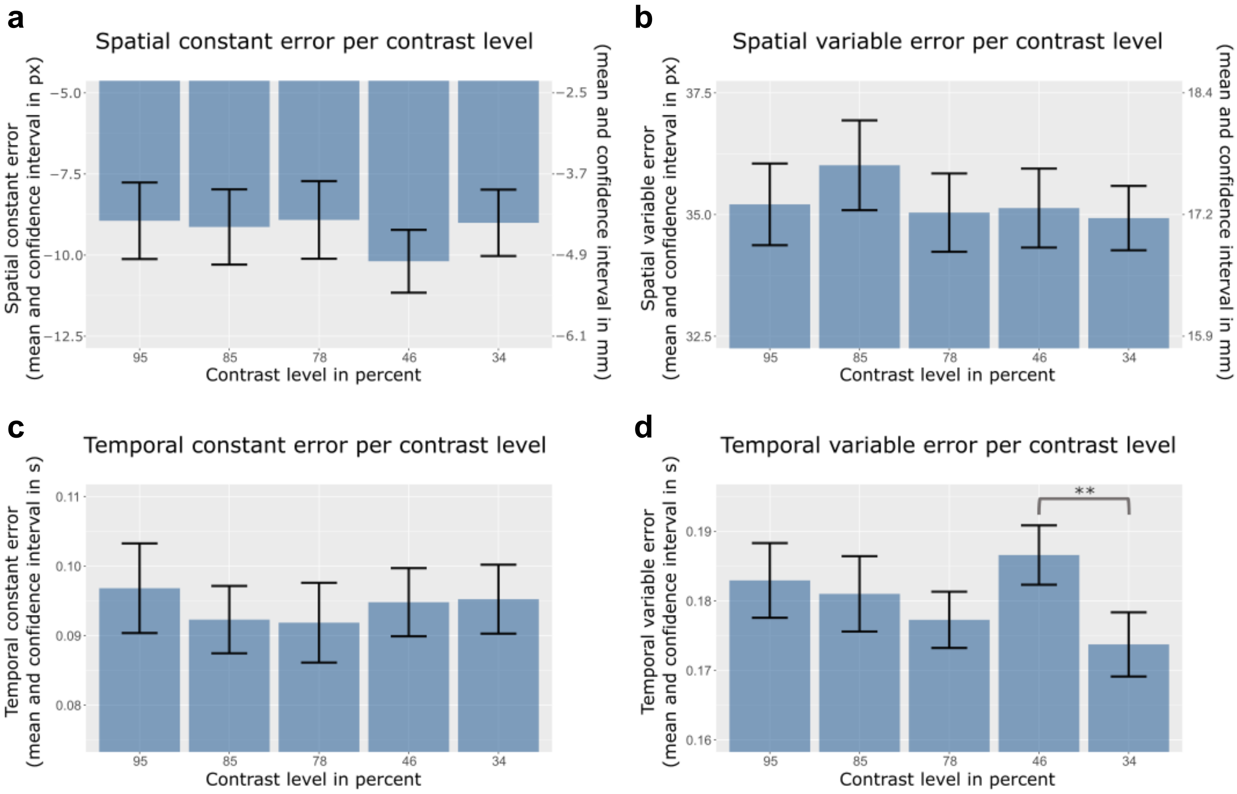

Figure 2-4. Results of the multilevel analysis: The Effect of different contrast levels on the spatial constant error (A) Spatial variable error (B), temporal constant error (C), and temporal variable error (D). Error bars indicate within-subject confidence intervals adjusted for the within-subject design as suggested by Loftus and Masson (1994)

To test for contrast as a possible confound or mediator in Experiment 1, in Experiment 2 contrast levels instead of blur were manipulated, and the resulting spatiotemporal interception performance was measured. Changes in contrast did not systematically affect spatial or temporal performance in the applied interception task. There was only one significant but unsystematic effect of contrast on *temporal precision* indicating less precision for the second-lowest contrast (46% Michelson Contrast) than the lowest contrast level (34% Michelson Contrast). *Spatial responses* and also *temporal accuracy* were independent of the contrast level of the ball, contradicting the idea that coincident changes in contrast have caused the results found in Experiment 1.

2.4 General Discussion

The aim of the current study was to disentangle the previously reported negative effect of blur on interception performance (e.g., H. Zhao & Warren, 2017) into an effect on spatial vs.

temporal precision. Two experiments were run to examine the effect of systematic reductions of the acuity and contrast of a visual stimulus on spatial and temporal precision in a manual interception task. Based on earlier findings indicating a higher sensitivity of the visual system towards spatial when compared to temporal information (O'Connor & Hermelin, 1972; Recanzone, 2009), we predicted a significant effect of diminished vision on spatial precision but none, or a smaller effect, on temporal precision (both measured as variable errors). Our results seem to only provide partial support for this notion.

2.4.1 Spatial precision

The results of Experiment 1 showed that participants' spatial precision indeed decreased with increasing blur. These results of the spatial variable error are in line with previous findings indicating a negative effect of visual blur on visual acuity at the perceptual level (e.g., Johnson & Casson, 1995) and on performance measures (e.g., H. Zhao & Warren, 2017).

Especially, the highest blur level caused a significantly reduced precision in comparison with most of the other blur levels corroborating the finding that especially high levels of blur can hamper interception performance (Mann et al., 2007). Yet, there was no effect on spatial precision when using different contrast levels (Experiment 2). Given that the contrast levels were matched to the levels of blur, this suggests that the decrease in spatial precision in Experiment 1 was not due to a coincident decrease in the contrast level when blurring the object. The results of Experiment 2 appear to be in contrast with a number of studies showing significant performance deteriorations with decreasing contrast in visual tasks, such as visual search or target discrimination tasks (Deeb et al., 2015; Owsley & Sloane, 1987; Wood et al., 2014; Wood & Owens, 2005). To the best of our knowledge, however, our study is the first to have examined the effects of contrast manipulations on manual interception performance. However, it should be noted that the chosen contrast levels were way beyond thresholds and might, therefore, not be appropriate to detect performance differences. As outlined above, the contrast levels were matched to the blur levels in Experiment 1 due to the aim to rule out contrast as a confound or rather mediator. Therefore, the smallest contrast used in the current study was 34%, whereas other studies used also lower levels of 24%, 12%, 6% (Johnson & Casson, 1995), or 10% (Thompson et al., 2006).

2.4.2 Temporal precision

Regarding the manipulations' impact on temporal precision, the prediction that neither blur nor contrast should affect temporal precision as much as spatial precision, was neither supported by the results of Experiment 1 nor Experiment 2. To start with the latter, in Experiment 2 there was an unsystematic effect on temporal precision. Given that there was no effect for spatial precision, it follows that the results of Experiment 2 do clearly not support the initial hypothesis.

Concerning Experiment 1, blur revealed very similar z-values for both, the temporal and the spatial precision measures (see Figure 2-3). Taken at face value, these results seem to suggest that blurring vision impairs temporal precision in a similar way as spatial precision when intercepting a moving target. However, this interpretation would be in conflict with both the theoretical predictions (O'Connor & Hermelin, 1972; Recanzone, 2009) and previous findings by Brenner et al. (2014) who revealed no effect of blur on temporal precision. There are several possible explanations for this discrepancy: First, the previously reported results may not generalize or transfer to our interception task. In contrast to most of the studies investigating the effect of blur on performance, the current task was conducted on a touchscreen. This might impose different demands on the subject compared to, for instance, intercepting a real ball with a cricket or baseball bat (e.g., Brenner et al., 2014; Mann et al., 2010). Second, the effects may depend on the way blur was induced. In contrast to others, we used image processing (Gaussian blur) to blur only the target instead of lenses (e.g., Brenner et al., 2014; Bulson et al., 2008; Bulson et al., 2015) or contact lenses (e.g., Mann et al., 2007; Mann, 2010) blurring whole vision. When using lenses, the distance between the target and the observer plays an important role: clarity increases with decreasing distance. In our study, distance was held approximately constant, and the amount of blur was the same throughout a trial. We believe that blurring whole vision might impose completely different demands on the participant: In our design there was a clearly visible ground line, indicating the 'landing position' and thereby defining the time, when the participant had to tap the screen. If that line would have been blurred, too, identifying this landing position might have become more difficult, because the exact point might be represented less precisely. That means, participants would not have known when to tap because of a spatial problem: localizing the ground line. In other words, this might have resulted in a temporal error which may not have been caused by an error in motion prediction or interceptive action, but rather by the less clear spatial location of the ground line. Third, the effects might be mediated by a third factor, namely, potential concomitant changes in the target's perceived size. Blurring means that the boundaries visually fade out resulting in a less clearly defined size. That means that the outer points of the ball were more widely distributed the more it was blurred but as well the background intruded more with increasing blur. If only the outer points were taken as a criterion, this might have led to the perception of increased size (but note that this was neither tested nor self-reported by any of the participants). If so, it might have been more difficult to identify the center of the ball, which was important to fulfil the temporal part of the task (i.e., to intercept the target *when* its center crossed the ground line). That means that a predominantly spatial problem (identifying the center) resulted in a temporal effect (reduced temporal precision). Future research should examine and control for such effects by checking whether the center is indeed less precisely identified in blurred objects (e.g., in a stationary task). Fourth, previous studies have shown that visual manipulations can systematically impact velocity perception (Gegenfurtner & Hawken, 1996), which would, contrary to our hypothesis, result in temporal errors in the current task. A detailed analyses and discussion of velocity effects can be found in the Appendix 6.1. In short, in both experiments participants intercepted more delayed for faster velocities, but no effects on the temporal variable errors were evident. If the chosen blur manipulations indeed change the perception of velocity this might be reflected in changes in temporal accuracy.

2.4.3 Spatial accuracy

In both experiments, we found a general tendency to horizontally undershoot the spatial location of the target at the interception point. In Experiment 1 this tendency increased with increasing levels of blur, whereas in Experiment 2 contrast had no effect on the spatial accuracy. The effect of blur is in congruence with the findings of H. Zhao and Warren (2017) who reported that blurred stimuli led to more undershooting than less blurred stimuli[6]. However, the overall undershooting conflicts with predictions from extrapolation research (Fulvio et al., 2015), showing that when occluding curved trajectories participants either predict locally linear or locally quadratic continuations, none of which would lead to undershooting in the current task.

2.4.4 Temporal accuracy

Consistently in both experiments, participants showed delayed reactions towards the moving stimulus. This general tendency might be explained by the incapability of humans to use acceleration information for their time to arrival estimation (Benguigui et al., 2003) and interception performance (Brenner et al., 2016). During the occluded part of the trajectory vertical velocity increases, but participants should be unable to predict this increase, at least if they are not able to learn from previous trials with the same acceleration (Brenner et al., 2016). This should lead to delayed reactions as found in both experiments of the current study and consistent with the findings of Brenner et al. (2016) who showed delayed reactions when the

[6] Please note that their measure ('spatial accuracy') was still an amalgam of spatial and temporal accuracy. Therefore, an undershooting effect might as well be treated as an 'too early' reaction.

time point of tapping was clearly defined and not free to choose as in the current paradigm. Additional results supporting this notion can be found in the Appendix 6.1 when discussing the effects of occlusion times on the temporal accuracy. Interestingly, in Experiment 1, blur significantly affected the size of the delay, whilst contrast in Experiment 2 had no effect.

Based on the argumentation H. Zhao and Warren (2017), that increasing levels of blur imply reduced spatial frequencies and that, therefore, the object should appear to move slower than a less blurred one (K. R. Brooks et al., 2011; Diener et al., 1976; Smith & Edgar, 1990), one would expect that perceived reduced speed (increasing blur) should lead to more delayed responses. Yet, the opposite was the case: With increasing blur, the temporal accuracy (constant error) was decreased meaning that participants' overestimation of the ball's movement-time diminished. We argue that this finding is not necessarily questioning the assumption of perceived reduced speed but might instead be resolved by one of following potential explanations: Firstly, it is conceivable but still unlikely that blurring may – perhaps somewhat counterintuitively – have facilitated participants' interception performance. Second, despite thorough instructions participants might have not reacted towards the center of the ball but instead (unintendedly) attended the 'edge' of the ball. The more the ball was blurred the closer to the ground its outer points appeared (before occlusion) and the earlier they would have crossed the line (during extrapolation). If participants attended the 'edge' of the ball, they might have pressed earlier with increasing blur because the outer points of the ball were spread wider. Third, it is possible that participants associated specific blur levels with specific ball types that implied characteristics like mass. A recent study has shown that time to contact estimations depend on the mass of a visual stimulus probably due to explicit heuristics or even implicit conclusions from mass to falling speed (Vicovaro et al., 2019).

In Experiment 2, no effects of reduced contrast where found, indicating that the results of blur were not due to changes in contrast which is in line with a study on time to contact estimations that found no effect of contrast, or luminance levels (Landwehr et al., 2013). Yet, a vast amount of studies showing altered velocity perception for moving stimuli with low contrast levels would predict effects on temporal accuracy (Feldstein & Peli, 2020; Thompson, 1982; Thompson et al., 2006). For instance, Battaglini et al. (2013) found a main effect of contrast levels on speed perception. They showed that decreasing contrast leads to an underestimation of target speed (even during occlusion) which should result in delayed interception responses in the current paradigm. As explained above, this discrepancy might be due to the relatively high contrast levels used in the current experiment (and potentially also the experiments in Landwehr et al., 2013).

2.4.5 Additional Factors and limitations

The current study was specifically designed to analyze the effect of manipulations of blur on interception performance in a task simulating a ball flight curve. Obviously, there is a vast number of other factors found to impact performance in interception, for instance, concerning properties of the task (cf., Bosco et al., 2012; Brenner & Smeets, 2009; Brouwer et al., 2000; Brouwer et al., 2005; Tresilian et al., 2003; Tresilian & Houseman, 2005) or participants' characteristics (e.g., fatigue, Barte et al., 2020; amount of stabilization, Couto et al., 2020; sports experience, Yu & Liu, 2020). While the investigation of interindividual differences was not part of the current study, some task-related factors (stimulus velocity, side, and occlusion time) were manipulated to produce variability. Full insight about additional separate analyses and their discussion are provided in the Appendix 6.1. Note in this regard that these factors were not of central interest to our research question. Since no 0 s occlusion condition was included in the experiment, our study design does not allow and hence cannot dissociate whether the effects found for blur result from a misperception of the visible part of the trajectory or erroneous extrapolation during the occluded part. Nonetheless, it should be noted that studies on time to contact and speed estimations reported common underlying mechanisms (Battaglini et al., 2018) and electrophysiological correlates for visible and occluded targets (Makin et al., 2009).

As explained above, in the current design, perceived target size might be a factor mediating the effect of blur. Previous interception research reveals no consensus about effects of target size: for instance: in a batting task measuring interception performance as temporal error, Brenner et al. (2014) found no effect of different ball sizes. In interception tasks using a manipulandum, Tresilian et al. (2004) and Tresilian et al. (2009) found no consistent main effect of target size on movement time, the spatial variable error, or the constant error, but on maximum movement speed. In contrast, Brouwer et al. (2005) and Tresilian and Houseman (2005) revealed a significant effect of target size on movement time. These results indicate that certain aspects of interceptive actions (like movement time) can be influenced by the size of the target, but often, specifically the spatial and temporal errors were not affected. To conclude, we cannot rule out that increases in perceived target size (if they were present) might have affected the reported results. However, the above-mentioned literature does not provide clear evidence for this hypothesis. Future research should focus on the impact of such task-related factors and the possible moderators of and interactions with blur. Furthermore, it might be advantageous to investigate interindividual differences in the temporal and spatial performance measures, as studies indicate that, for instance, sports experience (e.g., Yu & Liu, 2020) and the amount of stabilization (learning, e.g., Couto et al., 2020) might impact participants' performance.

If not due to substantial differences in the task demands or the way of blurring, the effects of blur on both temporal measures in Experiment 1 might be due to space-time-associations in interception tasks that we aimed to disentangle. Despite our experimental rigor to disambiguate spatial and temporal contributions to the motor response, temporal estimates of the ball's movement were not completely independent of spatial perception. That is, to predict when the ball's center would cross the ground line, participants needed to perceive its location at certain timepoints. Therefore, when spatial precision was diminished due to noisier spatial representations during presentation and/or extrapolation, temporal precision should be affected as well. One result supporting this notion is the positive association between temporal and spatial difference scores found in both experiments (see Appendix 6.1). This is in contrast to the often-found trade-off between temporal and spatial responses in interception paradigms (e.g., Tresilian et al., 2009). The current results seem to suggest that temporal and spatial responses were not perfectly independent of each other in the applied paradigm.

It should be mentioned that in contrast to other studies (e.g., Brenner & Smeets, 1997) participants' heads were not fixated using a chin rest. We did not use a chin rest to allow participants to rotate their head and ensure optimal conditions for interception performance (Mann et al., 2019). Though participants were asked to keep their head at a distance of approximately 50 cm from the screen, it is possible that participants have slightly moved their head (back and/or forth). Therefore, we could not specify and report visual angles with certainty, and hence refrained from doing so. In future studies the use of chin rests might be advisable, if one aims for better experimental control at the costs of less ecologically valid interception performance or if the movement range of the stimuli is relatively small. Furthermore, modelling air resistance and gravitation forth of the earth within the target's motion might help to improve the ecological validity of future studies (e.g., Kreyenmeier et al., 2017; Vicovaro et al., 2019).

In reaching and grasping tasks an important theory has emerged from research on the contributions of the ventral and dorsal visual pathways, referred to as the two visual systems or dual-pathway theory (Goodale et al., 1991; Goodale & Milner, 1992; Milner & Goodale, 1995). According to this theory, the predictions regarding the effects of blur and contrast on an interception task would have been very different. More specifically, the dual-pathway theory claims that there are two visual streams within visual processing. One, the ventral pathway (‘what’), functions to create a conscious percept of the visual stimulus, while the other, the dorsal pathway (‘where’), is thought to work in a more goal-directed fashion, sub-consciously guiding our actions. Based on the differences regarding their innervating properties, concrete hypotheses about effects of blur or contrast on different types of tasks have been postulated. In short, the dorsal pathway only includes magnocellular input which is characterized by fast processing and high sensitivity towards contrast, whereas the ventral pathway is characterized as a magno- and parvocellular system including slower transmission with high spatial resolution and colour-sensitivity. These physiological differences suggest that blur, as a reduction of the spatial resolution, should first and foremost impact processing within the ventral, but not necessarily the dorsal pathway (Norman, 2002). On the other hand, decreases in contrast should have an effect mainly on action-based tasks, requiring more dorsal information processing. In general, an interception task as applied in the current study is thought to be a goal-directed, mainly dorsally processed task. Consequently, performance in interception tasks should be mainly affected by changes in contrast and not by changes in blur. Our findings are seemingly not in line with these predictions. Interestingly, however, recent research calls into question the clear distinctions between the two pathways (Milner & Goodale, 2008) and more recent research has shown that the systems tend to interact (e.g., Cañal-Bruland et al., 2013). If true, this interaction may explain our findings, that blur affected a supposedly highly action-directed and therefore dorsally processed interception task, whilst contrast did not (see also Mann, 2010), at least regarding the chosen levels. Indeed, as participants had some time to observe the object before it was occluded and reached the ground line, there might have been enough time for the slower parvocellular system to process all information and for both streams to interact. Moreover, to investigate the role of visual input for interception performance it might be advisable to include eye-tracking in future studies, as recent interception studies suggest close associations between eye and hand movements and confirm the important role of eye movements on interception responses (de la Malla et al., 2017; Fooken et al., 2016; Fooken et al., 2021; Kreyenmeier et al., 2017).

On a final note, we deem it likely that both response modality and the modality of stimulus presentation play important roles in determining spatial and temporal precision in manual interception (see also Loeffler et al., 2018). As concerns response modality, future research may be well advised to compare different ways to respond, for example, by contrasting verbal vs. motor responses. Regarding the modality of stimulus presentation, future research about the differences in sensitivity towards spatial and temporal information may also focus on the auditory modality, as it has been shown that the auditory system is more dominated by temporal than by spatial information (O'Connor & Hermelin, 1972; Recanzone, 2009). It follows that another way to test the hypothesis we sought to shed light on in this paper, may be to manipulate the quality of auditory information, thereby testing the counterpart of the hypothesis, namely that reductions of auditory qualities should more strongly affect temporal than spatial precision.

In summary, in two experiments we tested whether participants' spatial precision would suffer more severely from visual manipulations of blur (Experiment 1) and contrast (Experiment 2) than temporal precision in a manual interception task. Whilst contrast had no systematic effect on neither error score, blurring the moving object reduced both spatial and temporal precision similarly.

END OF PUBLICATION

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3 Study II: Tau and kappa in interception – how perceptual spatiotemporal interrelations affect movements.

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Abstract

Batting and catching are real life examples of interception. Due to latencies between the processing of sensory input and the corresponding motor response, successful interception requires accurate spatiotemporal prediction. However, spatiotemporal predictions can be subject to bias. For instance, the more spatially distant two sequentially presented objects are, the longer the interval between their presentations is perceived (kappa effect) and vice versa (tau effect). In this study, we deployed these phenomena to test in two sensory modalities whether temporal representations depend asymmetrically on spatial representations, or whether both are symmetrically interrelated. We adapted the tau and kappa paradigms to an interception task by presenting four stimuli (visually or auditorily) one after another on four locations from left to right with constant spatial and temporal intervals in between. In two experiments, participants were asked to touch the screen where and when they predicted a fifth stimulus to appear. In Exp. 2, additional predictive gaze measures were examined. Across experiments, auditory but not visual stimuli produced a tau effect for interception, supporting the idea that the relationship between space and time is moderated by the sensory modality. Results did not reveal classical auditory or visual kappa effects and no visual tau effects. Gaze data in Exp. 2 showed that the (spatial) gaze orientation depended on temporal intervals while the timing of fixations was modulated by spatial intervals, thereby indicating tau and kappa effects across modalities. Together, the results suggest that sensory modality plays an important role in spatiotemporal predictions in interception.

Keywords: spatiotemporal, kappa, tau, interception, Eye-Tracking

3.1 Introduction

In many daily activities, humans must coordinate their movements both temporally and spatially to intercept a moving object such as when catching a fly ball. In such situations temporal and spatial characteristics need to be processed and integrated to act successfully (Fischman & Schneider, 1985; McBeath, 1990; Oudejans et al., 1996; Savelsbergh & Whiting, 1988). In addition, to catch a ball one needs to predict its future location at a concrete point in time. Past research has shown that human perception of space and time, however, is by no means infallible and sometimes subject to bias. For example, when participants are asked to reproduce the duration of a sound, they show longer reproduction durations when they are holding a long stick between their fingers compared to a shorter stick (Cai & Connell, 2015). A recent review suggests that these interrelations between space and time perception depend on the sensory input, and corresponding differences between visual and auditory information processing in particular (Loeffler et al., 2018). Therefore, the main aim of the current study was to empirically test spatiotemporal interrelations across different modalities in an interception task. To develop and validate a suitable test-bed to study spatiotemporal interrelations in interception, in a first experiment, we adapted paradigms of two well-established spatiotemporal illusions, namely tau and kappa effects (e.g., Abe, 1935; Benussi, 1913; Cohen et al., 1953; Gelb, 1914). Thus far, these two phenomena have been mainly investigated in the perceptual domain. In a second experiment, we then further validated and examined differences between the visual and auditory modalities by additionally using measures of predictive gaze behaviors.

3.1.1 Interception relies on prediction

To start with, actions like catching a ball are typically referred to as interception tasks. They are defined as situations in which one stops the movement of an object by crossing the object's trajectory at the correct time, e.g., with the hand or a baseball bat. To successfully intercept an object in motion one needs to accurately plan and execute movements to be in the right place at the right time. Due to sensorimotor delays of 100ms this requires predictions of temporal and spatial motion characteristics of the actor, his/her surroundings or both (Fiehler et al., 2019). Predictions as part of anticipation are based on fundamental perceptual (e.g., visual) and attentional skills (Hodges et al., 2021; Loffing & Cañal-Bruland, 2017). As such they have been widely studied for visual stimuli often including eye tracking as a measure of oculomotor processes highly intertwined with motion prediction and interception (Fooken et al., 2021; Fooken & Spering, 2020).

3.1.2 Spatiotemporal predictions and interrelations

As alluded to above, complex predictions underlying interception are based on perceptual and related processes, including e.g. attention and working memory (Hodges et al., 2021). However, human perception of time and space is far from perfect and can be influenced by other available information. For instance, temporal perception (e.g., the presentation duration of a line) can be affected by spatial information (e.g., the length of the line) and potentially vice versa. It is not surprising that spatial and temporal representations are interrelated when considering that in many situations temporal and spatial features are correlated. Consider the following example: when planning your way to work, two important components to evaluate which route you should take are the distance and the duration. Often both are associated with each other (the longer the distance, the more time you will need to reach the office), but this association is not necessarily perfect. Some other aspects might play a role as well such as speed or traffic. That means that assuming a strong correlation between time and space may not always be correct and, in fact, may lead to systematic errors, for instance, in anticipating time of arrival based on the distance or vice versa. Assuming strong correlations between time and space might also impact our interception behavior, e.g., when planning where to move on a football pitch, when to grasp for a fly ball, or how fast to accelerate one's own movements. Typically, the higher a juggler throws a ball, the more time she has before catching it. Still, other features can impact the flight duration and might distort her predictions or automatized movements and result in interception errors, e.g., aerodynamic features of different balls.

To conclude, human perception typically relies on the assumption that longer durations come along with longer distance, and consequently it may not be surprising that research has shown that judgements of time can be impacted by spatial information (and potentially vice versa). However, the exact relationship between temporal and spatial representations is not resolved: There is an ongoing debate about whether representations of time and space impact each other reciprocally (symmetrical relationship) or whether spatial representations have a larger influence on how we perceive time than vice versa. The last notion was proposed in the asymmetry hypothesis (see Casasanto & Boroditsky, 2008; Loeffler et al., 2018; Winter et al., 2015) which is based on the *Conceptual Metaphor Theory* (CMT; Lakoff & Johnson, 1980b). It is assumed that the more abstract representations of time depend asymmetrically on the more concrete spatial representations. This is reflected in language: spatial metaphors are frequently used to describe temporal aspects, especially in the context of movements (e.g. 'The weekend is getting closer') whereas temporal metaphors are only rarely used to describe spatial concepts (e.g., 'I am five minutes from the central station', see Casasanto et al., 2010). Several studies support this theory. For instance, it was shown that the duration of presentation of a line is perceived to be longer with spatially larger lines. On the contrary, when participants were asked to reproduce the length of a line, this was not affected by presentation duration (Casasanto & Boroditsky, 2008; for a pre-registered replication, see Whitaker et al., 2022).

On the other hand, another idea about spatiotemporal effects has been put forth, referred to as *A Theory of Magnitude* (ATOM; Walsh, 2003), suggesting a symmetrical interrelation. According to ATOM, space, time, and quantities are all processed by a common magnitude system. The core assumption of ATOM is that if all entities share the same neural processing system and consequently attentional and representational resources, there is no reason to expect asymmetrical interrelations between temporal and spatial representations. Instead, it is proposed that both domains impact each other reciprocally. This notion has received empirical support, for instance, by showing that not only judgements of time (duration of a sound) can be influenced by spatial characteristics (e.g., length of a stick), but temporal characteristics can influence spatial percepts as well (Cai & Connell, 2015).

To summarize, both theoretical approaches are supported by empirical studies. While – prima facie – these findings seem to contradict each other, Loeffler et al. (2018) recently suggested that the use of different sensory modalities might explain this discrepancy: Studies supporting an asymmetrical relationship mainly used visual stimuli for both, the spatial and the temporal task, whilst a symmetrical relationship was supported by studies using different modalities (for an overview, see Loeffler et al., 2018).

3.1.3 Task modality as moderator

Differing sensitivities of modalities explain the discrepancy between ATOM and CMT: The visual system was shown to dominate spatial perception, whereas temporal perception is more dominated by the auditory modality (O'Connor & Hermelin, 1972; Recanzone, 2009). When using mainly visual tasks, as in the studies supporting CMT, representations of temporal aspects of the task might be less precise than spatial aspects. More specifically, introducing the idea of representational noise might shed light on the role of sensory modalities (Cai & Wang, 2021). In several experiments, Cai and Wang (2021) showed that the effect of a context domain on a target domain was modulated by the amount of representational noise (coefficient of variation) within the target domain. If there is more representational noise, the respective dimension is thought to be represented with more uncertainty and might therefore be more prone to influences by the context domain. Applied to the idea of different sensitivities of modalities this means that – because the auditory system is less sensitive towards spatial information – in a mainly auditory task one would expect a spatial representation to be noisier and therefore less stable. Consequently, the spatial representation can be more easily influenced by concurrent temporal information. On the other hand, in a mainly visual setting the temporal representation should be very noisy and therefore prone to be influenced by spatial information. It might therefore be possible to integrate both theories into one model when including task modality in the model's predictions.

3.1.4 Tau and kappa effects

Understanding if spatial characteristics affect our perception and prediction of time and potentially vice versa requires disentangling and manipulating time and space independently. A useful testbed for independent manipulations, might lie in two perceptual illusion effects, called *tau* and *kappa effects* (Abe, 1935; Benussi, 1913; Cohen et al., 1953; Gelb, 1914; Helson & King, 1931). Previous research has already identified these effects as promising tools to test ATOM against CMT (Alards-Tomalin et al., 2014; Reali et al., 2019).

The *tau effect* is described as the impact of temporal intervals ('context') on spatial judgements ('primary judgement'). Benussi (1913), for example, asked participants to give a relative judgement about one of two spatial intervals built through the presentation of three successive lights (one interval between stimuli 1 and 2 and one interval between stimuli 2 and 3). Results showed that the relative judgements about space (e.g., 'the second interval was smaller') changed with the duration of the two intervals: the interval with the longer duration was judged to be spatially larger. The opposite effect, initially denoted as *S*-effect (Abe, 1935) and later called *kappa effect* (Cohen et al., 1953), illustrates the influence of spatial information ('context') on temporal judgements ('primary judgement'). In a typical paradigm, participants sit in a dark room and are presented with three successively illuminating lights. They are then asked which temporal interval was longer, the one between the first and second or second and third stimulus. Typically, participants chose the interval with the larger spatial distance between the lights to have the longer duration.

These findings were conceptually replicated and extended by the use of visual, tactile, and auditory stimuli (Helson & King, 1931; Scholz, 1924). In addition, further evidence for *tau* and *kappa* effects was presented for different tasks including, for instance, category judgements instead of relative judgements (Jones & Huang, 1982), reproduction paradigms (Price-

Williams, 1954) and memory tasks (Sarrazin et al., 2004; Sarrazin et al., 2007). Together, we deem the *tau* and *kappa* paradigms suitable testbeds to study spatiotemporal interrelations, if appropriately adapted for interception.

3.1.5 Eye movements

One way to further bridge the gap between mere perceptual processes – as investigated in tau and kappa paradigms – and interceptive actions may be offered by eye movement research. As mentioned before, eye movements have not only been found to be functionally highly related to motion prediction and perception (e.g., Goettker et al., 2018; Schütz et al., 2011), but hold behaviorally strong associations to interception as well (e.g., Goettker et al., 2019; Mann et al., 2019; Spering et al., 2011). Tracking errors of the gaze are highly related to interception errors (Fooken et al., 2016). Predictive eye movements to future target locations show anticipation of motion trajectories (Mann et al., 2019). It was shown that eye movements (pursuit) are based on perceived rather than actual target motion and consequently biases found for perception are often reported in tracking movements of the eyes, too (cf. Schütz et al., 2011). Perception and pursuit share a common initial motion processing phase and later split in separate pathways (Schütz et al., 2011). As such they are a useful tool to investigate the underlying processes of interception and fill the gap between the two perceptual spatiotemporal interactions in a new action-paradigm using an interception task: If effects are absent in the interception data, eye tracking data might indicate whether this highlights the dissociation between perceptual and action processes or whether the newly developed paradigm is not appropriate to trigger spatiotemporal biases.

3.1.6 Current Study

The aims of the current study with two experiments were twofold: First, we tested whether spatiotemporal (perceptual) illusions, called *tau* and *kappa* effects can impact interception performance. Second, it was analyzed whether there are differences between sensory modalities with auditory tasks strengthening the effect of temporal characteristics on spatial interception (*tau* effect) and visual tasks supporting the effect of spatial characteristics on temporal processing (*kappa* effect). Additionally, in an exploratory manner we tested for contributions of manipulations of the visual and auditory input (blur and volume). To test these hypotheses, in two experiments participants were presented with four successively appearing and disappearing dots or sounds to make them intercept the predicted fifth location at the predicted time of appearance. The first experiment served to test for effects in interception. In Exp. 2, besides replicating the interception results of Exp. 1, gaze data was used to i) validate the new *tau* and *kappa* paradigm of motion prediction, ii) address the role of stimulus repetition, and iii) answer the question whether the dissociation between perception and action might explain absent or unexpected effects.

3.2 Experiment 1

In Exp. 1, interception data (location and moment of tap) was analyzed to identify *tau* and *kappa* effects in an action task. Based on the low sensitivity of the auditory system to spatial information, it was hypothesized that the interception location would be increasingly overestimated in movement direction with increasing temporal intervals between target presentations, when stimuli were presented auditorily (*tau* effect). In contrast, as the visual system is highly sensitive to spatial and potentially lesser so towards temporal information, this should result in delaying interceptions with increasing spatial intervals (*kappa* effect). The opposite effects for each modality should be smaller or even absent due to the different sensitivities.

3.2.1 Methods

3.2.1.1 Participants

A total of 43 participants (17 male, M_{Age} = 24.2 years, SD_{Age} = 3.3 years, sample size similar to previous studies on interception, e.g., Schroeger et al., 2021) took part in the experiment. All provided informed consent prior to participation. Participants had to take part in a vision (Bach, 1996, 2006) and a hearing test (Cotral, Version 1.02B) prior to participation. A minimum visual acuity of 0.00 logMAR and contrast sensitivity of 1.7 log CS was required. Participants mean visual acuity was -0.18 logMAR (SD = 0.06) and contrast sensitivity was 2.18 logCS (SD = 0.14). If hearing threshold levels exceeded 30 dB (average between 500 Hz and 1000 Hz), participants were excluded from the analysis (average of all frequencies: M = 23.1 dB, SD = 2.49 dB). The study was approved by the local ethics committee.

3.2.1.2 Materials

We used an interception paradigm similar to the ones reported in two recent studies by Schroeger et al. (2021) and Tolentino-Castro et al. (2021). Participants performed an interception task on a 43’’ touchscreen (Iiyama PROLITE TF4338MSC-B1AG, 1920 x 1080, 60Hz, 2.1 megapixel Full HD, Multi-Touch-Monitor). The experiment was programmed with PsychoPy 3 (Peirce et al., 2019), in the coder view using Python script.

The visual stimuli were white circles (diameter 100 px) blurred with the help of Photoshop's (Adobe Photoshop, EUA) Gaussian blur tool with radii of 0 (no blur) and 60 pixels. Stimuli were presented on a black background (similar to Sarrazin et al., 2004). In each trial a circle was presented four times successively for 167 ms each, with constant temporal and spatial interstimulus intervals between presentations. Temporal intervals were 500 ms, 800 ms or 1100 ms and spatial interstimulus intervals 30 mm, 80 mm or 130 mm (see Figure 3-1a and 3-1b). Those values were chosen based on the properties of the touchscreen and pilot testing and are in the range of previously reported tau and kappa effects (e.g., temporal ISI: 250 ms – 2500 ms, spatial ISI: 30 mm and 50 mm in Abe, 1935). Piloting indicated that smaller temporal intervals made it impossible to reach the target location in time.

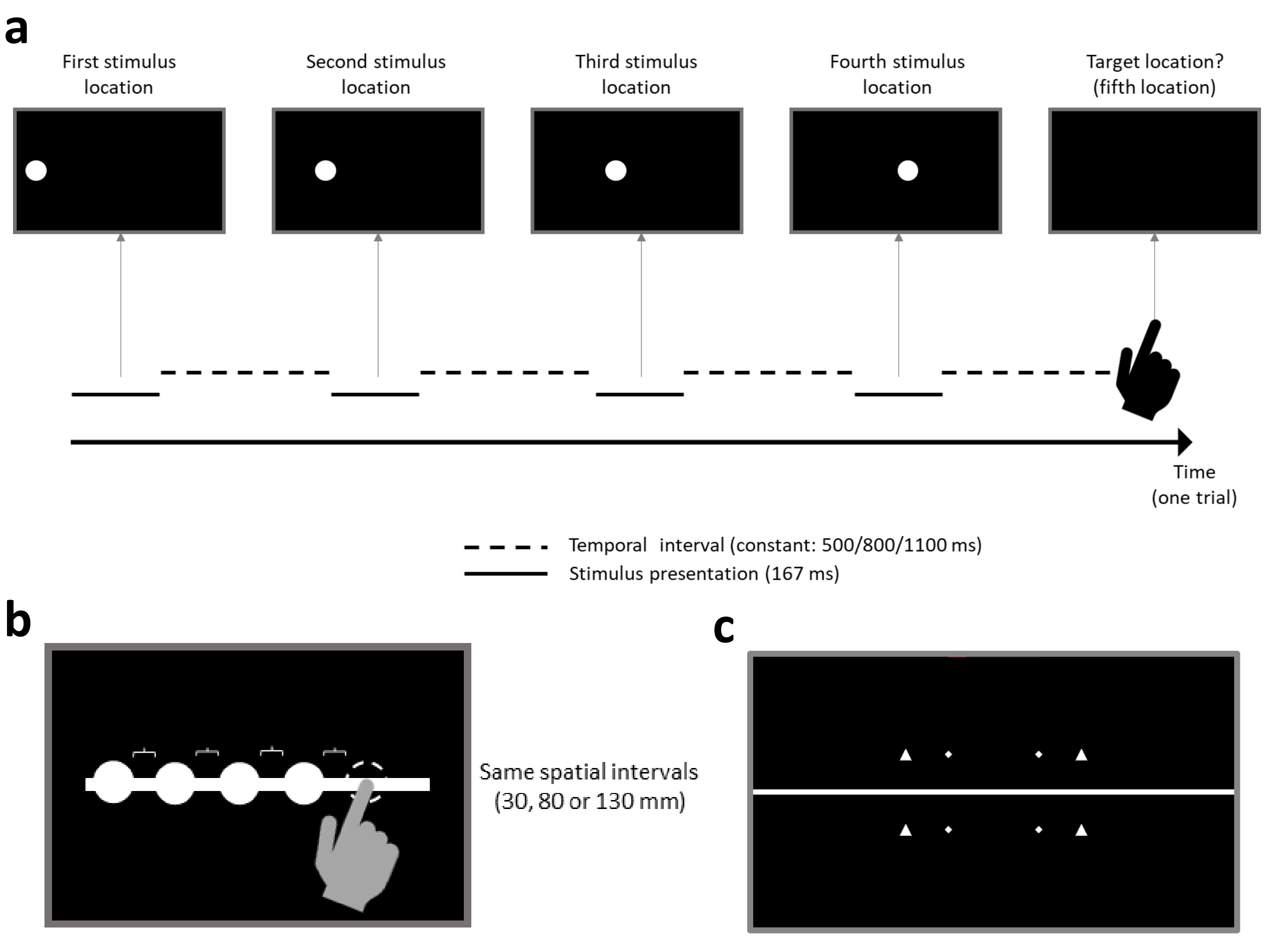

Figure 3-1. Experimental procedure. **a)** After pressing the start button, the stimulus (ball) appeared four times at the screen, and the fifth location and time had to be anticipated. Each presentation of the stimulus was 167 ms and the temporal interstimulus intervals were constant (500, 800 or 1100 ms). **b)** The spatial interstimulus intervals were constant, too (30, 80 or 130 mm). Please note that this is only an illustration, only one white circle was visible at a time. **c)** Illustration of the reference objects presented in Experiment 2 to analyze gaze data.

For the auditory stimuli 800 Hz pure tones were presented through two loudspeakers positioned at the right and left side of the touchscreen at the height of the ground line. Using the vector-based amplitude panning method (Pulkki, 1997) implemented in a Matlab Script (Politis, 2016) the exact same temporal and spatial intervals between sound presentations and stimulus durations were produced as in the visual part. The virtual sound source is created through adjusting the signal amplitude of either of the two loudspeakers (intensity panning) based on the vectors between the listener, the loudspeakers, and the virtual sound source. Instead of blurring (visual part) for the auditory experiment two volumes (loudness) were used: ~55dB and ~69dB. The design was reduced to two levels of blur or volume based on pilot testing and to reduce the number of trials to a reasonable amount.

3.2.1.3 Procedure

Participants were seated in front of the touchscreen at approximately 50 cm (eyes to screen). That means that 1 cm on the screen (~20 px) refers to approximately 1.15° visual angle (but please note that participants were free to move/turn their heads). At the beginning participants took part in a familiarization phase of 8 trials, using slightly different temporal (350 ms and 950 ms) and spatial intervals (10 mm and 100 mm) than in the main part of the experiments. During each practice trial, the white circle or sound (representing a ball) was presented on a white ground line successively four times (being occluded in between) before the fifth position had to be identified by tapping on the screen at the correct location and at the right time (see Figure 3-1). Participants received feedback about both types of errors (spatial distance and temporal difference) during familiarization. Temporal and spatial intervals between stimuli were constant per trial but altered randomly between trials.

The main experiment consisted of six blocks of 36 randomized trials each. The main trials of the experiment were similar to those of the familiarization trials with one exception: exact feedback was not provided at the end of each trial. Instead, after each block a pause of at least one minute was included during which participants received feedback as a percentage score of the correctly hit trials. A hit was defined as tapping on the screen at a maximum horizontal distance of 73.5 mm from the correct location and a temporal deviation of not more than two times the stimulus presentation time (2 x 167 ms). These values were chosen based on pilot data with the aim to keep the participants sufficiently motivated. Visual or auditory stimuli were presented in two separate stimulus conditions and the order of conditions was counterbalanced across participants. Half of the participants started the experiment with the three visual blocks, whilst the other half first attended the three auditory blocks.

Combining all variables, the procedure of the main experiment resulted in 3 (temporal intervals) x 3 (spatial intervals) x 2 (blur levels/volumes) x 2 (condition: auditory vs. visual) = 36 conditions. Each combination was repeated 6 times, resulting in 216 trials. The experiment lasted about 1 hour (including pre-tests, instructions, experimental testing and debriefing).

3.2.1.4 Data Analysis

First, a difference score between the actual spatial interval and the spatial response and a difference score between the actual temporal interval and the temporal response were calculated. Based on these scores, for each participant outliers, defined as more than three interquartile ranges below or above the first or third quantile, were excluded. This resulted in 0.02-1.85% data exclusion in Experiments 1 and 2 (see Table 6-9 in the Appendix for further details). To evaluate the effect of the context variable on the primary task, linear mixed models were run, with either the spatial response or the temporal response as dependent variable (Schroeger et al., 2021; Tolentino-Castro et al., 2021). For both models the spatial interval, temporal interval, and blur/volume as well as their interactions were included as fixed and random effects for participants and random intercepts were modeled. Due to singularity and convergence problems the model was then reduced by excluding successively the random parts with the smallest variation (Barr et al., 2013; cf. Barr, 2013; Brauer & Curtin, 2018). As index of the tau effect the fixed effect of the temporal interval on the spatial response was evaluated, whereas the kappa effect was investigated by addressing the fixed effect of the spatial interval on the temporal response (each tested through model comparisons with and without the respective fixed effect). Blur or volume were included as additional predictors and the interaction between blur or volume and the context variable was regarded to evaluate whether the size of the relationship can be modulated by the informational value (i.e., representational noise). The standardized estimate (due to scaled data) of each effect will be reported and labeled as β.

3.2.2 Results

3.2.2.1 Auditory condition

In the auditory condition, participants' **temporal response** was significantly impacted by the temporal intervals, $\beta = 0.90$, $\chi^2(1) = 221.86$, $p < .001$, indicating that participants were sensitive to the temporal manipulation. Overall, participants reacted too late (see reaction times compared to dotted lines in Figure 3-2a). As depicted in Figure 3-2a, the longer the temporal intervals were (columns from left to right), the later participants touched the screen. There was a small but significant negative effect of spatial intervals, $\beta = -0.02$, $\chi^2(1) = 6.64$, $p = .010$, as depicted in Figure 2a. For all three temporal intervals, the relationship between the spatial intervals and the temporal response tended to be slightly negative, as indicated by the negative slope. This contrasts with the expected positive impact of spatial interval on the temporal response and might indicate a reversed kappa effect. No other effects were significant (all *p*s > .471).

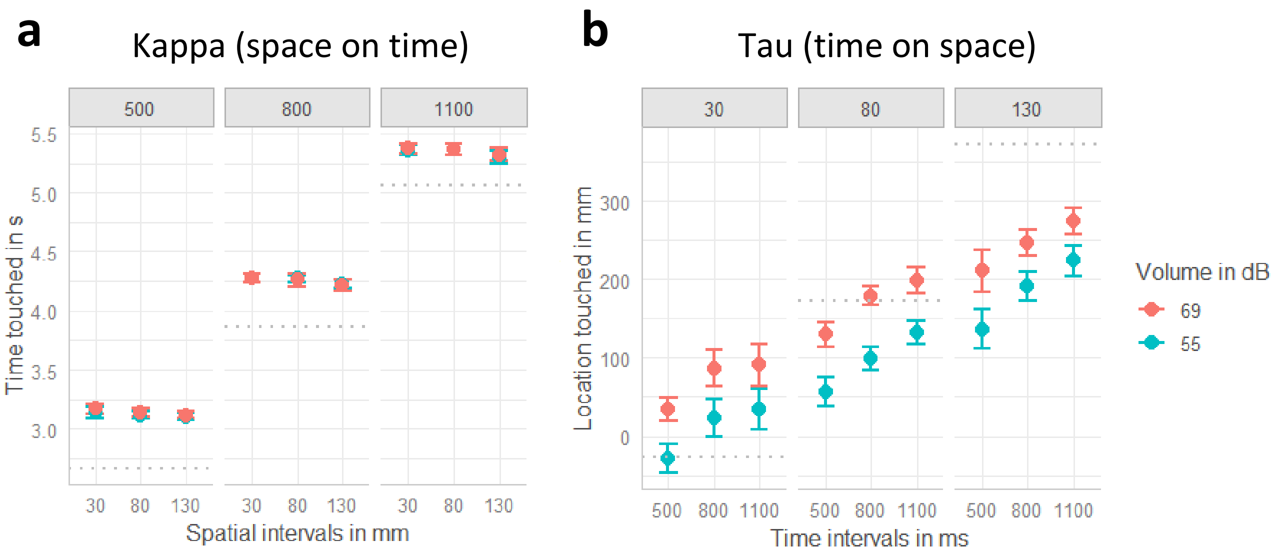

Figure 3-2. Plots of the auditory condition. Dots indicate means and error-bars indicate within-participant confidence intervals. **a**: Auditory kappa effect. Effect of volume, spatial and temporal intervals on the temporal response. One plot for each of the temporal intervals (500, 800, 1100 ms) is displayed. **b**: Auditory tau effect. Effects of volume, spatial and temporal intervals on the spatial response (0 refers to the center of the screen and higher values indicate taps further to the right). One plot for each of the three spatial intervals (30 mm, 80 mm, 130 mm) is displayed. The gray dottet lines indicate the correct time (a) or location (b).

For the **spatial response** the linear mixed model comparisons revealed a significant effect of spatial interval, $\beta = 0.42$, $\chi^2(1) = 57.03$, $p < .001$. The more distant the stimuli were (columns from left to right in Figure 3-2b), the further to the right (in movement direction) participants tapped, confirming that participants were able to dissociate the varying spatial intervals. Likewise, louder sounds (red dots in Figure 3-2b) led to spatial interception locations further to the right, β = 0.38, $\chi^2(1) = 59.81$, $p < .001$. In line with the hypothesis of an auditory tau effect, increasing temporal intervals resulted in reactions further to the right, β = 0.17, $\chi^2(1) = 39.28$, $p < .001$, as depicted by the positive slopes in the three columns of Figure 3-2b. There was a nonsignificant trend for an interaction between spatial and temporal intervals, β = -0.02, $\chi^2(1) = 2.98$, $p = .084$, indicating that the effect of temporal intervals tended to increase with increasing spatial intervals. None of the other interactions were significant (all *p*s > .130).

3.2.2.2 Visual condition

The analysis of the **temporal response** in the visual data revealed that, overall, participants reacted too late, as can be seen in Figure 3-3a (dotted line indicates the correct time and participants mostly reacted later). Approving the manipulation check, participants tapped the screen later with increasing temporal interval, β = 0.95, $\chi^2(1) = 247.95$, $p <.001$ (see three columns of Figure 3-3a). Additionally, when stimuli were blurred (blue dots in Figure 3-3a) participants tended to react later, but there was only a small effect, β = 0.03, $\chi^2(1) = 7.74$, $p = .005$. There was a negative effect of spatial intervals on the temporal response, β = -0.02, $\chi^2(1) = 4.09$, $p = .043$. As depicted by the slightly negative slope for each column in Figure 3-3a, participants touched the screen earlier with increasing spatial intervals, again suggesting a reversed kappa effect. None of the interactions between the three predictors reached significance (all *p*s > .324).

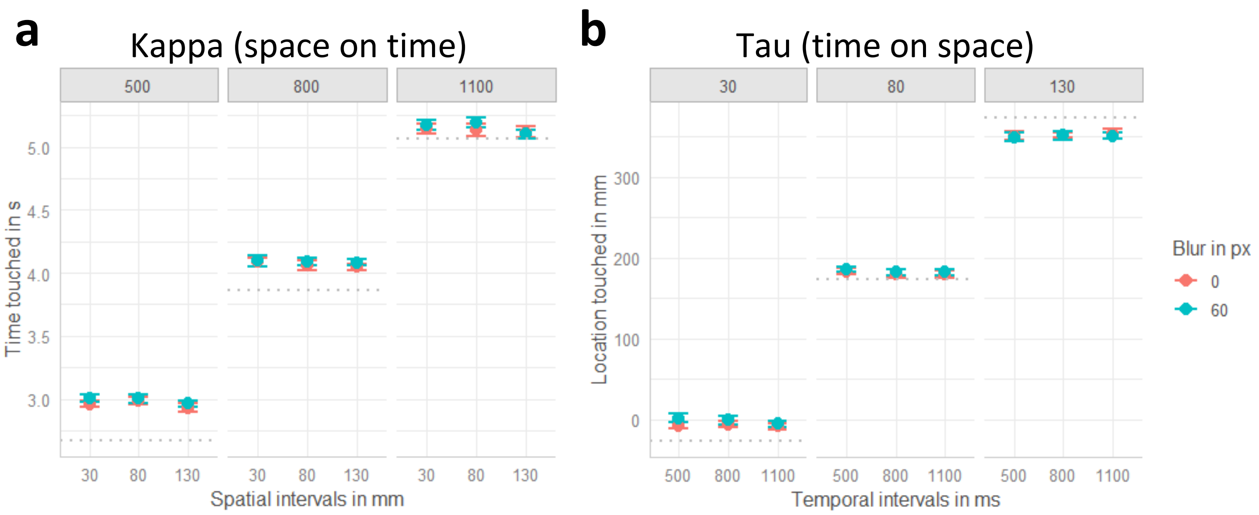

Figure 3-3. Plots of the visual condition. Dots indicate means and error-bars indicate within-participant confidence intervals. **a**: Visual kappa effect. Effect of blur, spatial and temporal intervals on the temporal response. One plot for each of the temporal intervals (500, 800, 1100 ms) is displayed. **b**: Visual tau effect. Effects of blur, spatial and temporal intervals on the spatial response (0 refers to the center of the screen and higher values indicate taps further to the right). One plot for each of the three spatial intervals (30 mm, 80 mm, 130 mm) is displayed. The gray dottet lines indicate the correct time (a) or location (b).

The **spatial response** to visually presented stimuli was significantly impacted by the spatial intervals, $\beta = 0.97$, $\chi^2(1) = 243.62$ p <.001 (manipulation check). The longer the spatial intervals were (see three columns from left to right in Figure 3-3b), the further to the right participants touched the screen. There was a small but significant effect of blur, $\beta = 0.01$, $\chi^2(1) = 4.72$, $p = .030$, indicating that participants touched the screen slightly more to the right for blurred stimuli (blue dots in Figure 3-3b). Most importantly there was no significant effect of the temporal intervals (p > .136), indicating no visual tau effect (all three slopes in Figure 3-3b are close to zero). The two-way interactions between spatial intervals and temporal intervals, $\beta = 0.01$, $\chi^2(1) = 5.30$, $p = .021$, and between spatial intervals and blur level reached significance, $\beta = -0.02$, $\chi^2(1) = 13.00$, $p < .001$. All other interactions did not reach significance (all *p*s > .232).

3.2.3 Discussion

Here, we tested whether spatiotemporal illusions like *tau* and *kappa* effects would impact motor responses, specifically, in a manual interception task. Results support the suggested *tau* effect, that is, the effect of temporal intervals on spatial responses for auditory stimuli. This is in line with previous research reporting, for instance, a *tau* effect for auditory stimuli on relative judgements (e.g., Jones & Huang, 1982) and in a memory task (Sarrazin et al., 2007). In contrast to our predictions, for visual stimuli the interception timing was not delayed with increasing spatial intervals. In fact, quite an opposite pattern of results was observed. That is, there was even a small effect in the opposite direction, potentially pointing to a *reversed kappa* effect that was present for auditory stimuli, too. A negative effect of spatial intervals on the temporal response, however, is in line with results reported by Roy et al. (2011) in an auditory classification task (i.e., whether the presented sound was a long or short sound). The authors explained this finding with the internal clock model of time perception (Treisman et al., 1990). According to this model time perception functions through a so-called pacemaker which is emitting pulses. These pulses are then recorded and accumulated by another unit in the system. With increasing distance between two stimuli, more attention is shifted towards localizing those stimuli and therefore less attentional resources remain on the temporal task. Consequently, pulses are missed resulting in a smaller total number of accumulated pulses. In the end, participants perceive a shorter temporal interval because less pulses were counted. Potentially, this phenomenon might explain the current results. However, as both the visual and auditory *reversed kappa* effects were very small and just reached significance, these results should be interpreted with caution.

We can think of three more possible explanations for the unexpected absent *classical kappa* effect: First, this is not the first study finding no evidence for a transfer of visual illusions to actions. Previous research on action tasks, namely interception and grasping, provided mixed results: many studies report a transfer of illusion effects (de la Malla et al., 2018; de la Malla et al., 2019b; Franz et al., 2000; Medendorp et al., 2018), others find no such effects (e.g., Aglioti et al., 1995; Haffenden & Goodale, 1998). A study on throwing performance reported mixed findings (Cañal-Bruland et al., 2013). We argue that the current results might therefore add to the ongoing debate about different visual processing streams for perception vs. action (Goodale et al., 1991; Goodale & Milner, 1992), but it should be noted that other reasons for the missing effects are possible. Second, participants might know about their bias and by controlling for it, they might overcorrect, thereby nullifying (or even reversing) the expected effect. Third, as previous research suggests, the difficulty of the task is an important prerequisite for the illusions (cf. Jones & Huang, 1982). Tasks in which the primary judgement was relatively easy, revealed reduced or even no effects (Jones & Huang, 1982): for instance, musicians showed no auditory *tau* effect in a task where the primary judgement was about frequencies (cf. Jones & Huang, 1982); *tau* and *kappa* in a memory task were only found for varying compared to constant spatial and temporal intervals (Sarrazin et al., 2004; Sarrazin et al., 2007); and the *tau* effect decreases with decreasing signal duration supposedly due to worse spatial representations for short presentation times (Bill & Teft, 1972). This latter argument can be explained by the representational noise hypothesis introduced before (Cai & Wang, 2021). The noisier a representation is, the more prone to influences it will be. Assuming that the amount of noise corresponds to task difficulty, an easy task for the primary judgement would result in a reduced or absent impact of the context. If this was the case in the current visual condition, this would suggest that the temporal task was relatively easy. Post-hoc analysis providing initial evidence for this argument are reported in the Appendix 6.2 (Figure 6-9). This idea is also in line with previous accounts on accuracy in interception suggesting that uncertainty in spatial localization might increase the reliance on prior information (Nelson et al., 2019). In our case, instead or priors, additionally available information might impact performance. If indeed task difficulty in relation with representational noise can explain absent effects, it would be advantageous to include a measure of task difficulty in future analyses. Given that originally *tau* and *kappa* were found for fewer presentations of spatial and temporal intervals (typically one or two) and that not all effects were present in the current task with repeated presentation, it is arguable that repetition may have decreased the task difficulty resulting in absent or small effects. If the number of repetitions ('events') makes the task easier by providing more time and presentations to learn and potentially adjust one's predictions, a measure of difficulty might be included when having access to participants' predictions on earlier stimulus events within each trial. A growing body of research shows that eye tracking might represent such a time-series-measure appropriate to evaluate motion prediction in interception tasks (for an overview, see Fooken et al., 2021). Eye movements may hence provide insights and help validate the new paradigm as a sensitive measure of perceptual biases, thereby indicating whether the dissociation between perception and action may account for the unexpected effects.

To summarize, whilst the auditory tau effect supports the initial hypothesis and is in line with previous research, the absence or even reversed visual kappa effect contrasts with most of previous reports. To i) replicate the interception results and ii) address two possible explanations for the absent *typical kappa* effects, a second experiment including eye tracking measurements was conducted.

3.3 Experiment 2

The aim of Exp. 2 was to test whether the gap between perception and action explains why increasing spatial intervals did not increase the temporal intervals and to identify the role of stimulus repetition ('events') on motion prediction. Therefore, we replicated Exp. 1 while additionally measuring eye movements.

3.3.1 Methods

3.3.1.1 Participants

In total 40 participants (19 male, M_{Age} = 24.2 years, SD_{Age} = 3.3 years; sample size similar to previous studies on interception, e.g., Schroeger et al., 2021) who did not enroll in Experiment 1 took part in the second experiment. Of the initially 45 collected datasets 5 were excluded from the analysis because participants did not fulfil the vision requirements (3) or due to technical problems with the eye-tracking measurement (2). All requirements were identical to Experiment 1. The eye tracking data of 8 participants could not be analyzed due to one of the following issues: extreme head rotation (n = 1), interference of clothes or accessories with the automated analysis algorithm (n = 2), reference objects (see Figure 3-1c) were partially cut, completely out of frame or occluded by participants' hands (n = 5). This means that finally gaze data of 32 participants entered the analysis. For detailed descriptive statistics see Table 3-1.

Table 3-1. *Descriptive statistics about the participants of Experiment 2.*

	Interception data (N=40)		Gaze data (N=32)	
Variable	mean	sd	mean	sd
age (years)	22.78	2.58	22.56	2.37
visual acuity (logMAR)	-0.14	0.08	-0.13	0.09
contrast sensitivity (logCS)	2.15	0.16	2.14	0.16
hearing threshold (dB)	23.54	1.95	23.81	1.99

3.3.1.2 Materials and Procedure

Materials and Procedure were identical to Experiment 1 with one exception: Due to an automatic analysis algorithm based on visual object detection using OpenCV (Bradski, 2000) for the eye tracking data (see below), eight reference objects (visual objects: 4 triangles and 4 rectangles) were presented on the screen within each trial (see Figure 3-1c). Participants were informed about these reference objects, and it was explained that they were only used for technical reasons and not important for the task.

3.3.1.3 Eye tracking

To record Eye tracking data, the portable system SMI ETG-2.6-1648-844 (SensoMotoric Instruments, Teltow, Germany; sampling frequency: 120 Hz for each eye, 30 Hz front camera) was used. Scan path videos were exported via the SMI BeGaze software and then analyzed frame by frame in Python (van Rossum & Drake Jr, 1995) with a self-written script using Spyder (Raybaut, 2009), Open CV (Bradski, 2000), math (van Rossum, 2020), matplotlib (Hunter, 2007), numpy (Harris et al., 2020), and pandas (McKinney, 2010). To do so, each frame recorded in reference to the viewer was transformed in reference to the screen (for a similar implementation, see MacInnes et al., 2018) and the gaze location was extracted through object detection. The code can be retrieved from the osf (https://osf.io/9nx3u/). The gaze locations (x and y coordinates on the touchscreen) per frame were saved and then analyzed in R, using the package 'saccades' (Malsburg, 2015) to categorize fixations and saccades, and the packages afex (Singmann et al., 2021), dplyr (Wickham et al., 2018), ggplot2 (Wickham, 2009), lmerTest (Kuznetsova et al., 2017), openxlsx (Schauberger & Walker, 2021), and reshape (Wickham, 2007) for the statistical analysis.

In contrast to the manual interception data, for the gaze data, earlier gaze locations and reaction times to the stimuli were used in the linear mixed models. Data regarding the third, fourth and fifth event (appearance of the ball) were considered and included as another factor ("event"). The first and second event were excluded because they were needed to build the first spatial and temporal interval meaning that no prediction is possible at that time of the trial. As relevant measures, the final fixation before the target appeared at event 3, 4 or (predicted) 5, was analyzed because previous studies showed that participants tend to fixate, for instance, predicted target locations in advance (Land & McLeod, 2000; Mann et al., 2019). Therefore, the temporal dependent variable was defined as the start of the final fixation before the target appeared, and the location where participants fixated immediately before the following event was taken as the spatial dependent variable. Additionally, the gaze location at the moment of interception was analyzed and these results are reported in the Appendix 6.2. Effects of and interactions between temporal intervals, spatial intervals, event, and volume (in dB) or blur were modeled.

3.3.2 Results

3.3.2.1 Interception performance

Overall, the results of the interception response of Experiment 2 replicated the results of Experiment 1: visually only a small, reversed kappa effect, $\beta = -0.01$, $\chi^2(1) = 9.05$, $p < .003$, but no significant tau effect was found, $\beta = -0.01$, $\chi^2(1) = 2.38$, $p = .123$; auditorily a significant tau, $\beta = 0.16$, $\chi^2(1) = 23.57$, $p < .001$, but no kappa effect was found, $\beta = -0.01$, $\chi^2(1) = 1.30$, $p = .254$ (for detailed results see Table 3-2 and Figure 3-4).

Table 3-2. Results of the linear mixed models' analysis for the interception performance in Experiment 2.

Auditory kappa (temporal response)	df	χ^2	*p*	Auditory tau (spatial response)	df	χ^2	*p*
spatial_ISI	1	1.30	.254	spatial_ISI	1	49.78 ***	<.001
temporal_ISI	1	228.30 ***	<.001	temporal_ISI	1	23.57 ***	<.001
blur	1	7.59 **	.006	volume	1	48.91 ***	<.001
spatial_ISI: temporal_ISI	1	9.39 **	.002	spatial_ISI: temporal_ISI	1	0.46	.498
spatial_ISI:blur	1	3.32 +	.069	spatial_ISI:volume	1	0.08	.772
temporal_ISI:blur	1	0.13	.719	temporal_ISI:volume	1	2.98 +	.084
spatial_ISI: temporal_ISI:blur	1	0.03	.868	spatial_ISI: temporal_ISI:volume	1	0.12	.730
Visual kappa (temporal response)	**df**	**χ^2**	***p***	**Visual tau (spatial response)**	**df**	**χ^2**	***p***
spatial_ISI	1	9.05 **	.003	spatial_ISI	1	253.29 ***	<.001
temporal_ISI	1	245.72 ***	<.001	temporal_ISI	1	2.38	.123
blur	1	17.75 ***	<.001	volume	1	9.03 **	.003
spatial_ISI: temporal_ISI	1	0.25	.615	spatial_ISI: temporal_ISI	1	5.40 *	.020
spatial_ISI:blur	1	0.18	.670	spatial_ISI:volume	1	2.40	.121
temporal_ISI:blur	1	1.01	.315	temporal_ISI:volume	1	0.51	.473
spatial_ISI: temporal_ISI: blur	1	0.24	.626	spatial_ISI: temporal_ISI:volume	1	0.25	.618

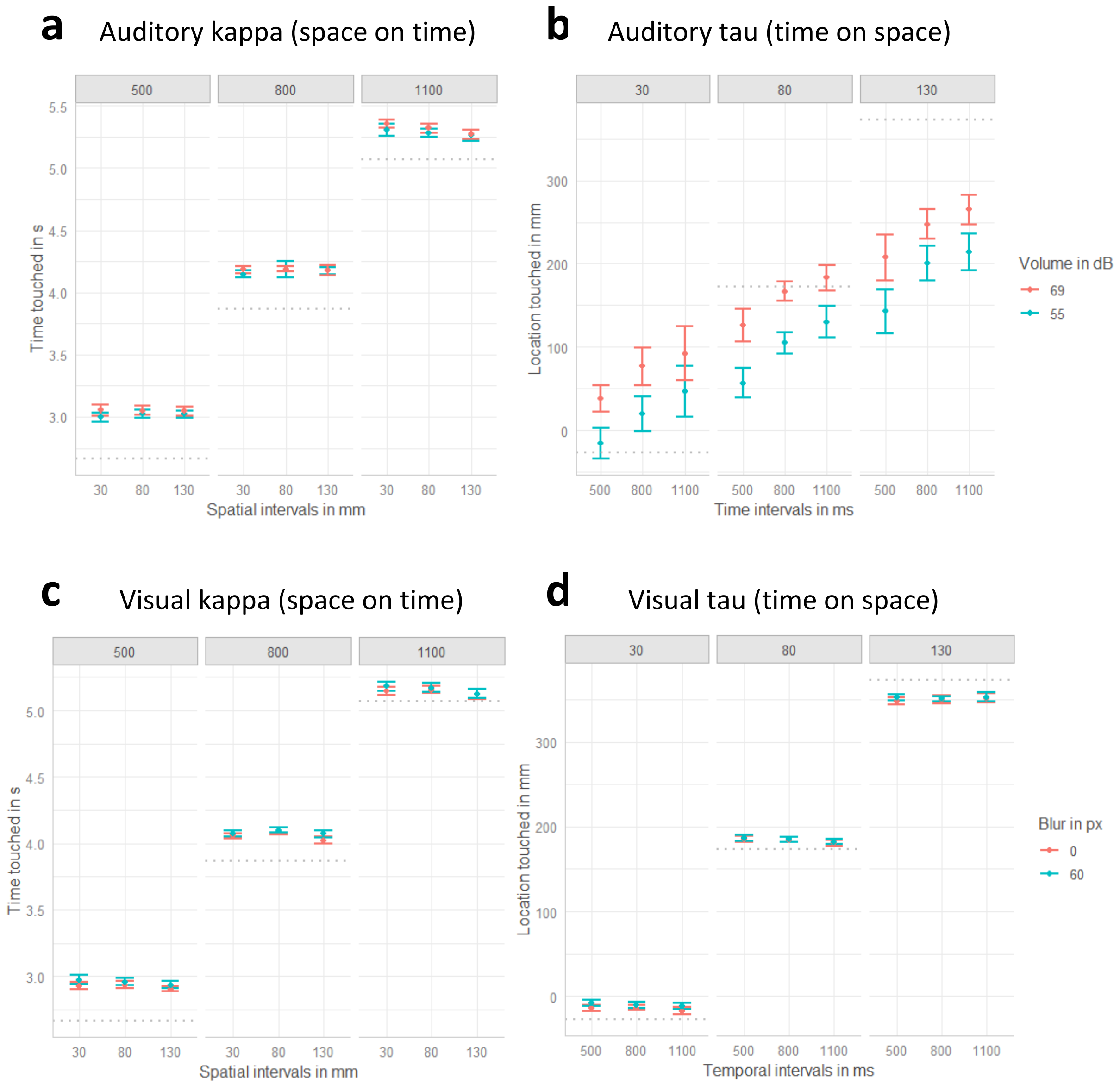

Figure 3-4. Interception results of Experiment 2. Dots indicate means and error-bars indicate within-participant confidence intervals. **a**: Auditory kappa effect. Effect of volume, spatial and temporal intervals on the temporal response. One plot for each of the temporal intervals (500, 800, 1100 ms) is displayed. **b**: Auditory tau effect. Effects of volume, spatial and temporal intervals on the spatial response (0 refers to the center of the screen and higher values indicate taps further to the right). One plot for each of the three spatial intervals (30 mm, 80 mm, 130 mm) is displayed. **c**: Visual kappa effect. Effect of blur, spatial and temporal intervals on the temporal response. One plot for each of the temporal intervals (500, 800, 1100 ms) is displayed. **d**: Visual tau effect. Effects of blur, spatial and temporal intervals on the spatial response (0 refers to the center of the screen and higher values indicate taps further to the right). One plot for each of the three spatial intervals (30 mm, 80 mm,

3.3.2.2 Gaze Behavior

3.3.2.2.1 Auditory condition

The location of the final fixation before the sound was started was analyzed to evaluate a possible tau effect. The linear mixed model comparisons revealed a significant effect of spatial intervals, $\beta = 0.17$, $\chi2(1) = 35.73$, $p < .001$, and volume (dB), $\beta = 0.22$, $\chi2(1) = 33.80$, $p < .001$. With increasing spatial intervals and for louder sounds, participants fixated further to the right (see Figure 3-5: the fixation timing increases for columns from left to right and for the red condition compared to the blue condition). Most importantly, with increasing temporal intervals participants fixated more to the right, $\beta = 0.23$, $\chi2(1) = 35.81$, $p < .001$. Furthermore, the event revealed a significant effect, $\beta = 0.61$, $\chi2(1) = 59.42$, $p < .001$. There were significant interactions between the spatial and temporal intervals $\beta = 0.05$, $\chi2(1) = 14.37$, $p < .001$, the spatial intervals and event, $\beta = 0.15$, $\chi2(1) = 33.06$, $p < .001$, the temporal intervals and event, $\beta = 0.11$, $\chi2(1) = 23.66$, $p < .001$, volume and event, $\beta = 0.15$, $\chi2(1) = 29.84$, $p < .001$, and spatial intervals, temporal intervals and event, $\beta = 0.04$, $\chi2(1) = 19.78$, $p < .001$. There was a non-significant trend for an interaction between temporal intervals and volume, $\beta = 0.03$, $\chi^2(1) = 3.07$, $p = .080$. No other effects reached significance (all *p*s > .086).

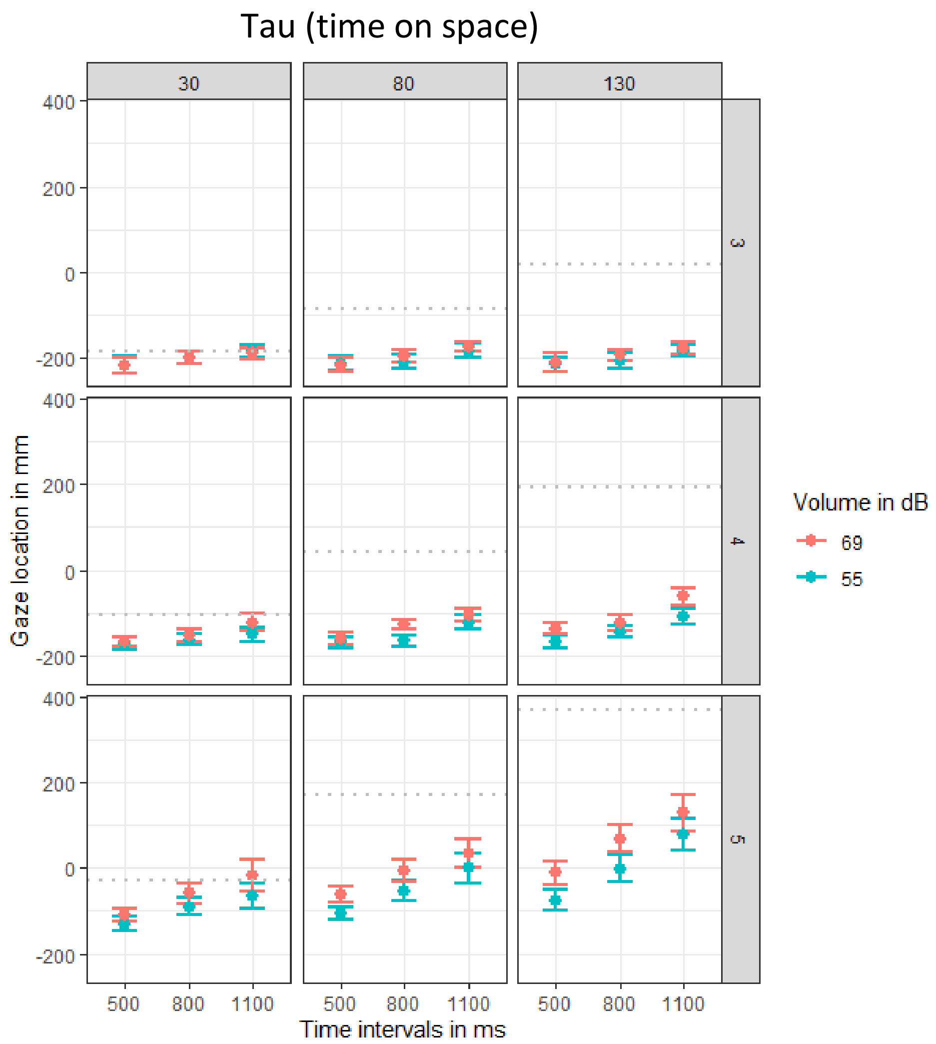

Figure 3-5. Plots of the auditory tau effect per event (third, fourth, or fifth apearance of the ball). Effect of volume, spatial and temporal intervals on the location of the final fixation. One plot for each of the temporal intervals (500, 800, 1100 ms) is displayed. Dots indicate means and error-bars indicate within-participant confidence intervals. The gray dottet lines indicate the correct location.

The analysis of the **timing of the final fixation** revealed significant effects of temporal intervals, $\beta = 0.45$, $\chi^2(1) = 87.71, p < .001$, volume, $\beta = 0.06$, $\chi^2(1) = 5.40, p = .020$, events, $\beta = 0.64$, $\chi^2(1) = 80.87, p < .001$, and most importantly, spatial interval, $\beta = 0.08$, $\chi^2(1) = 26.19, p < .001$. Logically, the longer the temporal intervals were (see Figure 3-6 three columns from left to right) or the later the ball event was (see Figure 3-6 three rows top-down) the later participants started their final fixation. Additionally, the larger the spatial interval were, the later the final fixation was initiated, as can be seen by the positive slope in each grid of Figure 3-6. The interaction between spatial and temporal intervals, $\beta = 0.04$, $\chi^2(1) = 15.53, p < .001$, spatial intervals and event, $\beta = 0.07$, $\chi^2(1) = 23.80, p < .001$, temporal intervals and event, $\beta = 0.21$, $\chi^2(1) = 68.22, p < .001$, and volume and event, $\beta = 0.06$, $\chi^2(1) = 10.09, p = .001$, reached significance. With increasing stimulus repetition (event), the effect of spatial intervals on the timing of the last fixation increased, as indicated by the increasing positive slope from top to down). Additionally, there was a significant three-way interaction between spatial intervals, temporal intervals, and event, $\beta = 0.02$, $\chi^2(1) = 10.18$, $p = .001$. All other interactions did not reach significance (all *p*s > .175) For a visualization of the results see Figure 3-6.

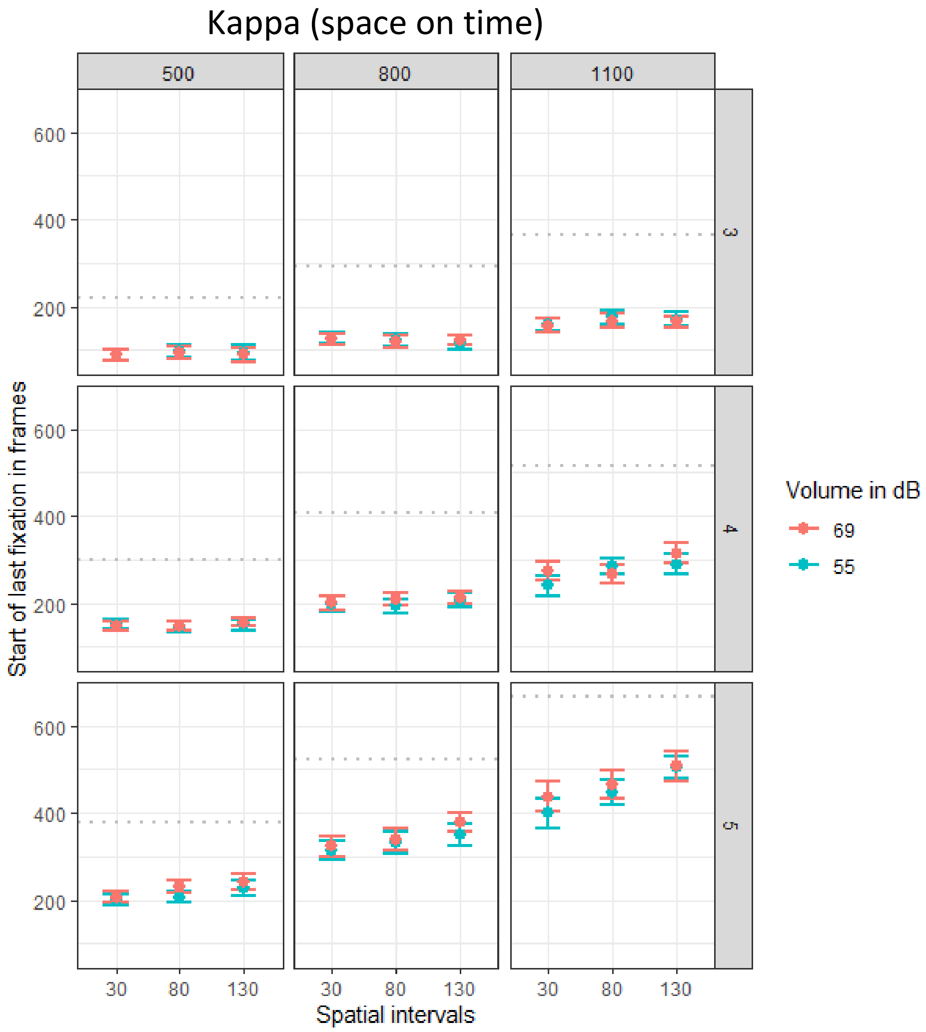

Figure 3-6. Plots of the auditory kappa effect per event (third, fourth, or fifth apearance of the ball). Effect of volume, spatial and temporal intervals on the start of the final fixation (in frames). Data was recorded with 120 frames per second. One plot for each of the temporal intervals (500, 800, 1100 ms) is displayed. Dots indicate means and error-bars indicate within-participant confidence intervals. The gray dottet lines indicate the correct time.

3.3.2.2.2 Visual condition

To analyze the tau effect in the gaze data, the location of the final fixation before the ball appeared was examined. Results of the visual data revealed that the spatial interval predicted where participants fixated, $\beta = 0.52$, $\chi2(1) = 74.53$, $p < .001$, and the temporal intervals impacted the gaze location, $\beta = 0.20$, $\chi2(1) = 74.93$, $p < .001$. Additionally, there was a significant effect of event, β = 0.63, χ2(1) = 86.89, p < .001, and an interaction between temporal and spatial intervals, β = 0.12, χ2(1) = 75.79, p < .001, indicating that the effect of the spatial intervals on the gaze location was larger for longer temporal intervals. There was also a significant interaction between spatial intervals and event, β = 0.28, χ2(1) = 83.20, p < .001, and a significant three-way interaction between spatial interval, temporal intervals and event, β = -0.02, χ2(1) = 10.82, p = .001. All other effects did not significantly affect the gaze location of the final fixation (all *p*s > .171). These effects are depicted in Figure 3-7.

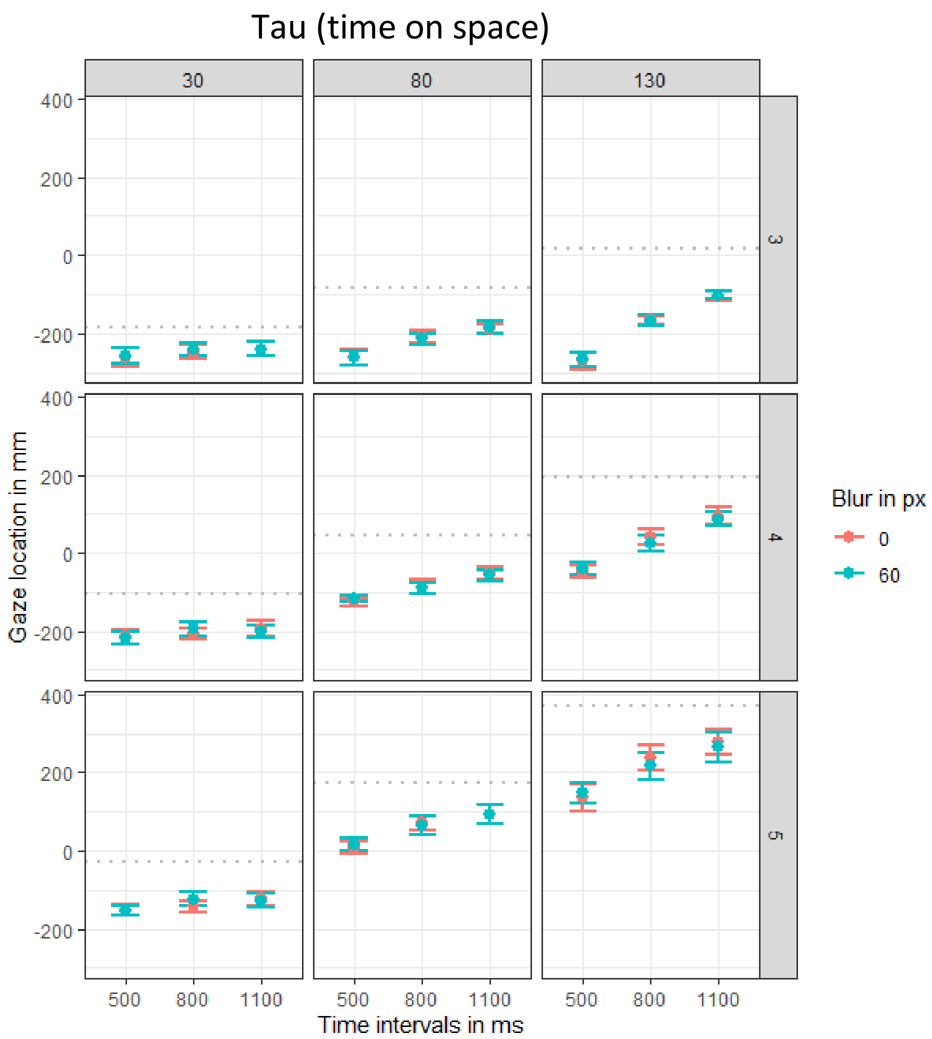

Figure 3-7. Plots of the visual tau effect per event (third, fourth, or fifth apearance of the ball). Effect of blur, spatial and temporal intervals on the location of the final fixation. One plot for each of the temporal intervals (500, 800, 1100 ms) is displayed. Dots indicate means and error-bars indicate within-participant confidence intervals. The gray dottet lines indicate the correct location.

As indicator of a kappa effect in the gaze data, the **time participants started their final fixation** was analyzed. The analysis revealed a significant positive effect of the temporal intervals on the timing of the last fixation, $\beta = 0.49$, $\chi^2(1) = 91.76$, $p < .001$. As can be seen in Figure 3-8 in the three columns from left to right, the last fixation was later initiated with increasing temporal intervals. Most importantly, there was a positive relation between the spatial intervals and the start of the final fixation, $\beta = 0.20$, $\chi^2(1) = 31.78$, $p < 001$. These two effects were further explained by their significant two-way interaction, $\beta = 0.08$, $\chi^2(1) = 27.82$, $p < .001$, indicating that the positive relation between spatial intervals and timing of fixation increased with increasing temporal intervals (the positive slope increases from left

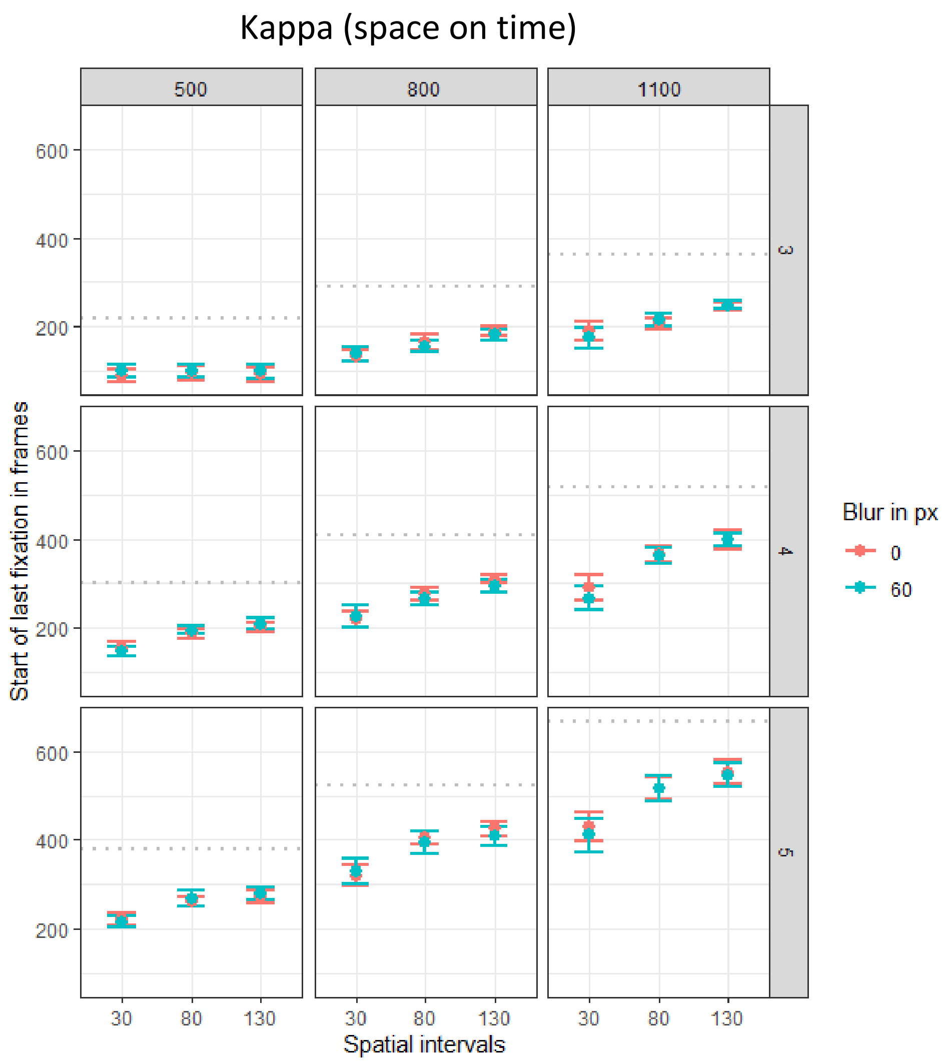

Figure 3-8. Plots of the visual kappa effect per event (thrid, fourth or fifth appearance of the ball). Dots indicate means and error-bars indicate within-participant confidence intervals. Left: Visual kappa effect. Effect of blur, spatial and temporal intervals on the start of the final fixation (in frames). Data was recorded with 120 frames per second. One plot for each of the temporal intervals (500, 800, 1100 ms) is displayed. The gray dottet lines indicate the correct time.

to right in Figure 3-8). Additionally, there was a significant effect of event, $\beta = 0.62$, $\chi^2(1) = 94.73$, $p < .001$, and significant interactions between spatial intervals and event,

$\beta = 0.06$, $\chi^2(1) = 17.22$, $p < .001$, temporal intervals and event, $\beta = 0.14$, $\chi^2(1) = 77.44$, $p < .001$. The effect of the spatial intervals on the initiation of the final fixation increased with the number of target events (increasing slopes from top to down in Figure 3-5). No other effects reached significance (all *p*s > .123).

3.3.3 Discussion

In Experiment 2 we aimed to replicate the results found in Experiment 1, namely an auditory tau effect for interception performance, and to extend and explain these findings, especially the absent visual kappa effect, by using eye tracking measures. Regarding the interception response, overall, we successfully replicated the effects found in Experiment 1: an auditory tau effect, a small reversed visual kappa effect, and no visual tau effect. In contrast to Exp. 1, where a small, reversed kappa effect was evident for the auditory data as well, the results of Exp. 2 provide no significant effect. The gaze data revealed indications of visual and auditory tau and kappa effects. The longer the temporal intervals, the further participants moved their gaze for the final fixation before stimulus presentation (either visually or auditorily). Additionally, for both modalities, participants initiated their final fixation before presentation later, the larger the spatial interval were.

As eye movements have been found to be highly correlated with motion perception and prediction (Schütz et al., 2011), this might indicate that the adapted paradigm was able to produce spatiotemporal illusions, at least at the level of spatiotemporal perception and prediction. Interestingly, these effects did not transfer to interception performance: For both modalities, the spatial intervals impacted when participants fixated but revealed small, reversed effects for interception. Although participants gaze location was affected by the temporal intervals in the visual condition, they did not intercept at those fixation locations. Auditorily both, gaze and interception location depended on the temporal intervals. These results will be discussed in more detail in the following General Discussion.

3.4 General Discussion

Intercepting a moving object relies on predicting the object's trajectory in space and time and executing precise movements (e.g., Fiehler et al., 2019; Land & McLeod, 2000). Interception performance might therefore be influenced by interrelations between spatial and temporal processing, as found for spatial and temporal judgements (e.g., Helson & King, 1931). A recent review suggests that seemingly contradictory hypotheses about spatiotemporal interrelations as proposed by ATOM vs. CMT can be consolidated when including sensory modality as a moderating variable (Loeffler et al., 2018). Following this rational, we proposed two hypotheses taking into account different sensitivities for spatial and temporal information across sensory modalities: i) in an auditory condition, effects of temporal intervals on spatial interception responses were predicted (*tau* effect), whilst manipulations of spatial intervals were assumed to have only small or no impact on temporal responses (no or small *kappa* effect); ii) for visual stimuli larger effects of spatial manipulations on temporal responses were expected (*kappa* effect), whereas temporal manipulations should not or only marginally impact spatial responses (no or small *tau* effect).

Our findings provided evidence for spatiotemporal interrelations in a new form of tasks – namely (auditory) interception – as compared to the previously reported effects on relative judgments (e.g., Jones & Huang, 1982) and memory retrieval (Sarrazin et al., 2004). Moreover, the results indicate that modality plays an important role as concerns the contributions of spatial and temporal characteristics of a task (O'Connor & Hermelin, 1972; Recanzone, 2009; Schmiedchen et al., 2012). Both experiments showed that in the auditory condition interception performance revealed a significant *tau*, but no classical (yet in Exp. 1 a small and reversed) *kappa* effect. In contrast to our predictions, also for visual stimuli no classical, but again a small and surprisingly reversed *kappa* effect was found across experiments. Also, in both experiments, no visual tau effect was found, in line with our predictions. Given that there was an auditory but no visual *tau* effect, together these results seem to support the notion that sensory modality plays an important role and should be considered when investigating spatiotemporal interrelations in interception.

3.4.1 Debate on ATOM vs. CMT

The current results are adding to the debate on ATOM (Walsh, 2003) and CMT (Lakoff & Johnson, 1980b). In contrast to previous research applying tau and kappa paradigms to solve the controversy between those theories (Reali et al., 2019), the current results clearly contradict the asymmetrical relationship proposed in CMT with higher impact of spatial characteristics on temporal judgements. Rather than finding a symmetrical or asymmetrical relationship between spatial and temporal representations, the size of effects in either direction may actually depend on other factors. Here, we showed that sensory modality is one of those factors. While previous research showed that for visual tasks typically larger effects of space on temporal judgements are found (e.g., Casasanto & Boroditsky, 2008), the current results revealed the opposite pattern for auditory stimuli. This seems to indicate that both the predictions of CMT of ATOM can be met depending on sensory modality. In this vein, perhaps the best way to capture and conceptualize the relationship between time and space is offered by the theory of representational noise (Cai & Wang, 2021).

3.4.2 Noise and modality

Cai and Wang (2021) propose that the interrelations between spatial and temporal representations are affected by the amount of representational noise. Assuming different levels of noise under varying sensory conditions might therefore be the theoretical basis of the presented results. The amount of noise for each modality might be inferred from the sensitivity of the respective modality towards spatial vs. temporal information. The finding that the auditory system appears to be dominated by temporal compared to spatial information (O'Connor & Hermelin, 1972; Recanzone, 2009) together with the imprecision of auditory localization in humans compared to visual localization (Middlebrooks & Green, 1991) points to the fact that less representational noise may be expected for temporal information. If spatial representations were very noisy, they may have been influenced by concurrent temporal information, thereby explaining why participants touched the screen further in movement direction of the stimulus.

Contrary to our hypothesis, blur and volume manipulations did not impact the size of the effects, questioning the assumption that they would increase representational noise of either spatial or temporal representations. Potentially these manipulations have not been appropriate for that purpose, especially as they mainly address the stimulus locations, but not directly the spatial and temporal intervals. For future research it would be beneficial to explicitly test the predicted changes in representational noise, before including them as manipulations on spatiotemporal interrelations. One problem with blurring stimuli is that an impact on (spatial localization) performance often is only found (if at all) for very high blur levels (Alais & Burr, 2004; Kramer et al., 2019; Mann et al., 2010). An alternative visual manipulation might hence need much higher levels of visual blur. For sounds, it is known that broadband noise can be much easier localized when compared to sinus sounds which might therefore be a better candidate as a potential manipulation of spatial representational noise for auditory stimuli. Our results of the auditory manipulation revealed only a main effect of volume on the interception location. Louder sounds were perceived to go further. Similar results of sound intensity on localization were obtained by Cañal-Bruland et al. (2018) for anticipation in tennis. Their investigation suggests that next to visual information obtained from a tennis stroke, auditory cues are used to estimate the ball’s trajectory. Louder sounds are associated with longer trajectories potentially because they are linked to stronger strokes. This is supported by the notion that auditory cues are more informative for shot power discrimination than visual cues (Sors et al., 2017), and that grunting intensities impact spatial predictions in tennis (Müller et al., 2019). Similar processes might have influenced participants' interception in the current study, if louder sounds were associated with stronger bounces. However, this manipulation seems not to have increased noise for either the spatial or the temporal representation.

The idea, that spatiotemporal illusions depend on variability or uncertainty was also raised by J. Brooks et al. (2019) and shown in Schmiedchen et al. (2013) for other spatiotemporal interrelations. J. Brooks et al. (2019) argued that reducing information to fulfill the task, increases the effect of such illusions, as can also be explained by a Bayesian model (e.g., Goldreich, 2007; Goldreich & Tong, 2013). For future research, the use of Bayesian models might proof especially helpful to address the role of representational noise. In Bayesian cue integration models (for an overview, see Seilheimer et al., 2014), noise, operationalized as the reliability of the sensory input, accounts for the weighting and integration of signal from various sensory modalities. To explicitly address the effect of noise on the size of spatiotemporal biases, such models may be particularly helpful and insightful.

3.4.3 Perceptual effects in interception

Interestingly, the absence of the illusion's effect in interception is in contrast with previous research on the transfer of visual perceptual illusions to interception (e.g., de la Malla et al., 2018; de la Malla et al., 2019b). Despite using a similar interception task, the current study differed in the type of stimuli applied to evoke an illusion: These previous interception studies investigated illusory motion, whereas the present stimuli might be rather comparable to, for instance, size illusions. Studies on such size illusions in motoric responses mostly applied grasping and throwing tasks. Overall, mixed results (Cañal-Bruland et al., 2013) have been reported with some studies providing evidence for a transfer (Franz et al., 2000; for a review see Medendorp et al., 2018) and others showing no such effects (Aglioti et al., 1995; Haffenden & Goodale, 1998).

In the following we argue that the missing effects in vision might not call for a general absence of such a transfer, but rather indicate the important role of additional factors. As alluded to above, the effects of space on time and vice versa seem to depend on the amount of representational noise. Asymmetrical effects of space on time are only expected when temporal noise is relatively high. If the temporal part of the task was simply too easy – meaning that participants were very certain/precise in their temporal response – no impact of spatial characteristics would be predicted. Further evidence for this notion was provided in the research on kappa and tau effects (e.g., Jones & Huang, 1982). For instance, longer stimulus presentation durations are associated with higher focus on spatial compared to temporal characteristics. That is, spatial characteristics are more precisely represented when each stimulus is presented for more time whereas temporal precision diminishes. Accordingly, Bill and Teft (1972) showed that the tau effect decreases with increasing signal duration. Additionally, Jones and Huang (1982) assumed that an increase of the entire duration of one trial makes it more difficult to remember the initial stimulus location. Therefore, the spatial interval should be less precisely represented. Consequently, they found that the tau effect increased, whilst the kappa effect decreased with increasing total time (Jones & Huang, 1982).

3.4.4 Perceptual effects in eye movements

Interestingly, the gaze data of Exp.2 largely deviates from the interception performance. Here, both effects were found for auditory and visual stimuli. Given that eye movements have been reported to be highly correlated with perceptual processes (Schütz et al., 2011), and tau and kappa have been reported for perceptual tasks, this finding might be interpreted as a first validation of the novel interception paradigm presented in this study to investigate these illusions.

Still, the discrepancy between interception and eye movement results are surprising given that eye movements were shown to contribute significantly to spatiotemporal prediction and temporal interception (Fooken et al., 2021). For instance, previous results indicate that fixation locations are highly correlated with interception locations (cf. Fooken et al., 2021). The divergent findings in the current study might underpin the suggested dissociation between perceptual (gaze) and action (interception) tasks, at least for visual information processing (Goodale et al., 1991; Goodale & Milner, 1992). Yet, other explanations (e.g., task difficulty) cannot be ruled out. As concerns the role of task difficulty (cf. Huang & Jones, 1982), the number of repetitions of the target presentation and the ISI (events) did not decrease the effects. Quite the opposite, effects were largest for the last event, contradicting the idea that the task was too simple (low amount of representational noise) due to repeated presentation. Post-hoc analyses (see Appendix 6.2) rather showed that with increasing repetition the variability in the spatial response was increasing.

3.4.5 Future perspectives

To the best of our knowledge, this study is the first to examine *tau* and *kappa* effects on interception performance. Therefore, the current study extends previous research in several ways regarding the application of the temporal and spatial task. While in early research on tau and kappa (e.g., Cohen et al., 1953; Helson & King, 1931), participants had to either focus on spatial or on temporal information (primary judgement) and ignore the second domain (context), here they had to process both information to successfully fulfil the task (to be in the right place at the right time). Moreover compared to research on ATOM and CMT (e.g., Cai & Connell, 2015; Casasanto & Boroditsky, 2008), the current interception task differs as the dependent measure is an amalgam of spatial accuracy (being in the right place) and temporal accuracy (at the right time). Even if in some studies on ATOM and CMT participants were not informed prior to task execution about which information (spatial vs. temporal) they had to reproduce/judge until the stimulus presentation was finished (e.g., Casasanto & Boroditsky, 2008), this is the first study in which participants had to indicate both information in one spatiotemporal response (i.e. a single touch). This new method has certainly some advantages but also disadvantages. One the one hand, it is a step into more dynamic scenarios where the participant interacts with the environment, therefore strengthening ecological validity. On the other hand, it might have reduced the effects, if participants had divided their attention between both tasks with sometimes only focusing on the spatial and sometimes only focusing on the temporal demands. More robust effects might be expected, if participants would only focus on either the spatial or the temporal response. Future research with separate experiments for spatial vs. temporal prediction are needed to better understand those interrelations. Finally, daily life mostly confronts us with input from different modalities at the same time. To fully understand human processing of time and space, multisensory studies are needed. It was already shown that cross-modality tau (Kawabe et al., 2008) and kappa (Bausenhart & Quinn, 2018) effects can be observed when temporal information is presented auditorily and spatial information visually. Also research in related areas, for instance, on the representational momentum (the final location of a disappearing moving object is perceived to be shifted in motion direction), indicates cross-modality effects from visually presented motion on tactile localization but not vice versa (Merz, Meyerhoff, et al., 2020). Similarly, the research on *tau* and *kappa* in interception should be extended for different modalities providing either temporal or spatial or both information at the same time to fully understand whether and under which conditions such interrelations impact human behavior in real world behavior (i.e., outside the lab).

To summarize the current study adds to research on spatiotemporal interrelations by showing an auditory tau effect in manual interception, that is, an effect of temporal intervals between sounds on spatial interception performance. It provides initial empirical support for the role of sensory modality as a moderating factor consolidating seemingly contradictory predictions and findings of A Theory of Magnitude and the Conceptual Metaphor Theory. The application of eye tracking further suggests differences in spatiotemporal interrelations between merely perceptual vs. action tasks.

END OF PUBLICATION

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4 Study III: Kappa effects modulate prediction and interception.

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Abstract

The more distant two consecutive stimuli are presented, the longer the temporal interstimulus interval (ISI) between their presentations is perceived (kappa effect). The present study aimed at testing whether the kappa effect not only affects perceptual time estimates, but also motor action, more specifically, interception. In a first step, the original kappa paradigm was adapted to assess the effect in temporal prediction. Second, the task was further modified to an interception task, requiring participants to spatially and temporally predict and act. In two online experiments, a white circle was successively presented at three locations moving from left to right with constant spatial and temporal ISI in between. Participants were asked to either i) indicate the time of appearance of the predicted fourth stimulus (Exp. 1) or to ii) intercept the predicted fourth location at the correct time (Exp. 2). In both experiments the temporal response depended on the spatial intervals. In line with the kappa effect, participants predicted the final stimulus to appear later (Exp. 1) or intercepted it later (Exp. 2), the more distant the stimuli were presented. Together, these results suggest that perceptual biases such as the kappa effect impact motor interception performance.

Keywords: perceptual illusion, kappa, tau, interception, motor performance

4.1 Introduction

When we estimate the elapsed time between spatially separated and sequentially presented stimuli, our temporal judgments have been found to depend on the spatial distance between those stimuli. The more distant the stimuli are presented, the longer the temporal interval is perceived – a phenomenon referred to as the *kappa* effect (Abe, 1935; Cohen et al., 1953). Likewise, the influence of temporal intervals between the presentation of stimuli on judgments about their spatial distance is a well-known perceptual bias referred to as the *tau* effect (Benussi, 1913; Helson & King, 1931). However, whether the distorted perception of time and/or space also leads to biased motor responses remains an open question that we sought to address in the present study.

To start with, in the classical kappa and tau paradigms, the temporal and spatial biases were observed in judgment tasks in which a succession of three stimuli was visually presented and the interval between the first and second stimulus had to be compared to the interval between the second and third stimulus – either regarding their temporal duration or spatial length (Abe, 1935). Later, modifications of this paradigm have been introduced extending the kappa and tau effects, for instance, to other sensory modalities (for instance, auditory perception(Henry et al., 2009; Henry & McAuley, 2009); tactile perception (Suto, 1952)) or tasks, including motor tasks (Sarrazin et al., 2004; Sarrazin et al., 2007). Initial support for the transfer of these perceptual phenomena to motor performance was provided for both visual and auditory stimuli in a sequence learning task (Sarrazin et al., 2004; Sarrazin et al., 2007). The authors made participants memorize a series of consecutively presented visual stimuli (i.e. dots) with varying spatial and temporal intervals between presentations. In separate experiments, participants then had to reproduce either the spatial or the temporal configuration of the learned sequences motorically by either dragging and dropping visual markers to the memorized location (using a mouse) or pushing a button in the memorized rhythm. They found that in certain conditions, the reproduced temporal intervals were affected by their spatial extent (kappa effect) and vice versa (tau effect). These findings indicate that kappa and tau effects can be reproduced in memorized motor sequences, that is, a motoric reproduction of learned sequences. However, whether tau and kappa also affect the planning and execution of future actions such as in interception performance where the prediction of spatiotemporal trajectories of moving objects is crucial, remains yet to be determined. In everyday tasks, temporal prediction is necessary to plan and execute future actions, such as when catching a ball or when avoiding collision with other objects (e.g., cars). A biased perception could hinder successful performance or, in the worst case, be disastrous, for instance, resulting in an accident. Whether kappa and tau effects not only influence perception, but also interception performance (i.e., action) remains to be determined. To address this lacuna, in the current study, we primarily aimed at systematically examining the impact of the kappa effect on interception performance. If the kappa- and tau-like effects found in memorizing and reproducing motor sequences (Sarrazin et al., 2004; Sarrazin et al., 2007), transfer to prediction, we hypothesized that the kappa effect should not only show in a perceptual temporal estimation task, but that it should also impact motor interception performance.

One problem with the classical paradigm typically used to investigate kappa is that it was not designed to test prediction, but to compare two previously experienced spatial or temporal intervals. In order to be able to assess whether the kappa effect modulates interception performance, we hence first had to modify the original paradigm and then to validate the modified paradigm. Therefore, in a first online experiment, the original kappa paradigm was adapted to assess the effect in a temporal prediction task. To this end, in an online experiment participants were presented with a temporal succession of three spatially separated targets and were merely asked to provide a mouse click *when* they expected the next target to appear. After having validated that the modified paradigm produced kappa effects regarding the estimates of the appearance of the final stimulus, in a second online experiment the task was then further adapted to an interception task. More specifically, participants were asked to spatially and temporally intercept the target by predicting its next location and time of appearance. In contrast to previous studies, this latter interception task allowed us to measure a temporal and spatial response at the same time, or in other words, in a single move. In both tasks, spatial (150/200/250/300/350 px) and temporal (700/900/1100/1300/1500 ms) intervals were altered randomly between trials (see Figure 4-1).

We hypothesized that in both experiments, spatial manipulations would result in changes in the temporal response, indicating a kappa effect in both temporal prediction (Exp. 1) and interception performance (Exp. 2).

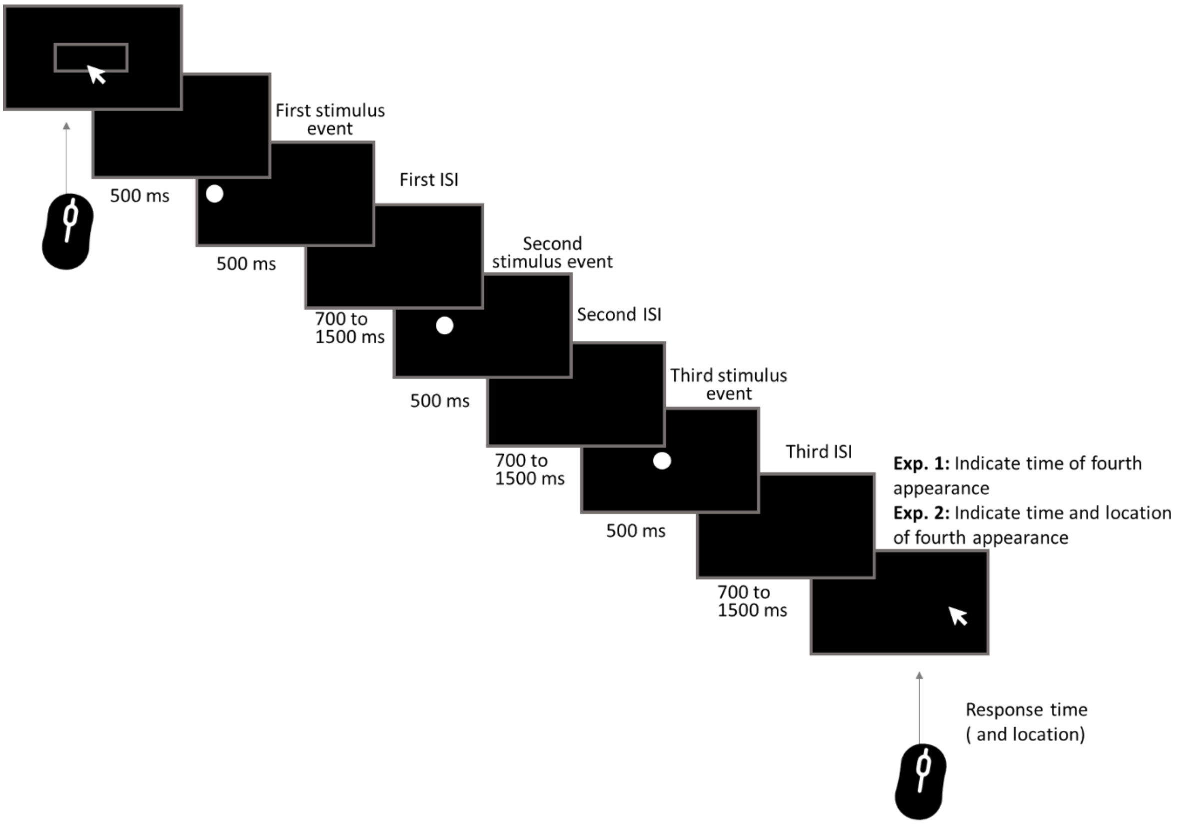

Figure 4-1. Structure of a single trial. Participants started each trial via a mouse/touchpad click. After a 500ms pause, the visual stimulus was presented for 500ms at the first location, it then disappeared for 700/900/1100/1300/1500 ms (interstimulus intervals = ISI) before reappearing again for 500ms at the second location (spatial intervals of 150/200/250/300/350 px). The disappearance and reappearance were repeated with the same temporal and spatial intervals and presentation times. After disappearing at the third location, participants were required to predict the fourth time (Exp. 1) and interception location (Exp. 2) of reappearance with the mouse or touchpad.

4.2 Results

4.2.1 Kappa effects in temporal prediction (Exp. 1) and interception (Exp. 2)

In Exp. 1, overall participants tended to respond too late, that is, later than the fourth stimulus would have appeared, as indicated by a positive temporal error ($\beta = 119.80$, 95 % CrI = 85.08 to 154.86, $P(\beta > 0) > 0.999$). Most importantly, in line with the predictions of the kappa effect, the spatial distances between presentations influenced participants' temporal response (see Figure 4-2 and Table 4-1). More specifically, in the modified prediction paradigm of Exp. 1, participants predicted longer temporal interstimulus intervals (ISIs) between more distant presentations for the first three distances (see Table 4-1). The effect becomes compelling when comparing the intervals of 200 pixels with intervals of 250 pixels (29.34 ms, 95% CrI = 10.91 to 47.74 ms, $P(\beta > 0) = 0.999$).

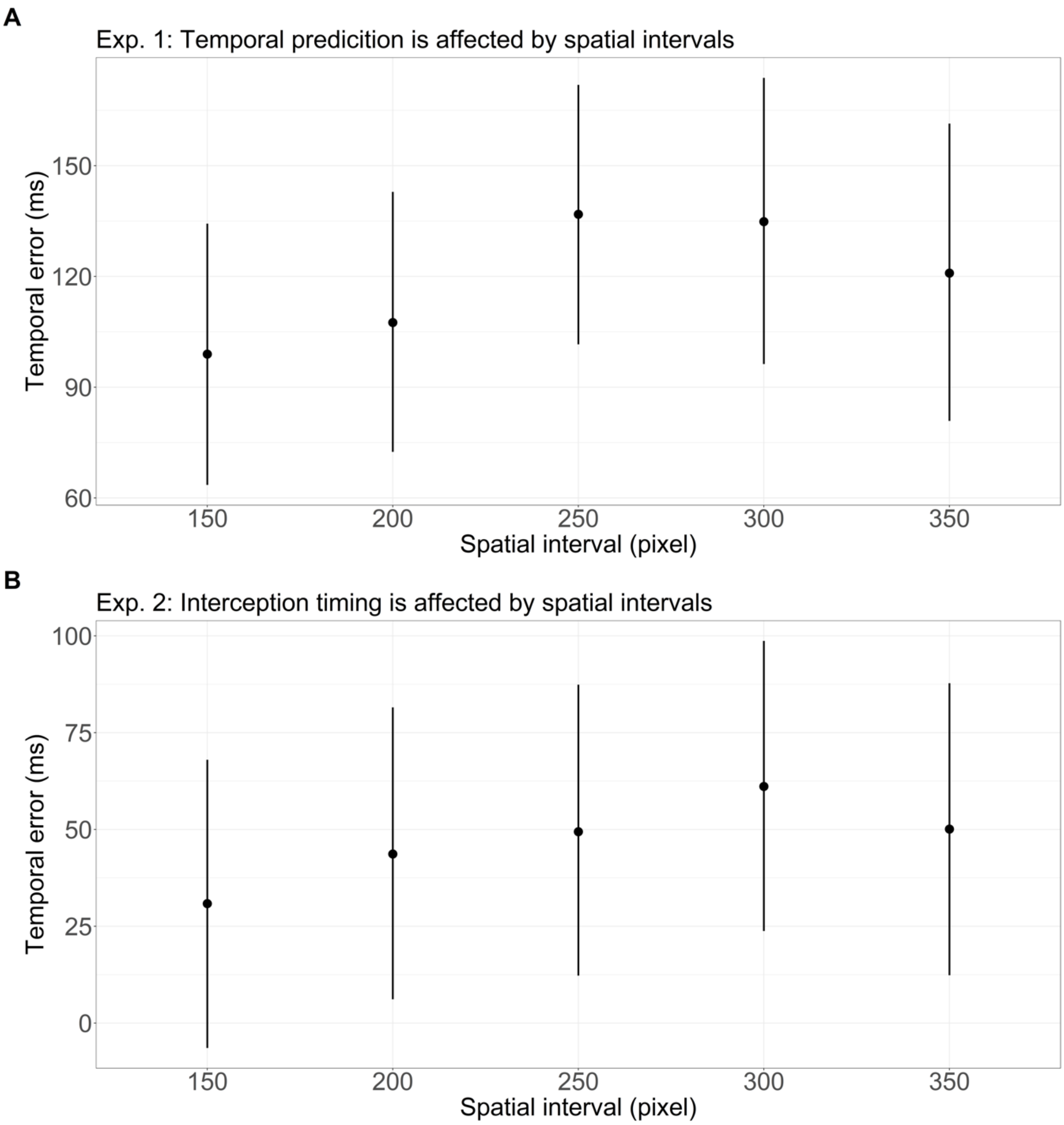

Figure 4-2. Model estimates (mean and 95 % CrI) of the temporal error for the different distances for Exp. 1 and Exp. 2. *Positive values indicate that the response was longer compared to the temporal ISI. A: Results of Exp.1 on temporal prediction: Participant's response times slowed down for a distance between 150 to 250 pixels when the spatial distance increased (kappa effect). B: Results of Exp. 2 on interception timing: Participants reacted later when the distance increased (kappa effect), except for the 350 px interval. Please note varying ranges on the vertical axis between the Figures.*

Table 4-1. Contrast estimates of the temporal error for consecutive spatial distances in Exp. 1. Positive values indicate that the response was longer in the consecutive level.

Effect	**Estimate**	**95% credible interval**	**P(beta) < 0**
200p vs. 150p	8.56	[-9.86 to 26.97]	0.18
250p vs. 200p	29.34	[10.91 to 47.74]	0.00
300p vs. 250p	-1.99	[-21.93 to 17.73]	0.58
350p vs. 300p	-13.94	[-32.93 to 4.91]	0.93

Similar to Exp. 1, also in Exp. 2 overall participants tended to respond too late, as indicated by a positive temporal error (β = 47.04, 95 % CrI = 12.38 to 82.01, P(β > 0) = 0.996). Most importantly, and as illustrated in Figure 4-2b and Table 4-2, also in the interception paradigm the spatial intervals of the circle influenced participants' temporal response. Again in line with a kappa effect, participants estimated the temporal delay between appearances of the circles to be larger with each consecutive spatial distance, except for the largest distance (see Table 4-1). The effect becomes compelling when comparing the intervals of 150 pixels with intervals of 300 pixels (30.24 ms, 95% CrI = 7.62 to 52.85 ms, P(β > 0) = 0.996).

Table 4-2. Contrast estimates of the temporal error for consecutive spatial distances in Exp. 2. Positive values indicate that the response was longer in the consecutive level.

Effect	**Estimate**	**95% credible interval**	**P(beta) < 0**
200p vs. 150p	12.80	[-8.84 to 34.36]	0.12
250p vs. 200p	5.76	[-16.01 to 27.64]	0.30
300p vs. 250p	11.68	[-9.55 to 33.26]	0.14
350p vs. 300p	-11.00	[-32.91 to 11.04]	0.84

4.2.2 Additional effect of temporal interstimulus intervals on response location in interception

Because interception allowed us to also examine the interception location, we also tested whether the temporal ISI impacted where participants intercepted, that is, whether there also was a tau effect. Results showed that, overall, participants' responses were spatially biased towards the right side of the actual stimulus location, indicating that they overshot the actual location (see Figure 4-3 and Table 4-3). This is specified by a positive spatial error (β = 23.32 pixel, 95% CrI = 16.42 to 30.22, P(β > 0) > 0.999). Notably, with increasing temporal ISI, the overshooting bias decreased.

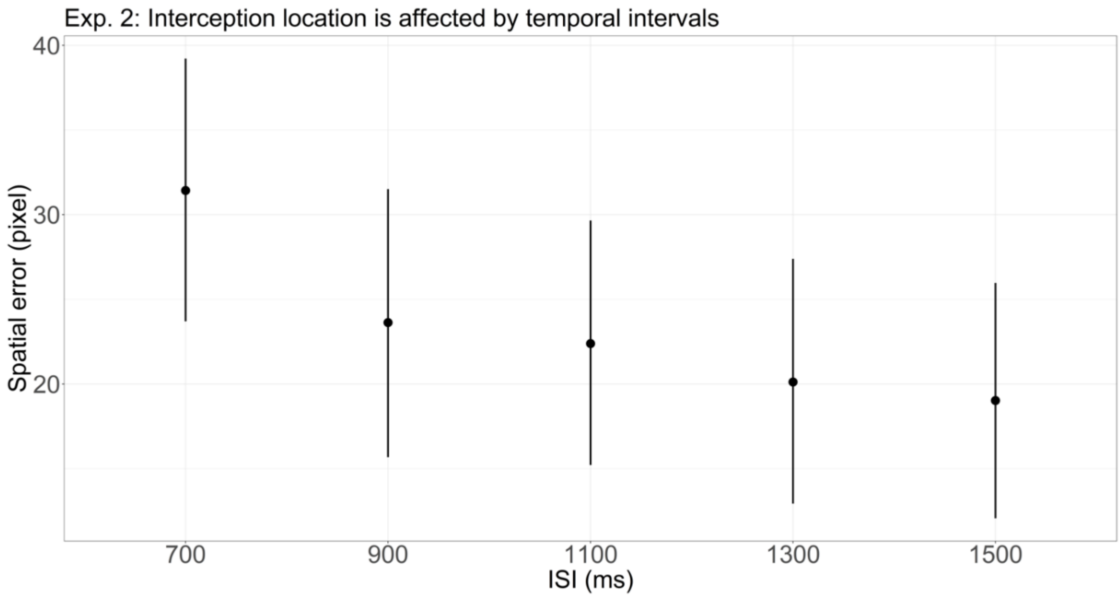

Figure 4-3. Model estimates (mean and 95 % CrI) of the spatial error for different interstimulus intervals (ISI) in Exp. 2. Positive values indicate that the response overshot the to-be-intercepted final location of the circle. Participant's response location shifted toward the left side the longer the ISI.

Table 4-3. Contrast estimates of the interception location for consecutive temporal intervals. Positive values indicate that the response location was more shifted towards in the movement direction of the circle (overshooting) than for the previous temporal ISI level.

Effect	β (pixels)	95% CrI (pixels)	P(β > 0)
900ms vs. 700 ms	-7.80	[-11.97 to -3.63]	1.00
1100ms vs. 900 ms	-1.24	[-5.66 to 3.13]	0.71
1300ms vs. 1100ms	-2.27	[-6.43 to 1.85]	0.86
1500ms vs. 1300ms	-1.09	[-5.33 to 3.18]	0.70

4.3 Discussion

The purpose of the present study was to test whether the well-established perceptual kappa effect also impacts interception performance. In a first experiment, the traditional kappa design was adapted to a temporal prediction task. In a second experiment, additional modifications of the task allowed to assess the kappa effect in motor interception. In line with the kappa effect, participants' temporal prediction increased with increasing distance between stimuli in Exp. 1. Similarly, in Exp. 2 the timing of interception was affected by the distance between stimuli. Specifically, participants intercepted the target stimulus later when distances between stimuli increased (kappa effect) (Abe, 1935; Cohen et al., 1953, 1955), with an exception for the largest spatial interval (350 px).

Together, the effects found in both experiments are in line with previous research on the kappa effect showing that temporal intervals between a sequence of stimuli are judged to have a longer duration when the stimuli are more distant (Abe, 1935; Cohen et al., 1953, 1955; Jones & Huang, 1982). Therefore, our findings extend earlier research by showing that the kappa effect transfers to motor actions. More specifically, adding to earlier reported effects on motor sequence learning (Sarrazin et al., 2004; Sarrazin et al., 2007), the current findings reveal an impact of kappa effects – and hence spatiotemporal biases – on temporal prediction and motor interception performance. The findings also enrich current debates about the coupling of perception and action (Goodale & Milner, 1992; Hommel, 2005; Prinz, 1997) and the impact of illusions, in particular, visual illusions such as the Müller-Lyer and Ebbinghaus illusions on motor performance for which some studies reported no evidence (Aglioti et al., 1995; Haffenden & Goodale, 1998), positive evidence (de la Malla et al., 2019a; Franz et al., 2000; Medendorp et al., 2018) and even mixed evidence (Cañal-Bruland et al., 2013).

When comparing the size of the temporal errors between Exp. 1 and Exp. 2 (see Figure 4-2), it becomes apparent that the size of temporal errors in the mere prediction task was almost twice as large as the temporal error in the interception task. This may be at least partially explained by previous research on time to contact estimations showing that a purely temporal response towards motion objects (similar to Exp. 1) does not exclusively depend on temporal, but also speed information (Chang & Jazayeri, 2018). If true, then it is reasonable to assume that participants may have used and perhaps integrated velocity, timing and spatial cues to perform the interception task in Exp. 2. In addition, the interceptive movement itself and/or its effects (i.e. the cursor moving across the screen) are likely to have provided additional online feedback allowing to update the interceptive movement, thereby contributing to smaller temporal errors.

Another finding of the interception task was that with increasing temporal ISIs participants overshot the target location less, which may be interpreted as a reversed tau effect, and therefore contrasts with the previously reported perceptual tau effects (Benussi, 1913; Helson & King, 1931). While an inverted kappa effect has already been reported for auditory stimuli (Roy et al., 2011), to our knowledge, this is the first time, an inverted tau effect was found. However, given that for several localization biases also inverted effects (i.e. biases in the opposite direction) have been reported, it might not be surprising to find such an inversion also for the tau effect. For instance, in contrast with the Representational Momentum effect, typically showing that a target's movement offset location is overshot (Freyd & Finke, 1984; Merz, Meyerhoff, et al., 2019), researchers have repeatedly reported an opposite effect, called the offset-repulsion effect (Merz, Deller, et al., 2019; Müsseler et al., 2002). Similarly, seemingly contradictory findings have been reported for movement onset locations described as the Fröhlich effect (Fröhlich, 1923) – that is, the perceived onset location of stimuli in motion is shifted in motion direction – or its' inversion, the onset-repulsion effect (Kirschfeld & Kammer, 1999). The original kappa and tau effects (but not their inversions), are often explained by models assuming that expectations about an underlying motion with constant velocity between presentations (slow speed priors) account for the biases (Goldreich, 2007; Goldreich & Tong, 2013). A novel theoretical account, referred to as the speed prior hypothesis (Merz, Soballa, et al., 2020; Merz et al., in press), which is also based on prior speed expectations likewise predicts and explains the reversed findings for several biases. This includes the aforementioned offset and onset repulsion effects, but also the inversed versions of kappa and tau effects. In specific, similar to the slow speed hypothesis, this hypothesis predicts smaller/larger spatial and shorter/longer temporal intervals depending on participants' *expectations* about the speed (priors), which may be different from the actual speed. Most importantly, it also accounts for possible inversions of the effects, depending on the velocity range administered in the task (i.e., the combination of temporal and spatial intervals). For slower presented speeds, a positive relationship between speed and the amount of overshooting is expected (length extension), while as soon as reaching a certain speed (half the speed of the prior), the overshooting should be reduced with increasing speed and even result in undershooting when exceeding the prior speed (Merz, Soballa, et al., 2020; Merz et al., in press). It is conceivable that the chosen temporal and spatial intervals in the current study perhaps met the reversal point for the kappa effects, therefore first resulting in a positive effect and then, for longer spatial intervals (where the speed exceeded half of the prior speed) an inversion of this relationship. In addition, the speed prior hypothesis (Merz, Soballa, et al., 2020; Merz et al., in press) may also explain the inverted tau effect: If the chosen spatial and temporal intervals resulted in a 'medium' speed range (i.e., speeds between half of the prior speed and the prior speed), this should have resulted in the observed inversed tau effect.

Finally, next to their many advantages, online studies also have a number of limitations such as no or less control over participants' behavior during experimentation, used screen sizes, the distance between participants and their screens and the fact whether they finally used a mouse or touchpad for performing the interception task. In Exp. 1 and Exp. 2, 24 out of 57 and 32 out of 53 respectively, participants reported to have used a computer mouse. Concerning the control of participants' behavior, for instance, few participants additionally reported that they produced rhythmical sounds with their mouths to support their performance in the temporal task. However, despite these challenges and potential limitations, we deem it it unlikely that such behaviors account for our results and findings because we not only found the predicted kappa effects, but we also replicated it across two separate online experiments. Regardless, we call for more research examining spatiotemporal biases in interception performance that allows for better controlled and ecologically more valid motor responses such as interceptive movements in a Virtual Reality setting.

4.4 Methods (Exp. 1 & Exp. 2)

4.4.1 Participants

Previous research has reported effects for sample sizes of n = 6 to n = 12 (Bill & Teft, 1972; Sarrazin et al., 2004). For the current study a sample size of approximately 55 was intended to compensate for less controlled environment of online studies. In Experiment 1, data of 57 participants who took part in the online experiment were further processed (Age: mean = 25.1 years, min = 18 years, max = 48 years; Handedness: 52 right-handed, 4 left-handed, 1 no preference; gender: 40 females, 17 males). 32 additionally recruited participants had to be excluded from further analysis, because they either did not finish at least the first block of 25 trials (n = 15), did not follow the instruction (n = 15), were too young (n = 1), or erroneously took part in both Experiments (n = 2). Whether participants followed the instruction to ignore the spatial position of the ball was indicated by a significant effect of distance between stimuli on participants response location. In Experiment 2, 53 newly recruited participants were included in the analyses (Age: mean = 25.6 years, min = 19 years, max = 55 years; Handedness: 44 right-handed, 9 left-handed; gender: 32 females, 20 males, 1 diverse). An additional 48 participants were recruited but excluded because they did not finish more than a few trials (< 25 trials, n = 41), did not follow the instruction (n = 7). For details about the exclusion of participants due to ignoring task instructions. To control whether participants followed the instructions to predict the circle spatially and temporally in Exp. 2, we checked whether the temporal ISI predicted the response time and whether the circle jumping distance predicted participants response location for every individual.

In both experiments, participants provided informed consent prior to participation. A link to the online study was distributed via mailing lists at national universities and through communication with students at the local sports science institute. The study was approved by the local ethics committee (Ethical Commission of the Faculty of Social and Behavioural Sciences at the Friedrich Schiller University Jena, number of approval: FSV 21/033). We confirm that all research was performed in accordance with the Declaration of Helsinki.

4.4.2 Materials

Both experiments were created with OpenSesame v3.3.4 (Mathôt et al., 2012) using OSWeb v1.3.13. We used Jatos v3.6.1 (Lange et al., 2015) as backend software for server-related management. During each trial, a white circle (20 pixels) was presented on a black background. The circle first appeared at -600 pixels from the center of the screen (negative values are to the left of the center, positive values to the right). Afterwards, the circle dis- and reappeared two times one after another moving to the right with spatial intervals of 150/200/250/300/350 pixels. Therefore, the correct extrapolated positions for the third event were -150/0/150/300/450 pixels from the center of the screen. The spatial intervals were chosen to resemble a relatively wide range of stimuli within the boundaries set by common screen dimensions (1920 x 1280 px). At each location, the circle was presented for 500 ms 32 and the temporal ISIs between presentations were 700/900/1100/1300/1500 ms. The presentation times and intervals are within the range of previously used times (Abe, 1935; Jones & Huang, 1982) and should allow for accurate timing on with common refresh rates of screens (e.g., 60 Hz).

Participants were instructed to indicate via mouse/touchpad click when (Exp. 1) or when and where (Exp. 2) they expected the stimulus to appear for the fourth time. That means that in Exp. 1 participants had to perform a temporal prediction task, whereas in Exp. 2 they were expected to intercept the target (i.e. the final stimulus).

4.4.3 Procedure

Before the experiment started, participants provided informed consent and filled out demographic questions regarding handedness, age, sex, etc.. Participants received verbal instructions supported by a visual depiction.

Figure 4-1 displays the structure of a trial. To center the mouse position at the start of a trial, participants had to click a start button in the center of the screen. Participants' task was to watch the succession of three visual stimuli (circles) presented with constant temporal and spatial intervals in between and then predict (Exp.1) or intercept (Exp. 2) the fourth (location and) time of appearance. The temporal ISI (5 levels) and distances (5 levels) varied randomly between trials in one block, resulting in 25 trials per block. The whole experiment included 5 blocks (repetitions), resulting in a total of 125 trials. The duration of the experiment was roughly 20 minutes, which proved to be a reasonable amount of time for an online study.

4.4.4 Data Analysis

We used R v4.0.5 for statistical analysis. The whole data set consisted of 6361 from 57 participants in Exp. 1, and 6239 experimental trials from 53 participants in Exp. 2.

Because participants might have reacted erroneously to the wrong stimulus presentation (reaction towards earlier presentation or overseen presentation), outliers defined as extreme values more than 3 times the interquartile range from the 25% or 75% quantile were excluded for each participant. This led to an exclusion of 50 and 40 trials in Exp. 1 and 2, respectively. After exclusion, the statistical analysis included 6311/6361 (99.21 %) from 57 participants in Exp. 1 and 6199/6239 (99.35 %) of all trials from 53 participants in Exp. 2.

Our first aim was to analyze the influence of the spatial distance between stimuli on response timing (kappa effect). These analyses included repeated measures on the level of subjects which could correlate. To allow for correlation within subjects we opted to use a Mixed Model approach (Meteyard & Davies, 2020). Additionally, we opted for a Bayesian approach because of more robust analysis when fitting mixed models and to avoid convergence problems (Eager & Roy, 2017).

Model fitting was done with the brms package (Bürkner, 2017) which provides an interface to fit Bayesian models using Stan (Stan Development Team, 2019). We mostly followed the workflow and recommendation of Kruschke (Kruschke, 2021). This includes prior predictive checks to choose sensible priors, converging checks of the sampling method of the posterior distribution of model parameters, and posterior predictive checks to get a (rough) sense of whether the model fitted the data adequately. Our reproducible analyses and data can be found at https://osf.io/675j4/ (DOI: 10.17605/OSF.IO/675J4). In the Linear Mixed Model, the fixed effect spatial distance (factor with 5 levels, 150 to 350 pixels) was included with a sliding contrast, comparing consecutive levels. Additionally, to estimate the variance and allow for correlations between measures, we included a random intercept and a random slope for participants. We used weakly informative priors, which are defined by a broad (not flat) distribution of priors to exclude unrealistic parameter values like a 100 s temporal error. Weakly informative priors are recommended compared to uninformative (flat) priors, to avoid overfitting by constraining the solution space of parameter values. Data from a yet unpublished study served as an estimation for the prior distributions. Our second aim was to analyze the influence of temporal ISI on response location. We ran the same analysis but with ISI (factor with 5 levels, 700 to 1500 ms) as a predictor for the spatial error.

The Bayesian Model provides a posterior distribution for every model parameter, representing the certainty of where the parameter lies in a specific range. To communicate this (un)certainty, we summarized the posterior distribution and present the estimated mean, the 95 % credible interval, and the probability of the parameter is larger than 0.

END OF PUBLICATION

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5 Discussion

5.1 General Findings

Based on the systematic literature review, described in Chapter 1.2, this thesis aimed to investigate spatiotemporal interrelations in manual interception for the visual and the auditory modality (for an overview, see Figure 5-1). Previous studies provided contradictory findings, either supporting a symmetric relationship between spatial and temporal perception or an asymmetrical relationship with larger effects from space on time. We hypothesized that these seemingly contradictory findings might result from the use of different modalities: for auditory input larger effects from temporal information on spatial responses are expected whereas visual stimuli should cause larger effects from spatial manipulations on the temporal response. Indeed, the results presented in this thesis highlight the important role of sensory input for the main direction and size of those biases (see Figure 5-1). First, it was shown that it is possible to dissociate spatial and temporal errors from the combined spatiotemporal interception response by finding differential effects of visual blur on spatial vs. temporal errors (Chapter 2, see upper part of Figure 5-1). The following two articles (Chapters 3 and 4) provided initial evidence that spatiotemporal interrelations transfer to interception but also highlighted modality- and task-specific constraints for such transfers (see findings in accordance with the hypothesis as indicated with a tick vs. unexpected results for the visual modality marked with a cross in Figure 5-1). The results presented in Chapter 3 further indicate the sensitivity of eye movements to spatiotemporal biases, supporting the close link between eye movements and perceived rather than physical motion (Schütz et al., 2011).

To summarize, results revealed that sensory modality plays an important role for spatiotemporal biases (e.g., Chapter 3 shows effects for audition but not vision) but does not explain all effects (Chapter 3 vs. 4 show seemingly contradictory effects in vision). An overview of the contributions of each study to answer the research question is provided in Figure 5-1. Representational noise or task difficulty might be underlying factors behind the modality-specificity hypothesis and further explain the divergent findings for visual stimuli. The following discussion includes a theoretical integration of the principles as well as the implications of the results for the framework of ATOM and CMT. Thereafter, the chosen methods will be discussed, limitations named, and practical considerations introduced. Finally, future directions will be proposed.

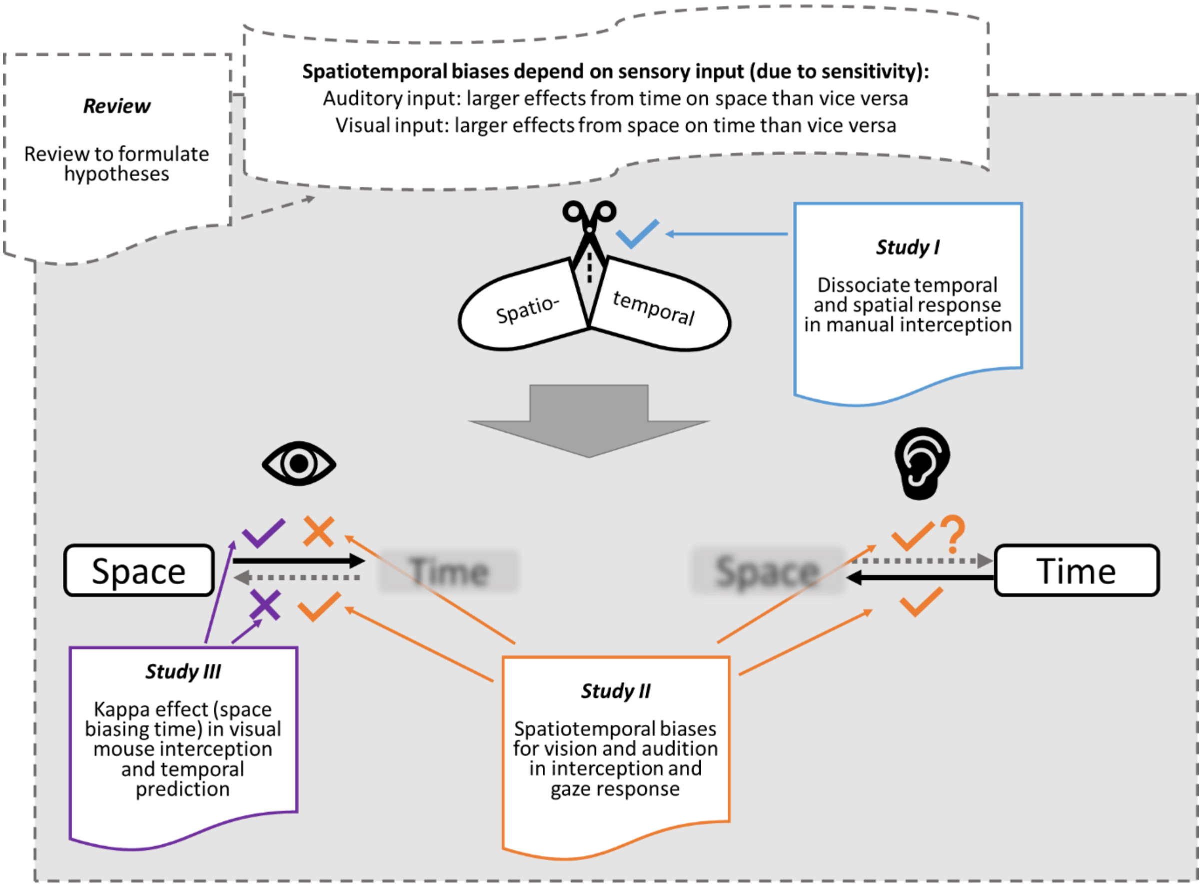

Figure 5-1. Overview of the general findings. The research question and methodological lineout of the current thesis were inspired by the systematic literature review reported in a Review (Chapter 1.2). Study I (Chapter 2) was a first attempt to disentangle the spatiotemporal interception response in a spatial and a temporal part. Next Study II (Chapter 3) provided initial support of the modality-specificity hypothesis by showing the differential effects for auditory but not visual stimuli. Finally, Study III (Chapter 4) attempts to reassess the visual effects highlighting the important contributions of other task characteristics except from sensory input.

5.2 Theoretical considerations

In the following section, the results of the reported studies will be related to the two competing theories, ATOM (Walsh, 2003) and CMT (Lakoff & Johnson, 1980a). According to ATOM, time and space are processed symmetrically by a shared analog magnitude system, whereas according to CMT, spatial representations grounded in movement have a stronger impact on temporal representations than vice versa. Our findings reported in Chapter 3 contrast the predictions of CMT, claiming that space necessarily has a bigger impact on time. Large effects of temporal intervals on spatial interception were found in the auditory modality, whereas visual stimuli only revealed very small effects from space on time. Thus, results presented in this thesis did not confirm an asymmetry with bigger spatial impacts on temporal performance than vice versa, as proposed by CMT. In contrast to previous studies arguing against a general asymmetry (e.g., Agrillo & Piffer, 2012; Cai & Connell, 2015), in all experiments of this thesis the spatial and temporal information were both characteristics of the same stimulus and not of two separate stimuli. Moreover, both spatial and temporal information were presented within the same modality (in this case auditory). Consequently, the current results broaden the debate by showing that the predictions of CMT do not hold even when both space and time are characteristics of the same stimulus.

In Chapter 1 we hypothesized differences between spatiotemporal interrelations across sensory modalities based on different sensitivities of the auditory and the visual system towards spatial and temporal information. For auditory stimuli, the prediction of larger effects of temporal intervals on spatial reactions was met, as reported in Chapter 3. However, our findings did not support the prediction that visual input leads to large positive effects of spatial on temporal representations and only small or no effects vice versa. For manual interception, spatial manipulations showed a small negative effect on interception timing but no effects vice versa. Gaze positions show initial evidence for all interrelation effects for both modalities. Interestingly, previous research on similar effects suggests that not (only) sensory modality per se is relevant for the size of the effects, but also task difficulty (Jones & Huang, 1982). For instance, an auditory tau effect (on frequencies) was absent when investigated in musicians (see Jones & Huang, 1982), suggesting that familiarity or experience modulates the effect. In a slightly different framework, Cai and Wang (2021) explain the interaction of spatial and temporal processing by considering representational noise as a moderator. They showed that certain stimulus characteristics (e.g., filled vs. unfilled length) can impact the amount of noise of spatial representations. This was measured as coefficient of variation in the response and was reported to modulate the effect of temporal manipulations on spatial judgements. The influence of temporal magnitudes scaled with the level of noise in the spatial representation. I argue that the effect of task difficulty proposed by Jones and Huang (1982) can actually be explained within the representational noise theory by Cai and Wang (2021) when assuming that increased task difficulty, defined as increased uncertainty, relates to the amount of representational noise. Both ideas are associated with increased variability in the response.

These two accounts might explain the divergent findings for visual stimuli in Chapter 3 vs. Chapter 4. While in a touchscreen-based interception task, participants' temporal response was only slightly negatively affected by the increasing spatial intervals, a prominent opposite effect (in line with the initial hypothesis) was reported in an online version using a mouse or touchpad as the response device. Note, adaptations of the paradigm in Chapter 4 (online study) were implemented, compared to the paradigm in Chapter 3. Specifically, we reduced the number of stimulus presentations (and consequently the spatial and temporal intervals) from four to three and increased the variability between trials, by increasing the range of spatial and temporal intervals from three to five factor levels. Both adaptations were chosen to increase task difficulty. Additionally, and most importantly, based on our hypothesis, that the expected kappa effect should be prominent, if the temporal representation is noisy, we tried to specifically increase the temporal demands of the task by increasing the duration of stimulus presentations from 167 ms to 500 ms. This adaptation was motivated by preceding research of Bill and Teft (1972) on the tau effect. They showed that longer stimulus presentation durations, meaning increased visual information, cause a decreased tau effect. This is interpreted as spatial information processing dominating over temporal information processing. Building on this idea, in Chapter 4 longer stimulus presentations were administered to increase the relative importance and acuity of the spatial information. This should result in relying relatively less on temporal information. Under these conditions, the kappa effect should become more pronounced. Support for this idea was provided by finding a significant kappa effect in Chapter 4 but not in Chapter 3 where shorter stimulus presentation durations were used.

In total, the results of Chapter 4 compared to the visual results in Chapter 3 – evidence for a kappa effect and an inverted tau effect vs. no or only very small effects – suggest that the attempt to increase task difficulty or representational noise was successful. However, a systematic investigation of those theories, including measures of noise, is necessary to critically evaluate this assumption and confirm the findings.

Another approach to increase noise (rather than solely observing differences between modalities) was the manipulation of blur (Recanzone, 2009) for vision and volume in audition, or pitch as used in a related study (Tolentino-Castro et al., 2022). However, the results obtained across experiments in this thesis question the validity of that approach. While the volume manipulation in Chapter 3 only showed a main effect but no interaction with either spatial or temporal intervals (which would be expected, if it increased representational noise and the effect sizes indeed depend on this noise), the manipulation of blur provided mixed results. In Chapter 2, blur decreased spatial accuracy and precision, as well as temporal precision, whilst it increased temporal accuracy. A decrease of precision (increase in variability) might be interpreted as an increase in representational noise. In Chapter 3, however, blur showed neither an effect on the temporal nor the spatial response, despite using the same amount of blur as in the previous study. Thus, it remains elusive whether manipulations, such as blurring or reducing volume, can increase representational noise of either space or time. Stronger blur than used in the studies reported here, or a wider range of different volumes might help to further investigate this problem. In fact, it was shown that relatively strong amounts of blur are necessary to decrease performance in racket sports like golf (Bulson et al., 2008), baseball (Brenner et al., 2014), and cricket (Mann et al., 2007), but also other sports, like basketball (Applegate, 1992; Bulson et al., 2015), rifle sport (Allen et al., 2016; Allen et al., 2018), or even judo (Krabben et al., 2021). These and additional manipulations could be tested in future research, including a (direct) measurement of representational noise (e.g., as coefficient of variation, Cai & Wang, 2021) and a careful consideration of spatial vs. temporal effects.

To summarize, the pattern of results suggests that rather than the type of the stimulus modality per se, the amount of representational noise determines the size of the effects. Task modalities modulate the amount of noise: For instance, the auditory modality produces more noise in spatial localization than the visual. In addition, other factors, such as presentation durations, have been shown to contribute to spatiotemporal interrelations. Whether changes of blur or volume also lead to varying amounts of representational noise needs to be addressed in future research.

An important aspect when discussing spatiotemporal predictions and interception is the (imputed) speed of the target. Even if a target is sequentially presented and no actual movement is depicted, there are indications that humans infer motion with constant speed between stimulus presentations. Recent models state that this speed-constancy explains a range of effects regarding localization biases (Goldreich, 2007; Goldreich & Tong, 2013). A new theory, building on this idea does not only explain the occurrence of the classic localization biases

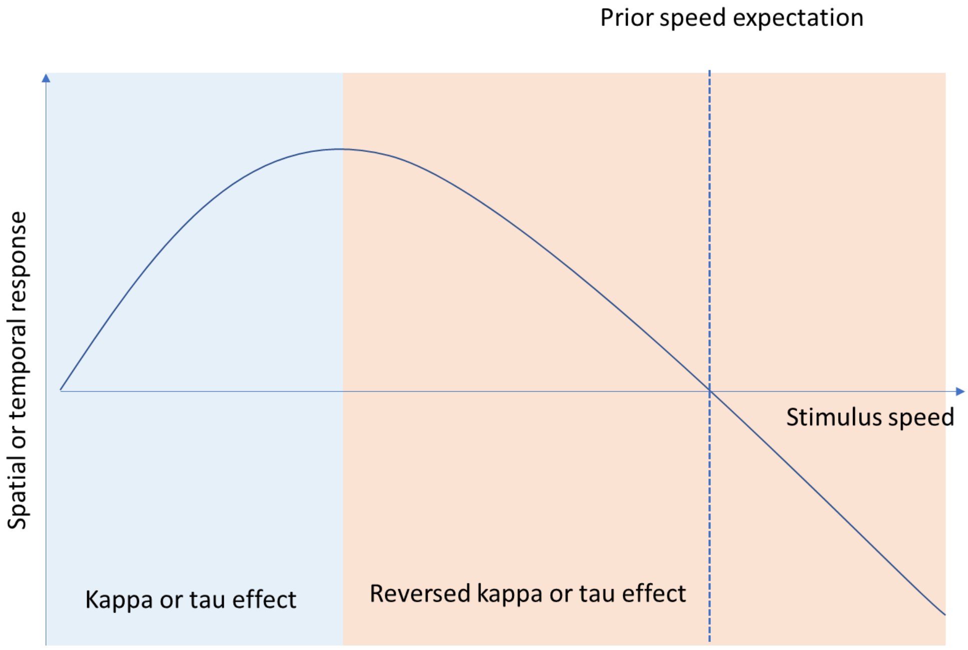

Figure 5-2. Explanation of the kappa and tau effects and their inversions by the speed prior account. Adapted from Merz et al. (2021).

(potentially including tau and even kappa), but also accounts for reversed effects, that is effects going in the opposite direction. In this theory, participants' expectations of the stimulus speed (priors) compared to the actual speed (i.e., the spatial intervals / temporal intervals) are of utmost importance. More specifically, the range of presented speeds should predict the reported effects. For relatively slow speeds (see left part of Figure 5-2), a length extension effect is hypothesized. Here, the length extension should translate to a positive relationship between actual speed and the amount of overshooting, in our case a tau or kappa effect. When exceeding half of the speed prior, however, the relationship reverses, predicting a reduction in the amount of overshooting with increasing stimulus speed (see middle part of Figure 5-2, reversal point). This reduction might result in undershooting when exceeding the speed prior (right part of Figure 5-2). In sum, as soon as the actual speed is higher than half of the speed prior, reversed effects are expected. Relating this theory to the findings in Chapter 4, it is possible that the spatial and temporal intervals resulted in speed ranges that included the reversal point. This should consequently lead to a positive effect of spatial intervals on the temporal response (kappa) for smaller spatial intervals. As speed exceeds half of the prior speed, that is, when distances between stimuli increase, the observed inversion of the effect would be expected (reversed kappa for longer spatial intervals). This model would further explain the reversed tau effect, assuming that the spatial and temporal intervals led to speeds higher than half of the prior speed. Although the results are in favor of this theory, research is needed to fully understand whether expectations about the inferred speed can explain the observed spatiotemporal biases. It remains unclear how speed priors arise. If it is possible to measure or predict the speed prior, this theory can be directly tested. Also, an investigation across the different effects that are covered within this theory (e.g., kappa and tau, representational momentum, Fröhlich effect) is required.

One could argue that interception does not allow the measurement of kappa and tau effects because it qualitatively differs from previous paradigms. In contrast to most studies, the manipulations of spatial or temporal intervals in a prediction task like interception, are only possible across and not within trials: In typical paradigms, a certain interval was followed by another interval and either ratings (Abe, 1935; Helson & King, 1931; Huang & Jones, 1982) on or adjustments (Bill & Teft, 1972) of the second interval in comparison to the first one were measured. Thus, the effect of one interval on another interval within that trial was analyzed. In contrast, in this task, the intervals were the same within each trial. Effects were meant to occur across trials, meaning that a relatively short duration of the intervals of one trial (compared to the other trials) was expected to reduce the predicted length of the spatial interval. In fact, for the scope of this thesis, it is not important, whether the reported effects are labeled as kappa and tau or not. We decided to keep the labelling because already previous experiments used similar across-trial approaches to assess these effects (e.g., in bisection tasks, Roy et al., 2011).

Furthermore, eye movements are essential for predictive processes (Fiehler et al., 2019). They provide retinal (high acuity vision) and extraretinal information (proprioceptive feedback and efference copy) used to predict target motion (e.g., Bennett et al., 2010; Spering et al., 2011). Moreover, studies showed a tight link between eye movement and interception accuracy (Fooken et al., 2021; Fooken & Spering, 2020). Surprisingly, the results of Chapter 3 seemingly contradict the tight coupling between eye and hand movements. Despite mixed evidence for spatiotemporal biases in manual interception, gaze data indicated tau and kappa effects in both vision and audition. However, at the time of interception, the effects were similar between eye and hand (see Appendix 6.2, Figure 6-16), indicating an association between manual interception and gaze location. An important advantage of eye-tracking was that expectations about previous events (earlier stimulus presentations within one trial) could be measured. Potentially, initial eye movements were more sensitive to perceptual perturbations but before executing the manual response, control mechanisms reduced or even eliminated the effects. Another possible explanation for the present results is that the stimuli all elicited the same eye velocity to track the target (or at least the eye velocity was not adapted enough towards the spatiotemporal intervals). That would mean that for longer spatial intervals, participants' eyes reached the relevant location later than for shorter spatial intervals. Likewise, the more time passes between presentations the further participants eyes can move, resulting in longer spatial predictions. Importantly, participants manual interception was generally delayed, indicating that additional processes might have contributed to the control of eye and hand at the time of interception. To address the possible interpretations, a more detailed analyses of eye movement kinematics (e.g., pursuit gain, eye velocity, saccade amplitude) using high resolution eye-tracking technology is required. In addition to the new interception paradigm, this also applies to the traditional perceptual paradigm on kappa and tau.

5.3 Methodological considerations and limitations

The previous paragraphs already identified some of the limitations of the reported studies and highlighted the need for future research. In the following, the limitations will be summarized, and additional considerations will be discussed. First, this chapter focuses on the chosen tasks, that is interception, and the related dependent measures. Next, advantages and disadvantages of the stimuli, namely the parabola trajectories used in Chapter 2 are addressed. Finally, I will outline how eye movements can help to answer our research questions and which challenges are still to be overcome.

5.3.1 Interception task

Choosing interception to investigate spatiotemporal interrelations has some advantages but also bears some problems. Interception, as a movement, requires simultaneous reactions in both space and time (Loeffler et al., 2018; Walsh, 2003) and thus involves interdependencies. Consequently, interception provides a useful tool to investigate spatial and temporal reactions simultaneously, and especially to address spatiotemporal interrelations. However, representational and motor interrelations might interact. This makes it difficult to dissociate whether the effects found in the interception response really result from impacts on a representational level (unless one favors the idea that percept and action representations are not that different as often assumed, e.g., Hommel, 2005; Prinz, 1997). Chapter 4, however, might provide indications, in favor of a joint representational basis, as nearly identical kappa effects were found on an action-level in spatiotemporal interception and perceptually for temporal prediction, where no interception movements and therefore no spatial response was included. The presented studies are first attempts to a more realistic task. Future research can be based on our findings to develop more ecologically valid paradigms. Yet, our computer-based task still differs from real catching or batting behavior. To generalize the current findings across interception tasks, additional studies with varying designs would be needed. For instance, previous research has shown that it makes a difference whether a touchscreen is operated with the finger or using a stylus (e.g., Olthuis et al., 2020). In the online interception study, the ecological validity for natural interception behavior like catching or batting might be reduced even more severely. However, this study might parallelize the challenges of e-sports and therefore be highly valid for another ecological setting. Additionally, due to the easy access of online studies, a wider range of possible participants (no local restriction) might even reduce the risk of only investigating a certain population as in most of the other experiments: students (predominantly from sport science or psychology institutes).

5.3.2 Manual vs. mouse interception

Interception on a computer using a mouse or touchpad differs from manual interception on a touchscreen or catching a real object. When intercepting using the computer mouse or touchpad, the motor action is transferred from a smaller two-dimensional coordinate system whose location is deviating from the target location – meaning that the movement takes place on the surface of a desk or touchpad while the action outcome (curser moving across the screen) happens in fronto-parallel plane. For instance, moving the mouse forwards, leads to an upward movement of the curser. This highly contrasts with manual interception (e.g., interacting with a touchscreen or catching a real ball) where the hand moves within the same space as the target.

If, however, the biasing processes addressed here take place at the level of mental representations, as suggested by the representational noise account (Cai & Wang, 2021), both methods should be able to measure spatiotemporal interrelations, which is also supported by the results of Chapter 3 and 4. Importantly, using a mouse (and transferring between different coordinate systems) is a highly trained skill in many young adults who were tested in the online experiments. Therefore, for this population it is very natural to control a visual object on the screen by moving the hand with the mouse on the desk and potentially similar processes are involved as for real world movements. Nonetheless, to address this problem and allow to draw more generalized conclusions, the obtained results need to be validated in an immersive setting that allows more realistic hand movements (e.g., in Virtual Reality).

5.3.3 Parabolic trajectories

The initial attempt to investigate interception of parabolic trajectories (Chapter 2) bore some problems that need to be taken into consideration when interpreting the results and planning future studies. Not all physical characteristics of parabolic throwing were considered when programming the target's movements (e.g., air resistance, magnus force). To increase ecological validity, more natural ball movements need to be simulated. Previous research showed increased accuracy of eye movements, interception and pointing performance for more realistic movement paths (e.g., Bock et al., 1992; de la Malla & López-Moliner, 2015; Delle Monache et al., 2019; Jörges & López-Moliner, 2017, 2020). Taking this into account, the relatively large errors observed in Chapter 2 might at least partially be explained by those missing physical characteristics. Still, simulating such trajectories is not easy and a variety of contributing factors should be taken into consideration. To fully account for all variables, a certain ball type and situation should be chosen (e.g., a batted baseball, Fooken et al., 2016), otherwise potentially important variables that humans naturally use to predict the motion of the ball might be missing and pose an additional source for temporal and spatial errors.

5.3.4 Eye-tracking

The newly developed method to automatically analyze the gaze position described in this study (see Chapter 3) was similar to previous accounts for head-mounted eye-tracking devices (MacInnes et al., 2018). In both approaches, the precision of the gaze data from this automated procedure compared to the traditionally used manual coding is not restricted by human abilities and shielded for human biases, which might have occurred especially in the reported studies on kappa and tau. The current approach extended the possibilities of previous implementations (e.g., MacInnes et al., 2018) to a situation in which the viewed area – that is the references frame – can change completely over time. This method could theoretically even be extended to a 360° visual angle, making a whole range of motions and consequently a high variety of tasks and paradigms possible. This freedom in movement of course came at the cost of less precision compared to high-resolution tower-mounted eye-trackers, where observers' heads are stabilized. These limitations, combined with the low spatial resolution and frame rate of the goggles, make it impossible to derive detailed eye movement kinematics (smooth pursuit, microsaccades, or drift). Due to the homography transformation involved in the presented method and the chosen location of the reference objects, gaze data is less precise close to the borders of the front camera image and the edge of the screen. Future studies might improve this method and therefore reduce the disadvantages by either using higher quality front cameras, adapt the locations of the reference objects, or improve the object detection algorithms. Additional measurements with high resolution eye-trackers that allow for more detailed analyses of smooth pursuit and saccades at the cost of restricted head movements might proof helpful in this context.

5.4 Practical considerations

The presented results are relevant in several contexts. On the one hand, they contribute to illusion or bias literature, showing that there are situations in which perceptual effects transfer to impact motor responses. This finding might be of utmost importance in sports context, traffic, and other areas, where accurate spatial and temporal reactions are necessary for successful actions. If perceptual biases impact how humans, for instance, plan their hand movement to catch, hit or avoid a ball, the presented biases might result in errors during the execution of crucial movements. Practitioners might therefore profit from guidance on identifying situations in which erroneous predictions and reactions might occur and on how to avoid such impacts. It should be considered that one proposed reason for such interrelations is that humans have gained the experience that spatial and temporal magnitudes are often correlated and therefore build predictions/heuristics. That implies that in most situations it might actually be advantageous to representationally link space and time, because they naturally are associated. Still, errors might occur in situations in which this association is disrupted, or erroneous conclusions about either one of them are drawn. Identifying such situations might help practitioners to improve sports performance.

With the current fast development in human-machine interaction, it is crucial to understand how humans perceive their surroundings and which motoric reactions they might show. In an increasingly automated world, for instance regarding automated vehicles, a precise model of human behavior is necessary for a safe implementation. To predict whether a pedestrian is going to cross the street while a car is approaching, anticipatory movements, for instance, of the head are currently used (Lyu et al., 2021). As soon as human perception of, and action towards spatiotemporal characteristics are better understood, it might even be possible to make a prediction based on the situation instead of waiting for reactions from the pedestrian. These predictions can be crucial, as they might provide more time for the automated system to react and prevent a potential crash. In the future, prediction models based on characteristics of the situation and based on the pedestrian's behavior can be combined to cross-validate and increase predictive accuracy.

The results on eye movements indicated that gaze behavior might even be more prone to spatiotemporal biases. This is important, as eye movements and attention have been found to be closely related. Prior to saccades, premotor attention shifts to the saccade end points (Carrasco, 2011; Deubel & Schneider, 1996; Kowler, 2011; Montagnini & Castet, 2007; M. Zhao et al., 2012). In real world, if our attention is shifted towards less important locations or if our attention is shifted too late, dramatic consequences can be the result. For instance, in traffic when an approaching vehicle is noticed too late or not attended at all, human behavior can even lead to accidents.

Especially the discrepancy between Chapter 3 and Chapter 4 shows that other impact factors have to be considered in future studies, as for instance, representational noise (Cai & Wang, 2021). We know that when having several sources of information, we mostly rely on the less noisy (i.e., more accurate) source. For most contexts that might be visual information when trying to localize an object in space (Cavonius & Robbins, 1973; Recanzone, 2009). What happens, however, if visual information diminishes, like when it is foggy outside? In such a situation, information from other modalities might dominate the percept and potentially also motoric reactions. Similarly, processing of timing is typically dominated by auditory information (Recanzone, 2009; Welch & Warren, 1980). When the auditory signal is ambiguous, for instance due to interfering sounds, time estimates, and timing of motoric responses might rely on other sensory input. Applying the findings of Chapter 3 that spatiotemporal biases might differ between sensory modalities, important errors in behavior might occur in certain situations. For instance, localization performance and catching movements might be largely biased when relying mostly on auditory input, due to foggy conditions. Such consequences should be focus of future studies, including several modalities and integrating various signals.

5.5 Future directions

Despite the attempt to investigate spatiotemporal interrelations in a more realistic context – namely in interception - the current investigation was still administered in a laboratory or online-experimental setting using artificial stimuli. To evaluate whether these interrelations indeed impact natural human behavior, future research should administer similar tasks in a more realistic setting. New opportunities to test such effects with highly controllable and manipulatable variables (as necessary in these biases) are possible with technologies such as virtual reality. Recent developments also include eye-tracking devices within VR-glasses (e.g., Vive Eye Pro). These technological advances can be used to increase the practical relevance and ecological validity of experiments addressing spatiotemporal biases. Additionally, studies involving real targets and tasks are needed to evaluate whether the reported effects are relevant for everyday behavior.

In the reported investigations, we focused on vision and audition, but other modalities might be of interest for future research, too. For instance in touch, two very prominent spatial illusions have been reported: the representational momentum effect, showing that movement offset locations of a target are typically overshot (Freyd & Finke, 1984; Merz, Deller, et al., 2019), and the cutaneous rabbit illusions, showing that progressive movements of touches are perceived though only three points on the arm have been repeatedly stimulated (Geldard & Sherrick, 1972). This modality might be especially promising to test for an effect of representational noise on spatiotemporal interrelations. Given that skin areas are differently sensitive to spatial perception, this might allow to systematically manipulate spatial noise.

Additionally, humans do not live in a purely visual or auditory world but constantly integrate information from different modalities. In the presented study, biases from space on time and vice versa were only investigated within the auditory and visual modality, but not across (e.g., temporal information visually presented and spatial information auditorily presented). To provide a more realistic understanding of human behavior, multisensory integration should be addressed. When do such cross-modality interactions arise and why? Is it possible to avoid them? Kawabe et al. (2008) showed that the judgement of a visual spatial interval could be influenced by a concurrent temporal sound, providing evidence for a cross-modality tau effect. They used the typical three-stimuli paradigm but presented auditory sounds simultaneously whereby the first and the third sound were temporally matched with the first and the third visual stimuli, whilst the middle sound was temporally manipulated. When the temporal interval of the auditory stimuli was shorter, the corresponding visually presented spatial interval was reported to appear shorter as well. These findings show the importance of different modalities and the possible interactions across modalities. Bausenhart and Quinn (2018) extended the cross-modality effect to the kappa effect. Participants had to reproduce the duration of an interval between two sounds but were sometimes presented with two visual stimuli simultaneously. The reproduced duration was longer, when the two sounds appeared at different locations (two speakers) thereby creating a spatial interval than when they were produced from one stationary speaker only (no spatial interval). This effect was interpreted as a variant of the kappa effect. Interestingly, this difference was even increased when the auditory stimuli were accompanied by visual stimuli, suggesting a kappa effect across modalities. Future research should address the open question, when such cross-modality interactions arise to also allow for solutions to avoid them, in situations where they might have fatal consequences (e.g., in traffic).

To test whether indeed representational noise explains the size of the effects, it will be necessary to not only measure the noise (e.g., as coefficient of variation; Cai et al., 2018; Cai & Wang, 2021; Cicchini et al., 2012; Droit-Volet et al., 2008; Schulze-Bonsel et al., 2006) but also manipulate the amount of noise as for instance attempted by using static vs, dynamic (growing) lengths in Cai and Wang (2021). In the study presented in Chapter 3 we attempted to do so by, for instance, visually increasing the amount of blur or auditorily varying the sound's volume. Further manipulations within but also across modalities should be tested, to more profoundly argue in favor of or against ATOM and CMT. To further address this issue a careful operationalization of task difficulty and an assessment of representational noise is essential.

Psychology aims at describing, explaining, and predicting human behavior. For practical application these aims are of utmost importance to be able to successfully change behavior in situations in which it does not reflect adaptive actions. Recently, the prediction part was initiated by mathematical models e.g., using Bayesian observer models (e.g., Cai et al., 2018; Cai & Wang, 2021; Goldreich, 2007). Those models assume neuronal noise to be important, as in the representational noise account. Cai and Wang (2021) made use of Bayesian models to test for their predictions. More evidence across varying tasks and modalities is needed to further assess the validity and generalization of such models for spatiotemporal biases. In the long run, this will supposedly enable practitioners to detect and overcome difficulties of spatial and temporal perception and reaction, for instance, in sports or traffic and to avoid falling for such biases.

5.6 Conclusion

Space and time in human processing are not unambiguous physical entities but are subject to a variety of influences across processing steps and are typically strongly interrelated. Humans form representations of time and space and adapt their behavior towards spatiotemporal characteristics not only based on the raw sensory input but rather integrate this information with previous knowledge and context information (e.g., the respective other dimension). To better understand, explain, and predict perception and action towards spatiotemporal stimuli, further research is needed. This thesis provides an initial attempt to show the relativity of human processing of space and time by investigating spatiotemporal biases for visual and auditory stimuli in manual (hand and mouse) interception, as well as eye movements. Both eye and hand movements have been shown to be impacted by spatiotemporal biases, but the direction of these biases and the effect size depends on the sensory modality. Furthermore, the results indicate that additional factors play an important role. Presumably, their impact is explained by the amount of noise they evoke for both, spatial and temporal representations.

6 Appendix

6.1 Supplement to Chapter 2: Effects of visual blur and contrast on spatial and temporal precision in manual interception

This supplement was published together with the study in Chapter 2 and can be retrieved from https://doi.org/10.1007/ s00221-021-06184-8.

6.1.1 Materials and Methods

6.1.1.1 Power analysis

The sample size of 42 was chosen based on an a priori power analysis (5 repeated measures MANOVA, within factors) using G*Power 3.1 (Faul et al., 2007; Faul et al., 2009) with an estimated effect size of $f = .18$ (small effect of $\eta^2 = .03$), an alpha = .05, a high power = 0.8 and a correlation among repeated measures of $r = .5$.

6.1.1.2 Target motion

The ball's movement was defined by the parabola equations and the velocity in horizontal direction. The resulting distance and duration can be taken from Table 6-1 in the Appendix.

Table 6-1. Additional information of the stimuli.

Velocity in x-direction $v_{x,start}$	**Parabola equation**	**a in 1/px**	**d in px**	**Distance in x-direction**	**Duration**
3 px/frame	$-0.01x^2 + 600$	0.01	245	490 px = 24.0 cm	2.72 s
4 px/frame	$-0.01x^2 + 600$	0.01	245	490 px = 24.0 cm	2.04 s
5 px/frame	$-0.01x^2 + 600$	0.01	245	490 px = 24.0 cm	1.63 s
3 px/frame	$-0.005x^2 + 550$	0.005	332	663 px = 32.5 cm	3.69 s
4 px/frame	$-0.005x^2 + 550$	0.005	332	663 px = 32.5 cm	2.76 s
5 px/frame	$-0.005x^2 + 550$	0.005	332	663 px = 32.5 cm	2.21 s
3 px/frame	$-0.0025x^2 + 500$	0.0025	447	894 px = 43.8 cm	4.97 s
4 px/frame	$-0.0025x^2 + 500$	0.0025	447	894 px = 43.8 cm	3.73 s
5 px/frame	$-0.0025x^2 + 500$	0.0025	447	894 px = 43.8 cm	2.98 s

The following equations describe the targets motion:

$$v_x(t) = v_{x,start}$$

$$v_y(t) = v_{y,start} - gt$$

$$g = 2av_x^2$$

$$v_{y,start} = dav_x$$

6.1.1.3 Code for main analysis

The following code was used for multilevel model likelihood ratio test of the main analyses reported in the main manuscript:

```
baseline <- lme(errorscore ~ 1, random = ~1|participant/blur, data = data, method = "ML") (1)
model <- lme(errorscore ~ blur, random = ~1|participant/blur, data = data, method = "ML")(2)
anova(baseline, model)                                                                   (3)
postHocs<-glht(model, linfct = mcp(level = "Tukey"))                                     (4)
summary(postHocs)                                                                        (5)
confint(postHocs)                                                                        (6)
```

In addition to the main analyses of blur and contrast, the effects of occlusion time, velocity and flight direction were calculated. Separate multilevel models including one of those variables, blur (Experiment 1) or contrast (Experiment 2) and the interaction between both were run. All variables were included as continuous variables and fixed slopes, but random intercepts were modeled (see also Field et al., 2013). Previous research has shown that each of those variables might impact interception performance (e.g., Bosco et al., 2012; Brenner et al., 2014; Tresilian et al., 2009).

To evaluate whether temporal and spatial errors may reflect two independent entities of the intercepting action, we additionally explored the presence of associations between the spatial and temporal deviation variables (measured as absolute values). Using multilevel modeling of the effect of the spatial difference on the temporal difference variable, we compared a random intercept fixed slope model with a random intercept (no slope) model to look for a general relationship between those two variables. To examine potential interindividual differences in this relationship, we additionally compared a random intercept random (and fixed) slope model with a random intercept fixed slope model.

We correlated the participants spatial and temporal errors with each of the variables measured within the questionnaire. Depending on data distribution, Pearson's correlation coefficient or Kendall's rank correlation coefficient are reported.

Finally, to analyze performance between experiments we compared all error scores for the no-blur and highest-contrast condition between both experiments.

6.1.2 Experiment 1 – blur

6.1.2.1 Results

Table 6-2 in the Appendix provides an overview about the error scores per blur level, occlusion time, horizontal velocity, and side.

Table 6-2. Descriptive data of task performance. Means (and standard deviations) of each error score per factor level are reported. Negative values of the spatial accuracy indicate that participants undershot the trajectory whilst positive values represent overshooting. Concerning the temporal accuracy, positive values indicate that the participants' temporal response was too late.

Variable	**Spatial accuracy**	**Spatial precision**	**Temporal accuracy**	**Temporal precision**
Blur				
0 px	-7.73 px (20.36)	36.97 px (13.82)	0.100 s (0.206)	0.198 s (0.071)
10 px	-7.20 px (21.60)	36.15 px (13.12)	0.099 s (0.216)	0.202 s (0.072)
20 px	-8.14 px (21.49)	37.18 px (10.51)	0.082 s (0.208)	0.205 s (0.071)
40 px	-10.06 px (21.41)	37.52 px (11.62)	0.064 s (0.198)	0.210 s (0.068)
60 px	-13.40 px (22.33)	39.53 px (13.42)	0.041 s (0.215)	0.218 s (0.074)
Occlusion time				
0.3 s	-1.33 px (12.11)	23.57 px (13.15)	0.103 s (0.184)	0.153 s (0.067)
0.7 s	-9.60 px (21.28)	36.05 px (13.17)	0.103 s (0.216)	0.199 s (0.078)
1.1 s	-17.54 px (32.49)	45.61 px (11.80)	0.027 s (0.251)	0.225 s (0.070)
Horizontal velocity				
3 px/frame	-10.66 px (19.43)	32.05 px (13.05)	0.004 s (0.230)	0.198 s (0.071)
4 px/frame	-8.86 px (21.11)	38.05 px (11.97)	0.087 s (0.207)	0.202 s (0.059)
5 px/frame	-8.23 px (23.81)	41.48 px (12.13)	0.142 s (0.198)	0.198 s (0.060)
Side				
Left to right	-10.20 px (24.89)	35.55 px (11.24)	0.075 s (0.203)	0.209 s (0.072)
Right to left	-8.28 px (21.83)	36.80 px (13.47)	0.080 s (0.212)	0.207 s (0.066)

6.1.2.1.1 Spatial constant error

For the additional analysis only the models including either velocity or occlusion time revealed significant effects. There was a significant linear effect of velocity on the spatial constant error [$\chi^2(1) = 4.95$, $p = .026$]. With increasing velocity participants undershot the trajectory less. Another finding is that when including velocity as predictor, the significant linear effect of blur disappeared [$p > .723$] and there was no significant interaction between blur and velocity [$p > .430$]. The model including occlusion time revealed a significant main effect of occlusion time [$\chi^2(1) = 76.29$, $p < .001$], and blur [$\chi^2(1) = 8.29$, $p = .004$], but no significant interaction between them [$p > .192$]. With increasing occlusion time, participants undershot the trajectory more severely. The model for side showed no main effect of side and no interaction between blur and side [all *p*s > .303], while the main effect of blur remained significant [$\chi^2(1) = 11.65$, $p < .001$]. For an illustration see Figure 6-1 in the Appendix.

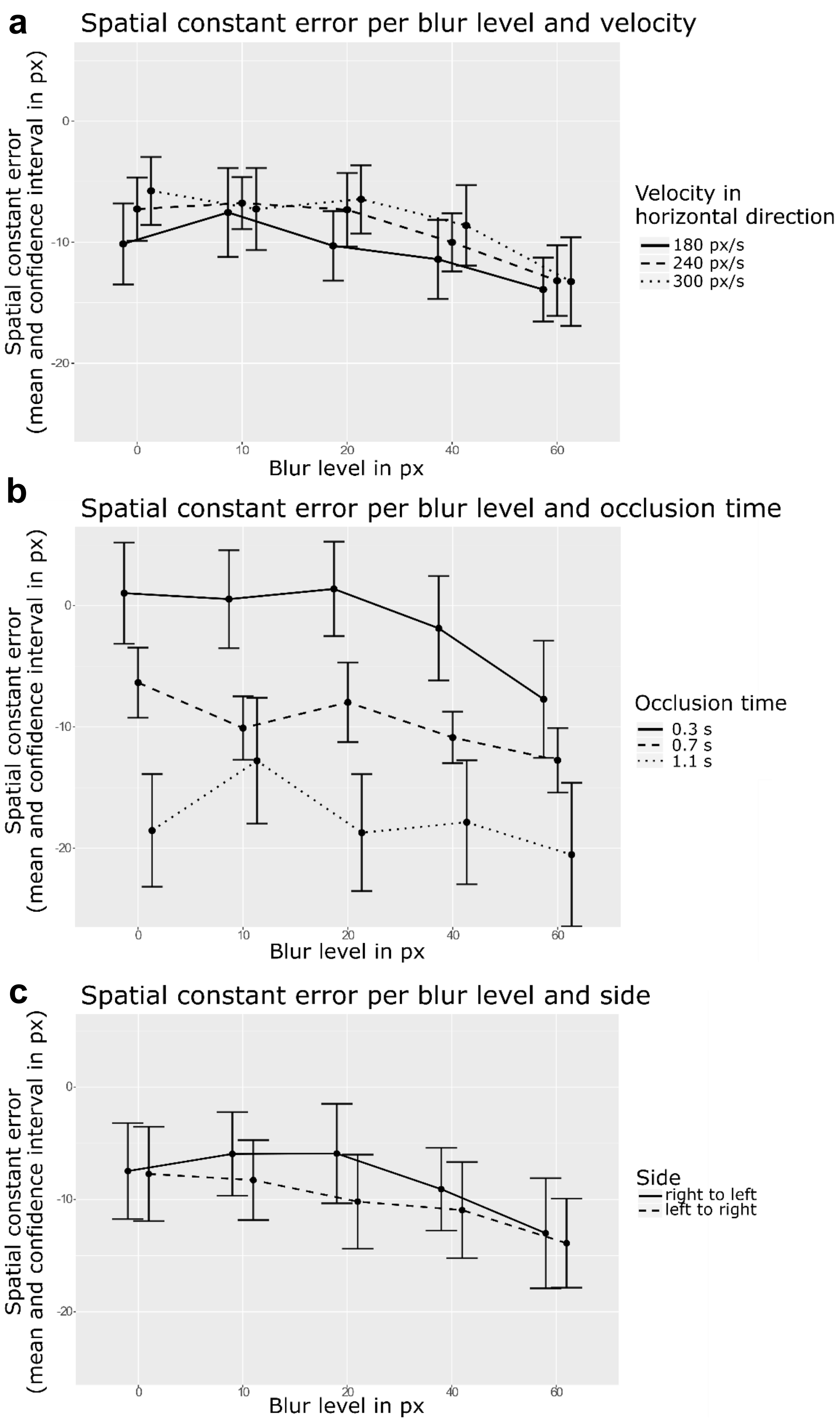

Figure 6-1. Effects of velocity (a), occlusion time (b), and side (c) on the spatial constant error per blur level. Displayed are means and confidence intervals per condition.

6.1.2.1.2 Spatial variable error

There was a significant effect of velocity [$\chi^2(1) = 94.45$, $p < .001$], and blur [$\chi^2(1) = 7.74$, $p = .005$], and a significant interaction between velocity and blur [$\chi^2(1) = 4.40$, $p < .036$]. Both variables increased the spatial variable error, but there was also a negative interaction. Both, higher amounts of blur [$\chi^2(1) = 17.86$, $p < .001$], and occlusion time [$\chi^2(1) = 388.96$, $p < .001$], increased the spatial variable error. Furthermore, there was a significant interaction between occlusion time and blur [$\chi^2(1) = 6.47$, $p = .011$]. With increasing occlusion time, the effect of blur decreased. When including side, only the effect of blur reached significance [$\chi^2(1) = 11.37$, $p < .001$, all other *p*s > .107]. Those results are illustrated in Figure 6-2 in the Appendix.

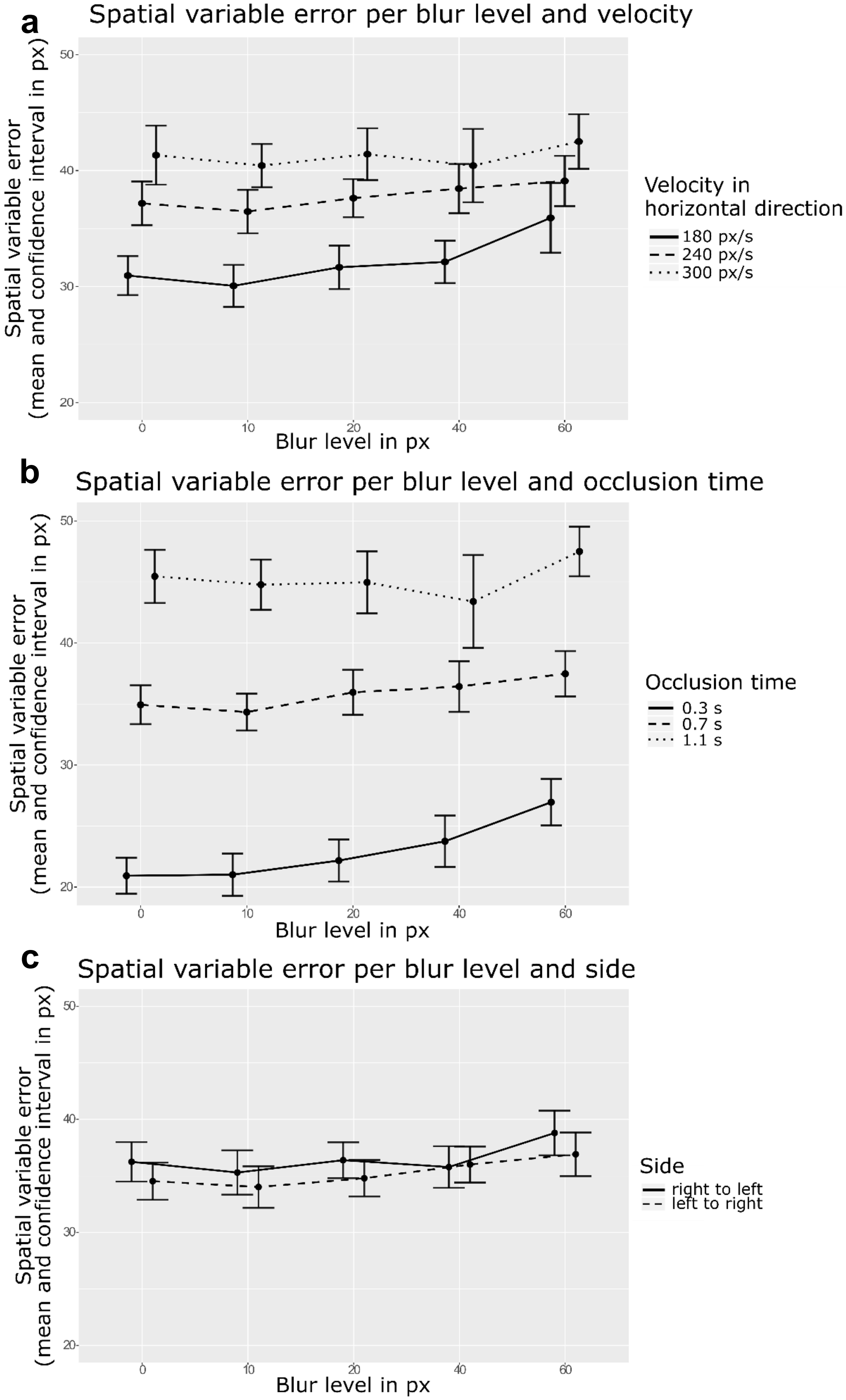

Figure 6-2. Effects of velocity (a), occlusion time (b), and side (c) on the spatial variable error per blur level. Displayed are means and confidence intervals per condition.

6.1.2.1.3 Temporal constant error

With increasing velocity, the temporal constant error increased significantly [$\chi^2(1) = 170.41$, $p < .001$]. Furthermore, blur still significantly decreased the temporal constant error [$\chi^2(1) = 17.53$, $p < .001$], and there was a significant interaction [$\chi^2(1) = 5.38$, $p = .020$]. With increasing velocity, the effect of blur was decreased. The model for occlusion time revealed a significant main effect of occlusion time [$\chi^2(1) = 52.52$, $p < .001$], and a significant main effect of blur [$\chi^2(1) = 19.72$, $p < .001$], on the temporal constant error, but the interaction missed significance [$p = .064$]. Both blur and occlusion time let to earlier responses (resulting in an increased temporal accuracy). Side had no significant main effect nor interaction with blur [all *p*s > .564], but there was a significant main effect of blur [$\chi^2(1) = 120.38$, $p < .001$]. These results are depicted in Figure 6-3 in the Appendix.

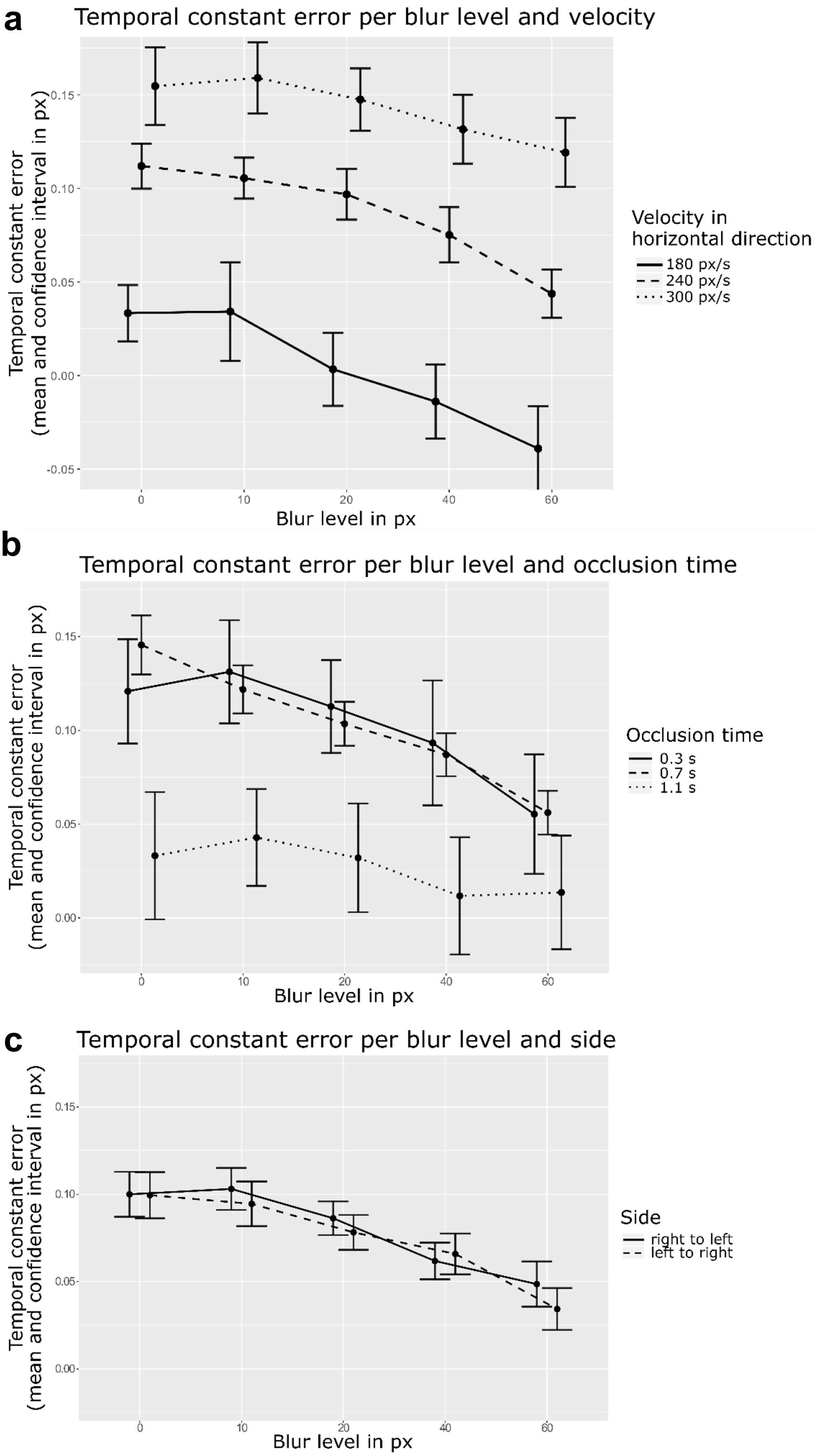

Figure 6-3. Effects of velocity (a), occlusion time (b), and side (c) on the temporal constant error per blur level. Displayed are means and confidence intervals per condition

6.1.2.1.4 Temporal variable error

For the model including random intercepts and fixed effects of blur, velocity and their interaction, there was neither a significant main effect of blur nor of velocity [all *p*s > .199], but a significant interaction between both [$\chi^2(1) = 4.22$, $p = .040$]. When adding occlusion time as predictor instead, the temporal variable error increased with increasing occlusion time [$\chi^2(1) = 106.19$, $p < .001$], but the analysis did not reveal a significant effect of blur [$p > .251$] nor a significant interaction between blur and occlusion time [$p > .316$]. Please note, that the temporal variable error was neither affected by side nor by the interaction between side and blur [all *p*s > .667], but there was a significant main effect of blur [$\chi^2(1) = 23.60$, $p < .001$]. Please see Figure 6-4 in the Appendix for an illustration.

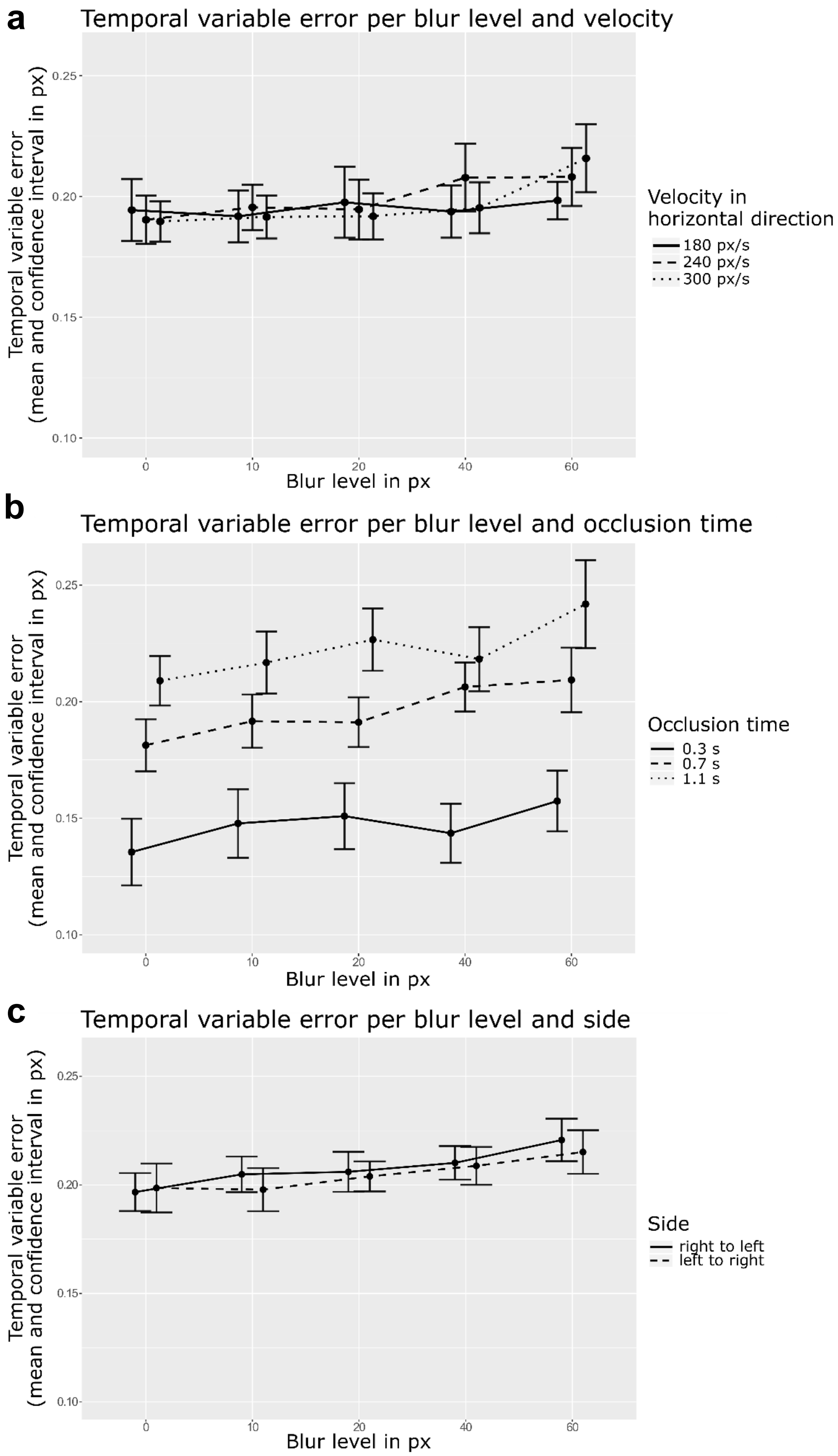

Figure 6-4. Effects of velocity (a), occlusion time (b), and side (c) on the temporal variable error per blur level. Displayed are means and confidence intervals per condition.

6.1.2.1.5 Association between errors

To evaluate whether the two error types are associated with each other, we ran additional analyses. There was a significant positive fixed effect of the spatial difference score on the temporal difference score [$\chi^2(1) = 319.91$, $p < .001$]. With increasing spatial deviation participants' temporal deviation increased (on a trial level). Furthermore, there was a significant random slope indicating interindividual variability in the relationship between the spatial and temporal deviation [$\chi^2(2) = 150.14$, $p < .001$]. These findings indicate a relationship between the temporal and the spatial deviation, but the strength of this relationship varied between individuals.

6.1.2.1.6 Correlation with constant errors

Regarding the data acquired via the questionnaire, there was a small but significant correlation between how many hours participants played electronic games per day and the temporal constant error [$\tau = .24$, $z = 1.99$, $p = .046$]. The error increases with an increasing number of playing hours. Additionally, there was a non-significant trend for a correlation between age and the spatial constant error [$\tau = .20$, $z = 1.76$, $p = .078$]. With increasing age, the spatial constant error increased. There were no other significant correlations (considering experience with electronic games on a touchscreen in hours per day, age in years, visual performance on acuity and contrast sensitivity, ball sport training in hours per week, touchscreen familiarity in hours per day, all *p*s > .158).

6.1.2.1.7 Correlation with variable errors

There were no significant correlations between the variable errors and the data of the questionnaire [all *p*s > .213].

6.1.3 Experiment 2 – contrast

6.1.3.1 Results

Table 6-3 in the Appendix provides an overview about the error scores per contrast level, occlusion time, horizontal velocity, and side.

Table 6-3. Descriptive data of task performance. Means (and standard deviations) of each error score per factor level are reported. Negative values of the spatial accuracy indicate that participants undershot the trajectory whilst positive values represent overshooting. Concerning the temporal accuracy, positive values indicate that the participants' temporal response was too late.

Variable	Spatial accuracy	Spatial precision	Temporal accuracy	Temporal precision
Contrast				
95%	-8.94 px (25.43)	35.21 px (7.56)	0.097 s (0.130)	0.183 s (0.041)
85%	-9.13 px (24.90)	36.01 px (8.94)	0.092 s (0.126)	0.181 s (0.036)
78%	-8.92 px (26.03)	35.04 px (8.42)	0.092 s (0.131)	0.177 s (0.036)
46%	-10.19 px (24.69)	35.13 px (7.57)	0.095 s (0.132)	0.187 s (0.036)
34%	-9.00 px (25.13)	34.93 px (7.78)	0.095 s (0.128)	0.174 s (0.038)
Occlusion time				
0.3 s	2.33 px (12.88)	18.98 px (4.04)	0.115 s (0.097)	0.123 s (0.026)
0.7 s	-10.10 px (26.57)	32.33 px (7.08)	0.125 s (0.131)	0.171 s (0.033)
1.1 s	-20.94 px (39.15)	42.11 px (8.74)	0.041 s (0.182)	0.202 s (0.045)
Horizontal velocity				
3 px/frame	-8.35 px (19.99)	29.89 px (5.27)	0.046 s (0.129)	0.175 s (0.036)
4 px/frame	-9.88 px (26.45)	36.10 px (8.12)	0.097 s (0.130)	0.176 s (0.036)
5 px/frame	-9.40 px (29.86)	38.41 px (8.88)	0.140 s (0.131)	0.176 s (0.035)
Side				
Left to right	-7.53 px (26.51)	33.60 px (7.84)	0.094 s (0.125)	0.178 s (0.035)
Right to left	-10.86 px (27.48)	34.07 px (7.21)	0.094 s (0.133)	0.182 s (0.035)

6.1.3.1.1 Spatial constant error

The spatial constant error was not affected by velocity, contrast, or their interaction [all *p*s > .595]. With increasing occlusion time, participants undershot the target more [$\chi^2(1) = 28.09$, $p < .001$], but contrast and the interaction of contrast and occlusion time had no significant effect [all *p*s > .803]. When adding side as predictor, the effect of contrast and the interaction of contrast and side did not show any significant effect [all *p*s > .371], and the effect of side slightly missed significance [$\chi^2(1) = 3.20$, $p = .074$], indicating more undershooting when the trajectory started at the right side. For an illustration, see Figure 6-5 in the Appendix.

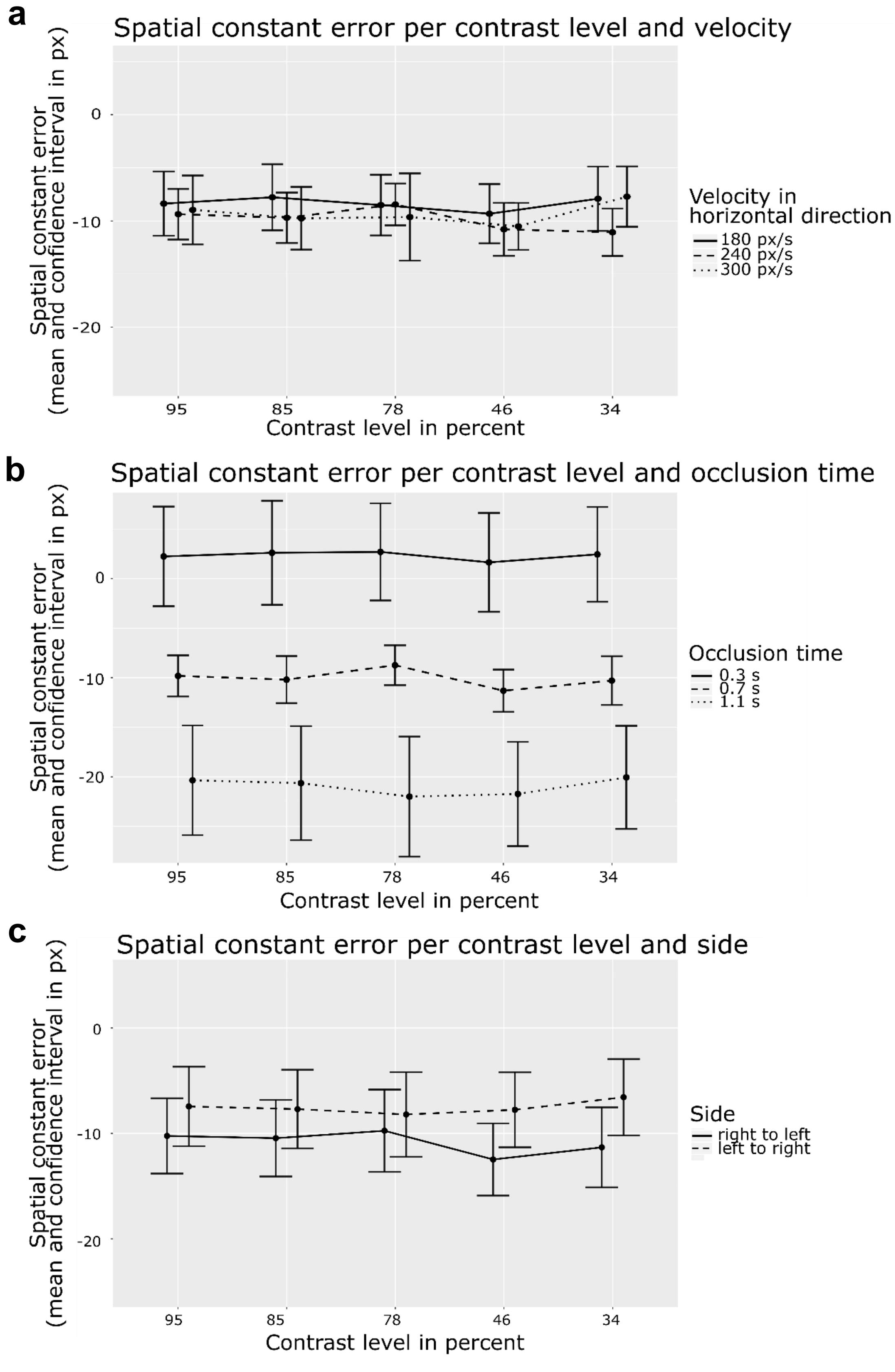

Figure 6-5. Effects of velocity (a), occlusion time (b), and side (c) on the spatial constant error per contrast level. Displayed are means and confidence intervals per condition.

6.1.3.1.2 Spatial variable error

The spatial variable error was significantly increased with increasing velocity, $\chi^2(1) = 42.68$, $p < .001$]. There was a non-significant trend that the spatial variable error decreased with decreasing contrast [$\chi^2(1) = 3.46$, $p = .063$], and that this effect decreased with increasing velocity [$\chi^2(1) = 2.89$, $p < .089$]. The model with occlusion time and contrast, indicated a significant main effect for occlusion time only [$\chi^2(1) = 118.72$, $p < .001$, all other *p*s > .222]. The spatial variable error increased with increasing occlusion time. When side was included as predictor, none of the main effects nor the interaction were significant [all *p*s > .152]. The effects of the additional factors on the spatial variable error are depicted in Figure 6-6 in the Appendix.

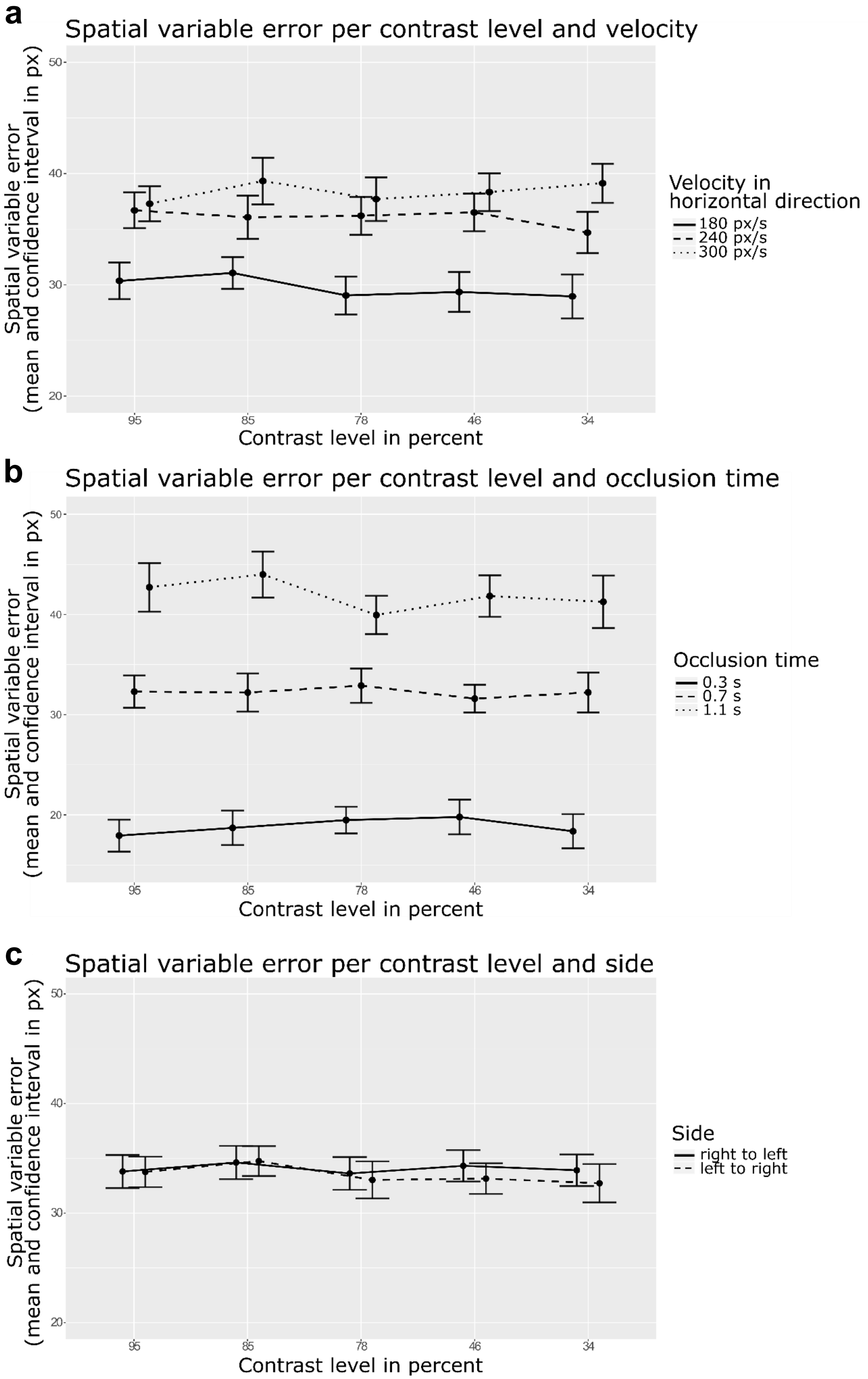

Figure 6-6. Effects of velocity (a), occlusion time (b), and side (c) on the spatial variable error per contrast level. Displayed are means and confidence intervals per condition.

6.1.3.1.3 Temporal constant error

The model of velocity revealed a significant positive main effect of velocity on the temporal constant error [$\chi^2(1) = 67.15$, $p < .001$], but no other significant effects [all *p*s > .630]. When adding occlusion time instead, the temporal constant error decreased (earlier reactions) with increasing occluded intervals [$\chi^2(1) = 10.73$, $p = .001$]. The other two effects were not significant [all *p*s > .884]. A model including side, contrast and the interaction of both did not reveal any significant results [all *p*s > .515]. Please see Figure 6-7 in the Appendix for an illustration.

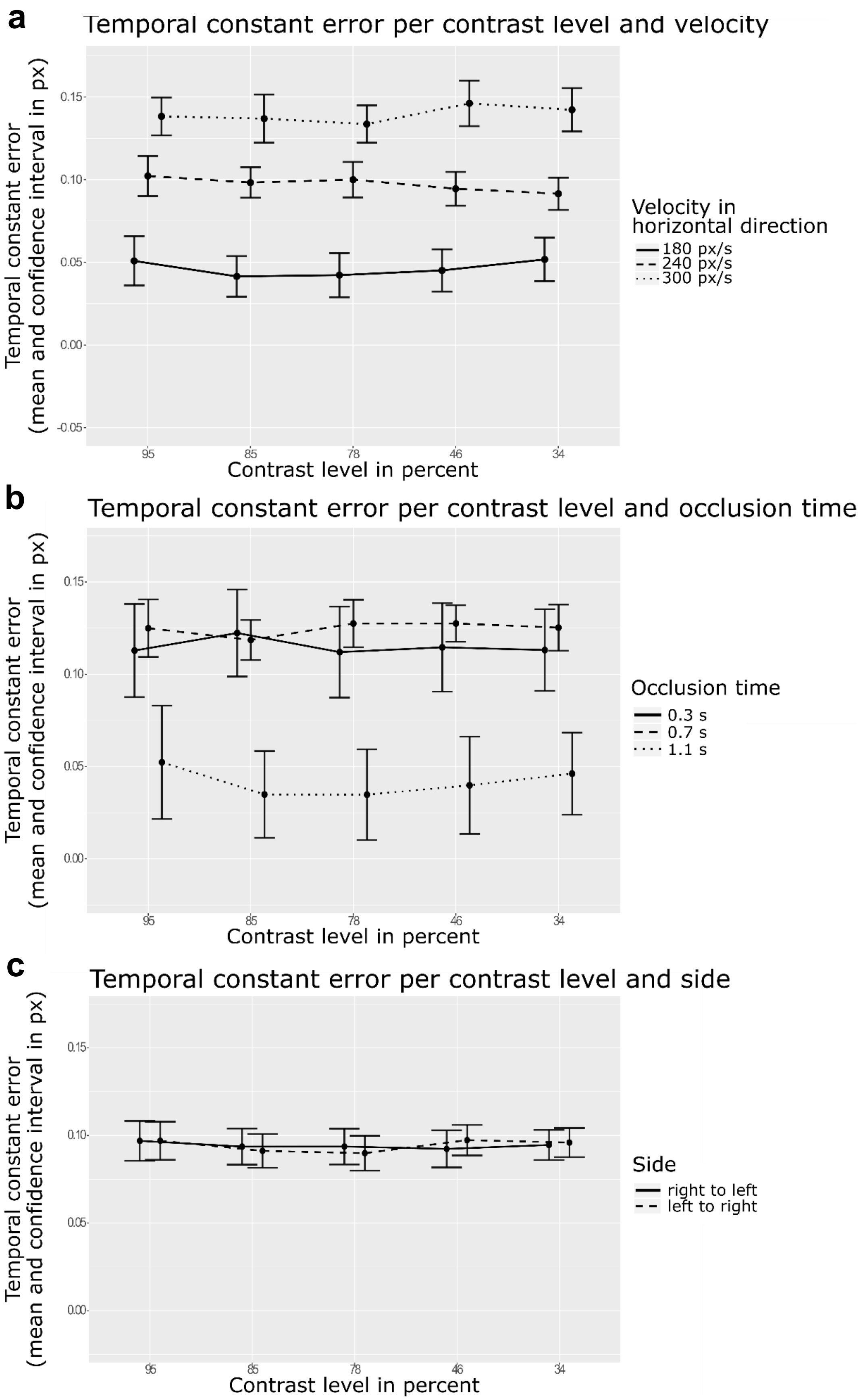

Figure 6-7. Effects of velocity (a), occlusion time (b), and side (c) on the temporal constant error per contrast level. Displayed are means and confidence intervals per condition.

6.1.3.1.4 Temporal variable error

When including velocity as predictor, none of the effects reached significance [all *p*s > .0714]. The model including occlusion time revealed no effects for contrast and the interaction between contrast and occlusion time [all *p*s > .842], but a significant main effect of occlusion time [$\chi^2(1) = 62.17$, $p < .001$]. The longer the occluded interval was, the more variable participants' responses became. There was no significant effect of side, contrast, or the interaction between both [all *p*s > .415]. These results are visualized in Figure 6-8 in the

Appendix.

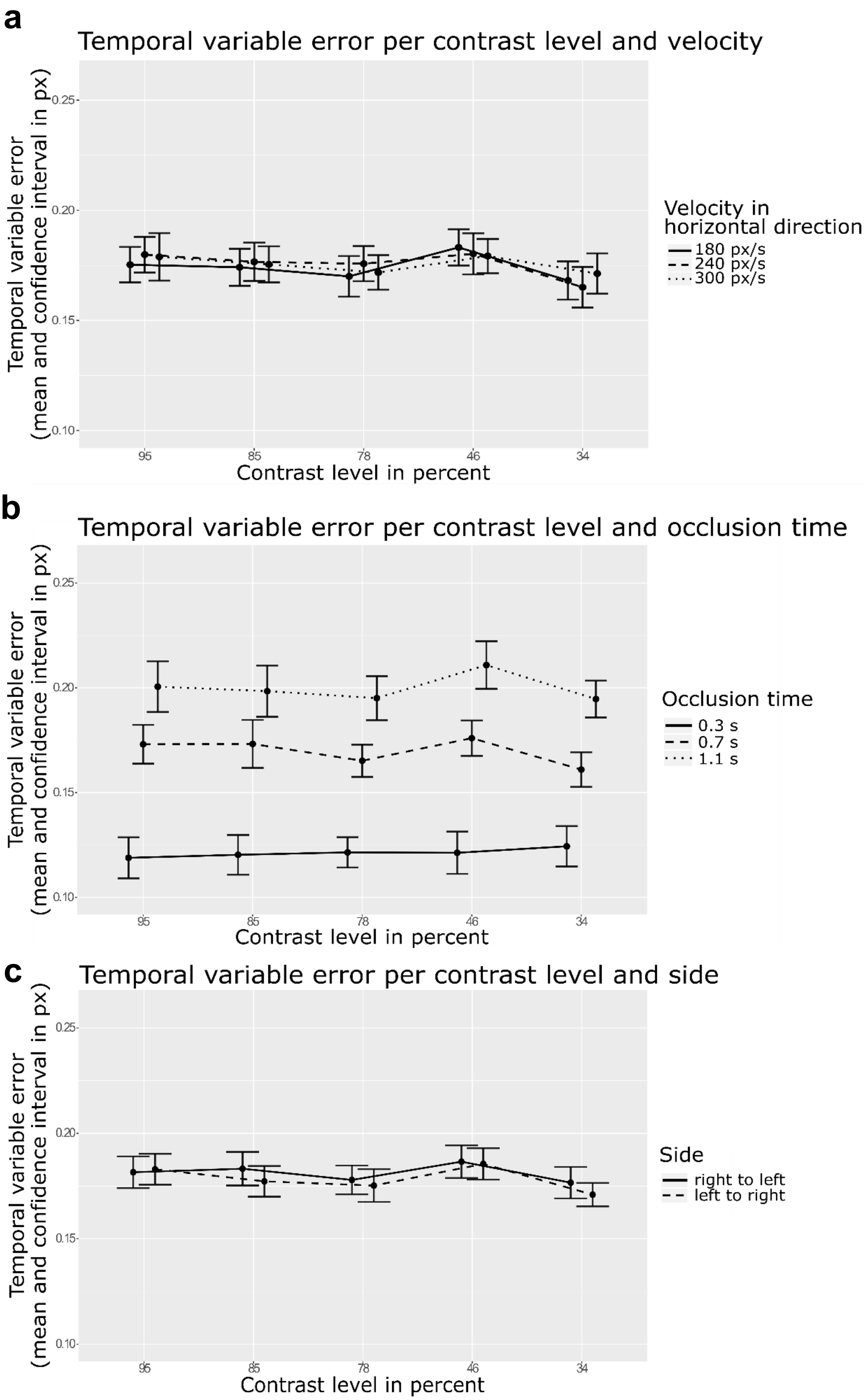

Figure 6-8. Effects of velocity (a), occlusion time (b), and side (c) on the temporal variable error per contrast level. Displayed are means and confidence intervals per condition.

6.1.3.1.5 Association between errors

To investigate associations between the temporal and spatial error per trial, multilevel models with trial as first and participant as second level revealed a positive fixed effect of the spatial difference score on the temporal difference score [$\chi^2(1) = 130.65$, $p < .001$]. Additionally, there was a significant random effect of the spatial difference score [$\chi^2(2) = 182.56$, $p < .001$]. This means that, overall, the temporal difference score was higher when the spatial difference score was higher but there was significant variability between participants in this association.

6.1.3.1.6 Correlation with constant errors

There was a significant correlation between the temporal constant error and the time participants spend playing electronic games per day [$\tau = .32$, $z = 2.62$, $p = .008$]. The more participants play electronic games, the later they touched the screen. Furthermore, there was a non-significant trend for a relationship between the temporal constant error and the time participants play electronic games on a touchscreen per day [$\tau = .22$, $z = 1.71$, $p = .086$]. Again, the error increased with increasing amount of playing time. There were no other significant correlations [all *p*s > .253].

6.1.3.1.7 Correlation with variable errors

The correlation analysis revealed a significant negative association between the spatial variable error and hours of ball sport training per week [$\tau = -.32$, $z = -2.67$, $p = .007$]. The more frequently participants played ball sports per week, the more precisely they hit the target. All other correlations did not reach significance [all *p*s > .201].

6.1.3.1.8 Comparison between both experiments

To examine whether the size of the constant and variable errors was similar across experiments, we compared the size of the error scores in the no-blur and highest contrast condition because those conditions were identical across experiments. Unpaired t-tests revealed no significant differences between experiments (all ps > .232). All error scores were quite similar across experiments.

6.1.4 General Discussion

Besides changes in blur or contrast, some other manipulations have been shown to impact interception performance in previous research as well as in the current study. Brenner et al. (2014) found that occluding the final part of a trajectory resulted in reduced temporal precision. During occlusion extrapolation is necessary to make any predictions of where and when a stimulus will be. Previous research has shown that extrapolation precision was decreasing with increasing distance to an occlusion point (Singh & Fulvio, 2005). In line with these findings, one would predict increasing spatial and temporal variability with increasing occlusion time. The current study supports this notion and thereby extends the findings of Brenner et al. (2014) by showing that increasing the occluded temporal interval decreased not only temporal precision, but also spatial precision and spatial accuracy in both experiments (more undershooting, see Figures 6-1b, 6-2b, 6-4b, 6-5b, 6-6b, and 6-8b in the Appendix). Moreover, the temporal constant error decreased with increasing occlusion time, indicating that the longer the occlusion interval was, the earlier participants reacted (see Figures 6-3b and 6-7b in the Appendix). In line with research on time to arrival estimation (Benguigui et al., 2003), indicating that humans are unable to use information about acceleration (second-order information) and instead extrapolate constant velocities (frequently updating) one would expect less delayed responses for shorter occlusion times, because the later the ball is occluded the faster its latest visible velocity was. Supporting this idea, for the smallest occlusion time (where velocity is already very fast before occlusion) the temporal response is less delayed (see Figure 6-3 and 6-7 in the Appendix).

The temporal constraints induced by manipulating velocity should lead to increased temporal precision at the cost of decreased spatial precision. Similar to others (Tresilian et al., 2009), we only found a negative impact on the spatial precision (see Figures 6-2a and 6-6a in the Appendix), while the temporal variability was not significantly affected in either experiment (see Figures 6-4a and 6-8a in the Appendix). Yet, this is in conflict with others showing a significant decrease in the temporal variability (Lim, 2015) or even a significant increase in the spatiotemporal interception variability (H. Zhao & Warren, 2017). Interestingly, except for spatial precision also temporal accuracy decreased (earlier reactions) with increasing horizontal velocity (see Figures 6-2a, 6-3a, 6-6a, and 6-7a in the Appendix) which might be caused by faster interception movements found in previous research (e.g., Brouwer et al., 2000; Tresilian et al., 2003). In Experiment 1 the level of undershooting of the target trajectory decreased with increasing horizontal velocity (see Figure 6-1a in the Appendix), but this effect was not found in Experiment 2 (see Figure 6-5a in the Appendix).

In both experiments, the starting side had no impact on most of the error scores (see Figure 6-1c – 6-8c in the Appendix). Only in Experiment 2 participants horizontally undershot targets slightly more, when they started at the right side, but this effect did not reach significance.

6.2 Supplement to Chapter 3: Tau and kappa in interception – how perceptual spatiotemporal interrelations affect

This supplement will be published together with the Study in Chapter 3 and is currently under revision.

6.2.1 Experiment 1

6.2.1.1 Results

6.2.1.1.1 Interception data

Outlier analyses led to 0.06-1.85% data exclusion (see Table 6-4).

Table 6-4. Excluded interception data due to outlier correction.

	Experiment 1		Experiment 2	
Outlier exclusion	visual	auditory	visual	auditory
spatial response	0.41%	0.06%	0.44%	0.02%
temporal response	0.84%	1.85%	1.00%	1.27%

6.2.1.1.2 Post-hoc analyses

To test whether task difficulty might explain the absent typical kappa effect in the visual domain, post-hoc the spatial and temporal error scores per task modality were plotted (see Figure 6-9). Indeed, the temporal responses were very similar for the auditory and the visual conditions, whilst the variation of the spatial responses was clearly higher in the auditory condition. If variability depicts uncertainty or noise, this may explain why in the auditory condition, there was an effect of the temporal context (low noise) on the spatial response (high

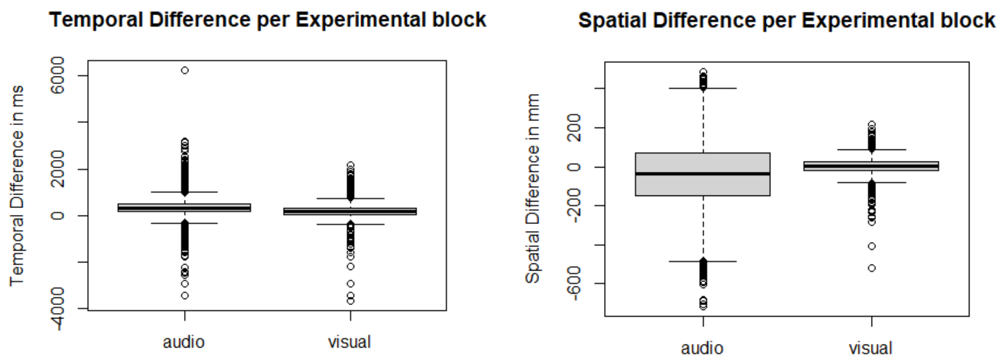

Figure 6-9. Descriptive data. Left: Temporal difference between the correct time and participants responses per condition. Right: Spatial difference between correct location and participants' interception location.

noise), whereas in the visual condition the spatial context (low noise) did not affect the temporal response (low noise).

Additionally, in an exploratory analysis we tested the representational noise hypothesis which states that more noise in the dependent variable will lead to larger biases of the manipulation. To this end, we inspected the individual effects per participant (kappa and tau) per modality (auditory vs. visual; see Figure 6-10). For all except the auditory tau effect, participant's effect sizes were relatively similar (narrow distribution). Therefore, we further analyzed the auditory tau effect, by correlating the individual size of the tau/kappa effects with the visual-relative-to-auditory reliability (indicated as quotient of variances) in localization (see Figure 6-11). There was no significant relation, $r = .211$, $p = .181$.

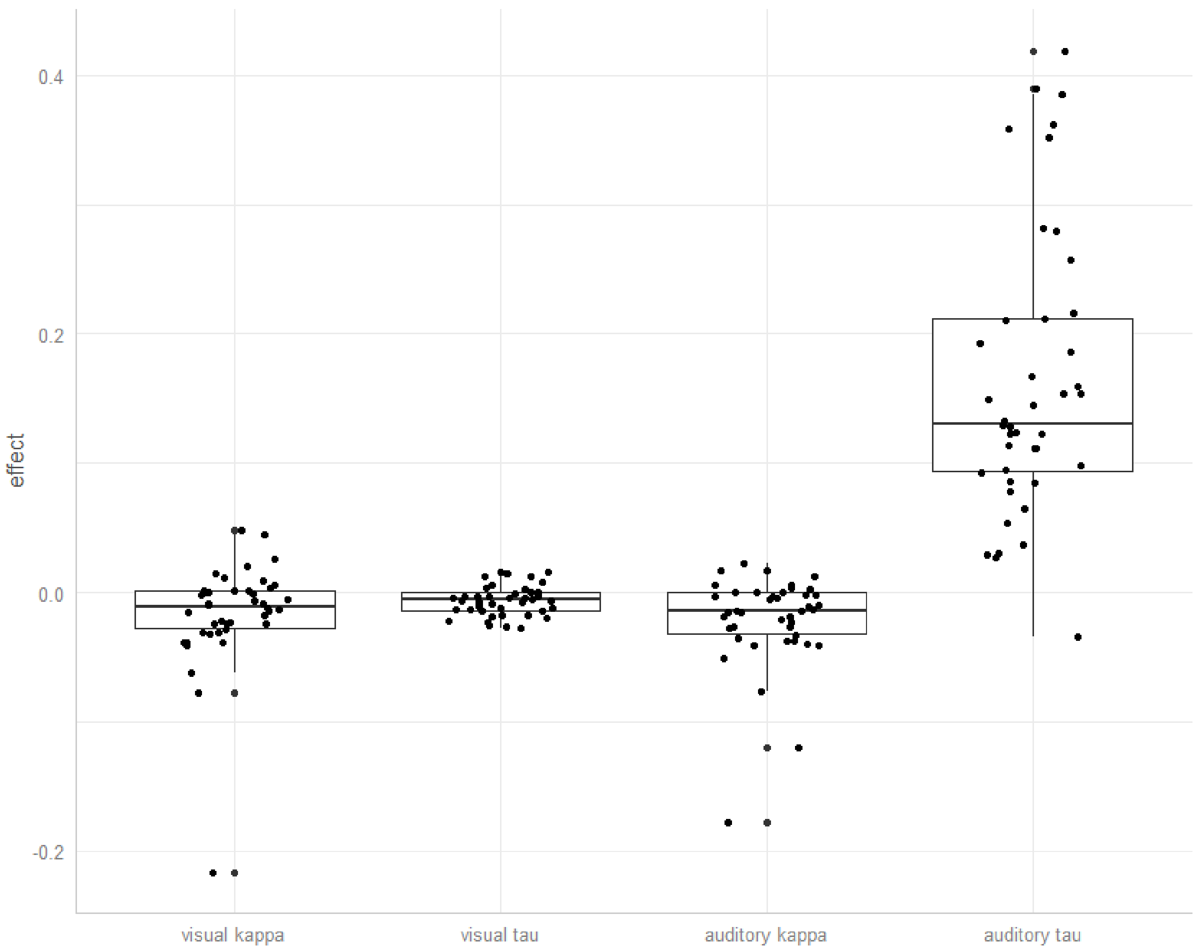

Figure 6-10. Individual effect sizes for kappa and tau effects per sensory modality.

Figure 6-11. Relationship between the auditory tau effect and the reliability of visual compared to auditory input in localization (quotient of variances). Higher values represent higher visual compared to auditory noise.

For auditory stimuli, volume only descriptively impacted the spatial and temporal variability, indicating that task difficulty did not increase with decreasing volume (Figure 6-12). Figure 6-13 shows that indeed the spatial error was more variable in the blurred condition, indicating that spatial localization was more difficult for blurred stimuli, but also the temporal error was affected.

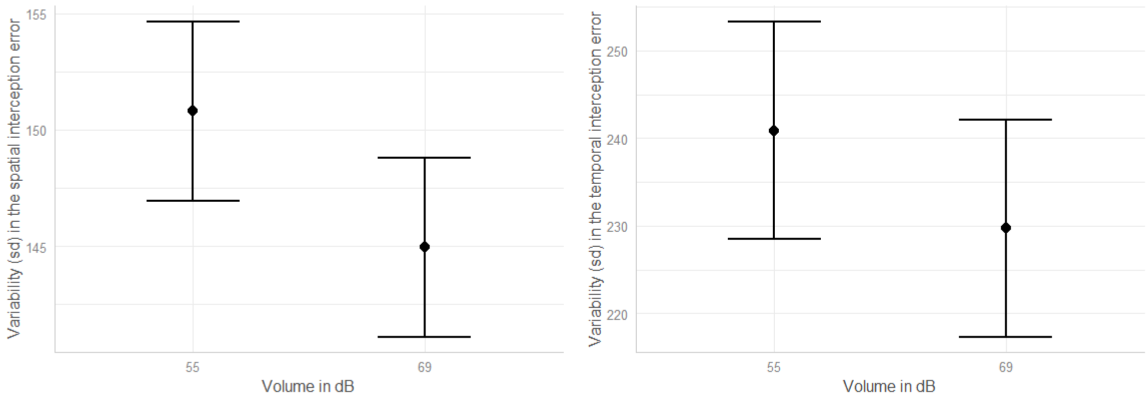

Figure 6-12. Variability of the spatial (left) and temporal (right) interception error per volume level. Depicted is the mean (dot) and the within-participant variability.

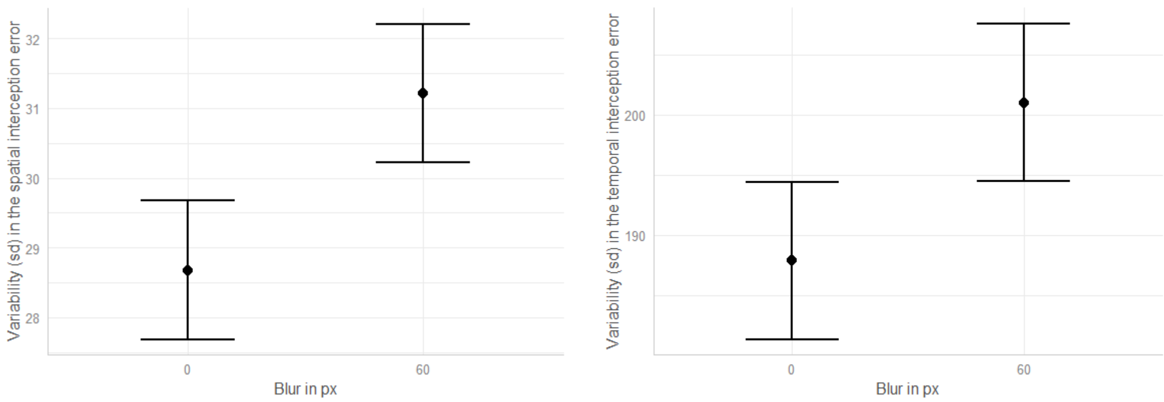

Figure 6-13. Variability of the spatial (left) and temporal (right) interception error per blur level. Depicted is the mean (dot) and the within-participant variability.

6.2.2 Experiment 2

6.2.2.1 Results

6.2.2.1.1 Interception data

Due to outlier exclusion, 0.02-1.27% of the data was rejected for analysis (see Table 6-4 in the Appendix).

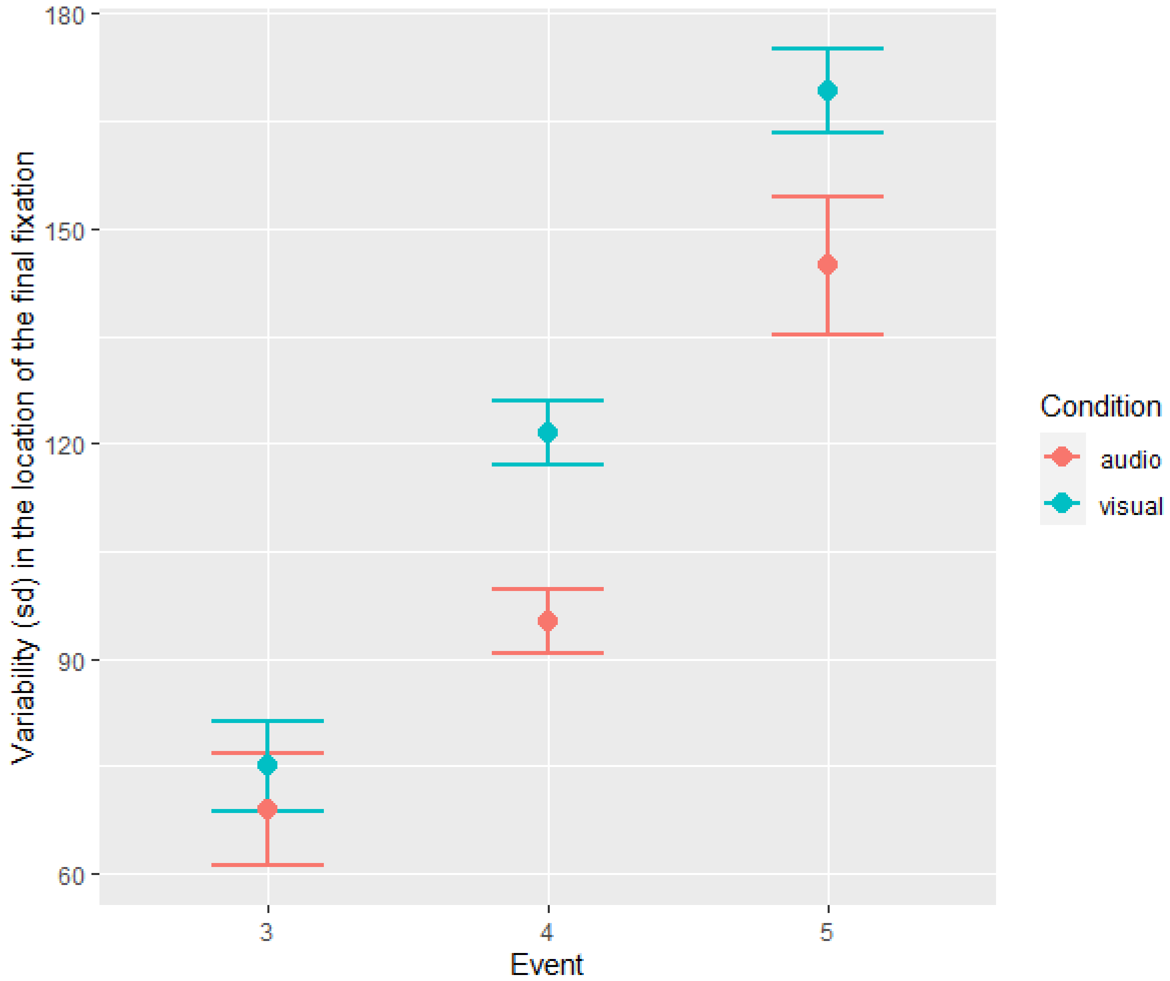

Figure 6-14. Variability of the gaze location per event. Depicted is the mean (dot) and the confidence intervals in the auditory and the visual condition.

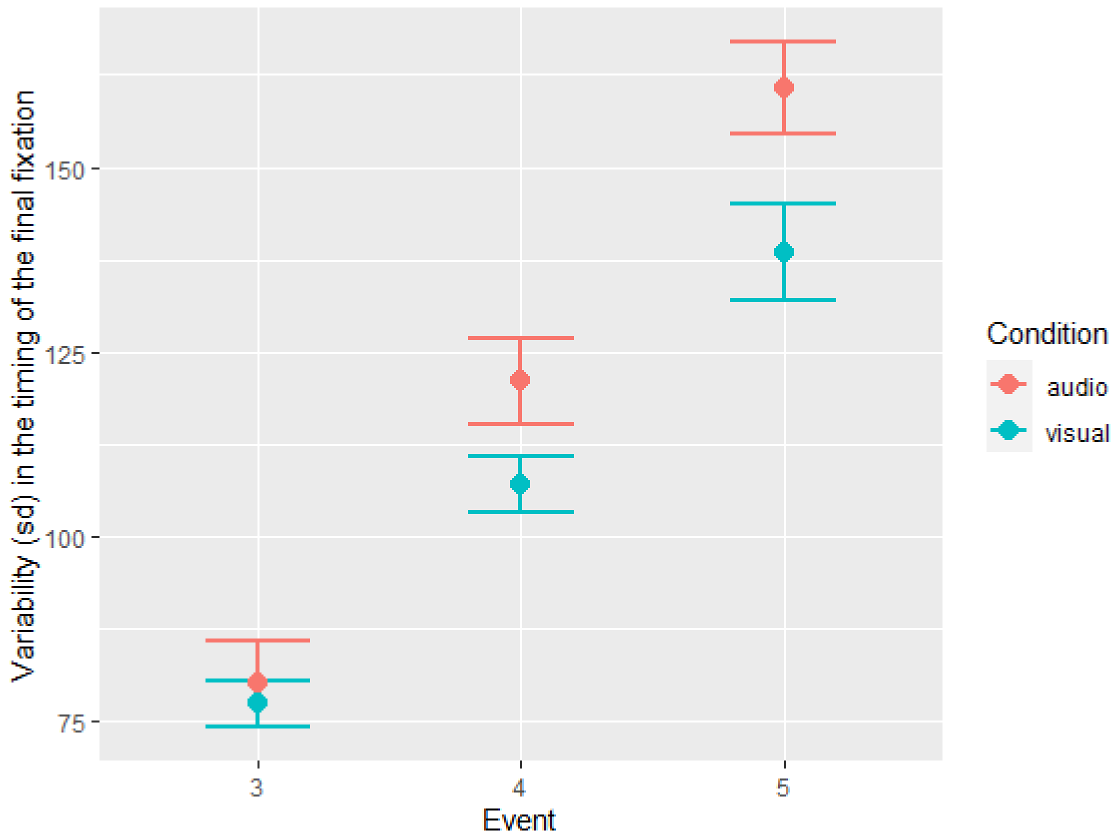

Figure 6-15. Variability of the initiation of the final fixation per event. Depicted is the mean (dot) and the confidence intervals in the auditory and the visual condition.

6.2.2.1.2 Gaze data

Results of the fixation at the moment of interception revealed no visual tau effect (see Figure 6-16).

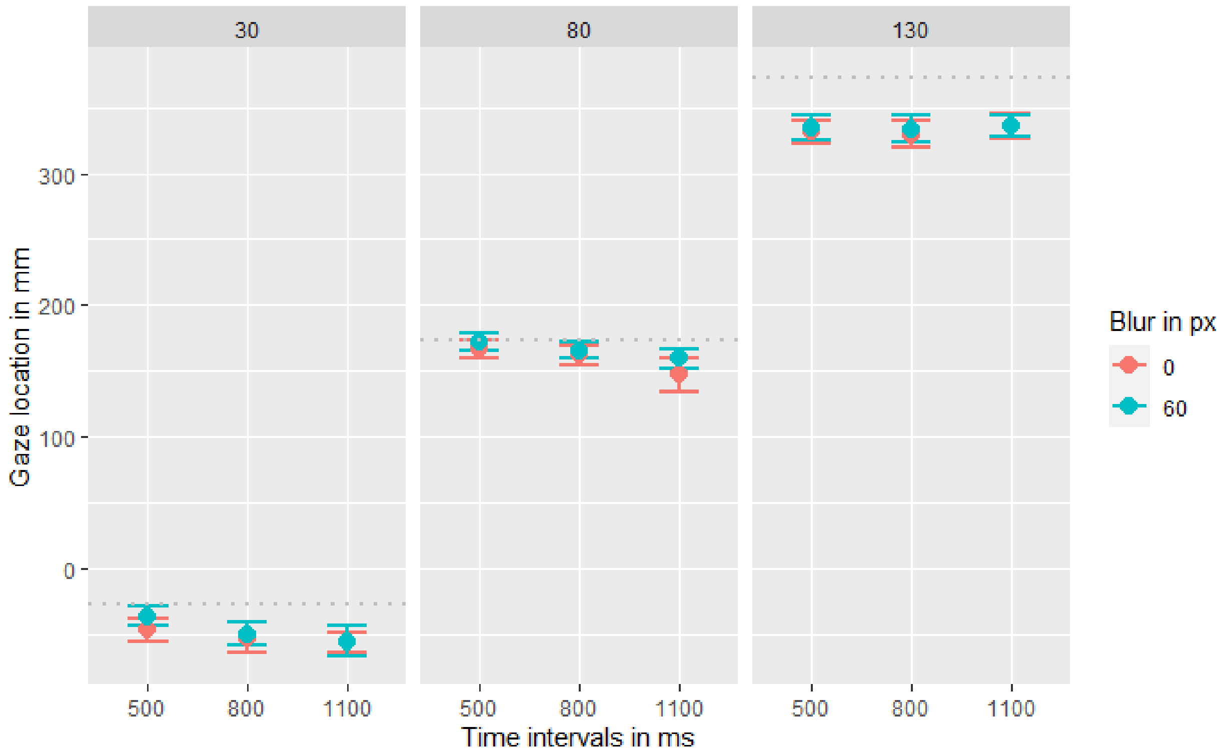

Figure 6-16. Visual tau effect (effect of temporal intervals on the gaze location at the moment of tapping on the screen). One plot for each spatial interval is displayed. Depicted is the mean (dot) and the within-participant variability in the auditory and the visual condition.

6.3 Author contributions

All projects were funded by the German Research Foundation (DFG), project numbers: CA 635/2-2 awarded to Rouwen Cañal-Bruland and RA 940/15-2 (and RA 940/15-1 for the Review in Chapter 1.2) awarded to Markus Raab. No conflict of interest was reported.

Chapter 1.2: Loeffler, J., Cañal-Bruland, R., Schroeger, A., Tolentino-Castro, J. W., & Raab, M. (2018). Interrelations Between Temporal and Spatial Cognition: The Role of Modality-Specific Processing. *Frontiers in Psychology*, *9*, 2609. https://doi.org/10.3389/fpsyg.2018.02609

JL, RCB and MR conceptualized and designed the study. JL conducted the literature search and wrote the first draft of the manuscript. All authors wrote, revised, and edited the manuscript. AS and JWTC incorporated the revisions and conducted additional literature searches. RCB and MR supervised the project.

Chapter 2: Schroeger, A., Tolentino-Castro, J. W., Raab, M., & Cañal-Bruland, R. (2021). Effects of visual blur and contrast on spatial and temporal precision in manual interception. Experimental Brain Research. Advance online publication. https://doi.org/10.1007/s00221-021-06184-8

RCB and MR conceptualized and designed the study. AS programmed the experiment. AS and JWTC collected pilot data and adapted the design. AS collected, visualized, and analyzed the data. AS wrote the first draft of the manuscript. All authors wrote, revised, and edited the manuscript. RCB and MR supervised the project.

Chapter 3: Schroeger, A., Raab, M., & Cañal-Bruland, R. (under review). Tau and kappa in interception – how perceptual spatiotemporal interrelations affect movements.

AS, RCB and MR conceptualized and designed the study. AS programmed the experiment. AS collected, visualized, and analyzed the data. AS wrote the first draft of the manuscript. All authors wrote, revised, and edited the manuscript. RCB and MR supervised the project.

Chapter 4: Schroeger, A., Grießbach, E., Raab, M., & Cañal-Bruland, R. (submitted). Kappa effects modulate prediction and interception.

AS, RCB and MR conceptualized and designed the study. EG programmed the experiment. AS and EG collected, visualized, and analyzed the data. AS wrote the first draft of the manuscript. All authors wrote, revised, and edited the manuscript. RCB and MR supervised the project.

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Ehrenwörtliche Erklärung

Hiermit bestätige ich, dass mir die geltende Promotionsordnung der Fakultät für Sozial- und Verhaltenswissenschaften bekannt ist, dass ich die Dissertation selbst angefertigt habe, keine Textabschnitte eines Dritten oder eigener Prüfungsarbeiten ohne Kennzeichnung übernommen und alle von mir benutzten Hilfsmittel, persönliche Mitteilungen und Quellen in der Arbeit angegeben habe. Die in dieser Arbeit inkludierten Publikationen sind in Zusammenarbeit mit Koautoren entstanden, welche an der Studienplanung und -auswertung, sowie an der Manuskripterstellung beteiligt waren (siehe Author contributions). Ich bestätige außerdem, dass keine kommerziellen Promotionsvermittler in Anspruch genommen wurden und dass Dritte weder unmittelbar noch mittelbar geldwerte Leistungen von mir für Arbeiten erhalten haben, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen. Ich habe diese Dissertation noch nicht als Prüfungsarbeit für eine staatliche oder andere wissenschaftliche Prüfung eingereicht. Ich habe weder diese, noch eine in wesentlichen Teilen ähnliche oder eine andere Abhandlung bei einer anderen Hochschule als Dissertation eingereicht.

Ort, Datum

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