Zur Homepage der Dissertation

The influence of an auditory accessory stimulus on target choice and reaction time with two visual stimuli

Vom Fachbereich 5
Philosophie/Psychologie/Sportwissenschaft
der Universität Oldenburg
zur Erlangung des Grades einer

Doktorin der Philosophie

angenommene Dissertation

KARIN ELISABETH TROIDL

geb. am 18.12.1970 in Nabburg

Erstreferent:	Prof. Dr. H. Colonius
Korreferentin:	Prof. Dr. A. Diederich
Tag der Disputation:	11. Januar 2002

Zusammenfassung

Wir sind im Alltag einer Vielzahl von visuellen Reizen ausgesetzt und müssen uns zu jedem Zeitpunkt für ein Blickziel entscheiden. Die Auswahl von Blickzielen ist ein komplexer Prozeß, der sowohl vom internen Zustand des Beobachters als auch von physikalischen Eigenschaften des Reizes bestimmt wird. Dabei müssen die Eigenschaften eines Reizes nicht auf eine Sinnesmodalität beschränkt bleiben. Vielmehr deuten neuere Forschungsergebnisse stark darauf hin, daß Informationen aus dem visuellen, auditiven und haptischen Sinnessystem bereits sehr früh zusammengeführt werden und so die Grundlage für Entscheidungsprozesse bilden können.

In der vorliegenden Arbeit wurde der Einfluß eines zusätzlich dargebotenen auditorischen Reizes auf das Antwortverhalten bei visuellen Reizen quantitativ untersucht. Dazu wurden in einer Reihe von Experimenten sakkadische Augenbewegungen erfaßt.

In *Experiment 1* war die Versuchsperson aufgefordert, möglichst schnell und genau auf einen beliebigen von zwei möglichen visuellen Reizen zu blicken. Mögliche Stimuluspositionen waren 8° und 24° jeweils rechts und links des Fixationspunktes. In einigen Durchgängen wurde zusätzlich zu den visuellen Reizen ein auditorischer Reiz am Ort eines der beiden visuellen Zielreize dargeboten, dem aber der Instruktion zufolge keine Beachtung geschenkt werden sollte. Der auditorische Reiz konnte entweder 50 ms vor oder nach oder gleichzeitig mit dem visuellen Zielreiz auftreten. Als abhängige Größen wurden jeweils Amplitude und Latenz der ausgeführten Sakkade erfaßt. Dabei konnten zum einen bereits bekannte Effekte wie z.B. intersensorische Bahnungseffekte nachgewiesen werden. So reagierten die Versuchspersonen immer schneller, wenn zusätzlich ein auditorischer Reiz dargeboten wurde als in rein visuellen Displays. Je früher der auditorische Reiz dargeboten wurde, desto stärker waren die Reaktionszeiten verkürzt. Ebenso repliziert werden konnte die in der Literatur als 'remote distractor-effect' (Findlay, 1982) bekannte Beobachtung, derzufolge die sakkadischen Reaktionszeiten bei Darbietung von zwei räumlich weit auseinander liegenden visuellen Reizen länger sind als bei Darbietung eines einzigen visuellen Blickziels.

Zum anderen zeigten die durchgeführten Experimente neue Aspekte auf: So zeigte sich, daß der auditorische Reiz die Häufigkeit, mit der ein bestimmtes Blickziel ausgewählt wurde und die Geschwindigkeit, mit der dies geschah, beeinflußte. Auditorisch unterlegte Reize wurden häufiger und schneller als Blickziel ausgewählt als auditorisch nicht unterlegte Reize. Die Effekte waren allerdings sehr viel kleiner, wenn beide visuelle Reize innerhalb einer Hemisphäre dargeboten wurden. Hier wurde häufig der näher am Fixpunkt liegende Reiz bevorzugt, obwohl dieser zeitlich später dargeboten wurde als der äußere Reiz. Für visuelle Reize innerhalb einer Hemisphäre waren die sakkadischen Reaktionszeiten auf auditorisch unterlegte Reize auch nicht verkürzt relativ zu solchen auf nicht auditorisch unterlegte Reize.

Um zu prüfen, ob die geringeren Effekte des auditorischen Reizes auf die Auswahl des Blickziels aufgrund einer unscharfen Lokalisation der Reize innerhalb einer Hemisphäre zustande kamen, wurden in *Experiment 2* Sakkaden auf auditorische Reize gemessen. Dabei zeigte sich, daß es tatsächlich häufig zu Verwechslungen der Reizpositionen innerhalb einer Hemisphäre kam.

Deshalb wurde in *Experiment 3* die Aufgabe dahingehend erleichtert, innerhalb eines Versuchsblockes nur auditorische Reize aus zwei möglichen Positionen darzubieten. Unter dieser geblockten Darbietungsweise gelang fast allen Versuchspersonen auch innerhalb einer Hemisphäre eine eindeutige Lokalisation der Reize.

Experiment 4 stellt eine Wiederholung des ersten Experiments in geblockter Darbietung der einzelnen Reizkombinationen dar. Darüber hinaus wurde, um zu verhindern, daß wieder nur auf den inneren Reiz geblickt wurde, dieser in seiner Helligkeit reduziert. Auch unter diesen Modifikationen konnten die Beobachtungen aus Experiment 1 im wesentlichen repliziert werden, mit einer Ausnahme: Auditorisch unterlegte Reize wurden auch innerhalb einer Hemisphäre häufiger als nicht unterlegte Reize ausgewählt; bei den Reaktionszeiten gab es keine Unterschiede. Dies mag darauf zurückzuführen sein, daß es in diesem Experiment mittels der Verringerung der Intensität des inneren Reizes besser gelungen war, ein Gleichgewicht zwischen beiden visuellen Reizen hinsichtlich ihrer Auswahlwahrscheinlichkeit herzustellen.

Insgesamt wurden die Ergebnisse dahingehend interpretiert, daß der auditorische Reiz zumindest in einem sehr frühem Stadium des Entscheidungsprozesses einen beschleunigenden Effekt auf die gesamte Hemisphäre ausübt. Die Beobachtung, daß auditorisch unterlegte Reize innerhalb einer Hemisphäre zwar häufiger aber keineswegs schneller ausgewählt wurden, unterstützt die Annahme unterschiedlicher Verarbeitungsstränge für das Auslösen und die Berechnung der genauen Richtung von sakkadischen Augenbewegungen (Findlay & Walker, 1999). So könnte die Darbietung eines auditorischen Reizes den Auslöseprozeß für eine Sakkade innerhalb einer Hemisphäre generell beschleunigen. Die genaue Amplitude der Sakkade hingegen wird durch denjenigen Punkt bestimmt, der auf einer räumlichen Auffälligkeitskarte die stärkste Aktivierung aufweist.

Die gewonnenen experimentellen Befunde konnten im Rahmen des von Diederich (1995, 1997) entwickelten Multi-Channel Diffusion Models erklärt werden. Es wird angenommen, daß sich die durch die Reize ausgelöste neuronale Aktivierung als Diffusionsprozeß mit verschiedenen (auditorischen und visuellen) Driftraten interpretieren läßt. Den Annahmen des Modells zufolge wird eine Reaktion ausgelöst, sobald der Diffusionsprozeß eine Schwelle überschreitet. Die Präsentation eines auditorischen Reizes wirkt sich, durch die zusätzliche Driftrate (hier wurde eine additive Verknüpfung von visueller und auditorischer Driftrate angenommen) beschleunigend auf den Prozeß aus. Eine solche Annahme scheint trotz der Instruktion den auditorischen Reiz zu ignorieren, gerechtfertigt, da er anscheinend auf basaler neuronaler Ebene dennoch eine Orientierungsreaktion hervorruft. Dies zeigte sich daran, daß die meisten Versuchspersonen viele Fehler machten wenn der auditorische Reiz an einer anderen Position als der visuelle Reiz präsentiert wurde (*Experiment 5*). Für alle Versuchspersonen ließen sich mit diesem Modell sowohl die mittleren Reaktionszeiten auf visuelle Einzelreize als auch auf visuell-auditorische Einzelreize erfolgreich anpassen. Durch geringfügige Modifikationen des Modells war es möglich, anhand des aus Beobachtungen von Darbietungen der Einzelreize gewonnenen Parametersatzes quantitative Vorhersagen für Auswahlwahrscheinlichkeiten und mittlere sakkadische Reaktionszeiten in Darbietungen mit visuellen Doppelreizen zu gewinnen. Reaktionen auf auditorisch unterlegte Reize konnten dadurch sehr gut vorhergesagt werden. Abweichungen zwischen den Voraussagen des Modells und den experimentellen Befunden gab es bei Sakkaden auf nicht unterlegte Reize. Bei diesen sagte das Modell durchgängig kürzere Reaktionszeiten vorher als sie beobachtet wurden. Allerdings stellen diese Reaktionen nur einen sehr kleinen Teil der gesamten Datenmenge dar. Nicht vorhersagen ließ sich der in Experiment 4 beobachtete Effekt, daß auditorisch unterlegte visuelle Reize innerhalb einer Hemisphäre zwar häufiger als auditorisch nicht unterlegte Reize ausgewählt wurden, die Reaktionszeiten darauf aber keineswegs kürzer waren.

Es wird deshalb vorgeschlagen das Modell um eine zweite Stufe zu erweitern. Die erste Stufe wird wie bisher modelliert mit der Einschränkung, daß das Überschreiten der Schwelle jedoch nur in einer Rechts-Links-Entscheidung resultiert. Erst in einer nachfolgenden Verarbeitungsstufe wird die Richtung der Sakkade differenzierter festgelegt. Dabei wird derjenige visuelle Reiz als Blickziel ausgewählt, für den nach einer gewissen Zeitspanne die Evidenz am größten ist. Mittels einer solchen Modifikation könnten auch die in Experiment 4 beobachteten Effekte erklärt werden.

Abstract

Goal. In a series of experiments, I investigated the influence of an auditory non-target stimulus on saccadic eye movements towards visual target stimuli.

Experiment. Subjects were instructed to make saccades towards any of two visual stimuli presented at an eccentricity of 8° or 24° to the right or left of the fixation point. Additionally, via a virtual acoustic environment, an auditory stimulus (white noise) was presented at the same eccentricity as one of the visual stimuli and with an stimulus onset asynchrony (SOA) of -50, 0, or 50 ms.

Results. Although subjects were to ignore the accessory auditory stimulus, results clearly indicate that it did have an influence on responses to the visual targets. With the visual targets in opposite hemispheres, a significant preference (in terms of choice probability) for the visual target accompanied by the auditory stimulus was observed under all SOAs. Nevertheless, if the visual stimuli appeared within the same hemisphere, the influence of the auditory stimulus on the selection process was weaker.

In the bilateral stimulus condition, an auditorily accompanied stimulus was responded to significantly faster than an un-accompanied stimulus. No differentiation was observed when both targets were presented in one hemisphere.

Modeling. In order to explain these results in terms of a quantitative stochastic model, I employed the *The Multi-Channel Diffusion Model* by Diederich (1995, 1997). The model was able to make good predictions on choice probabilities for all stimulus conditions. Concerning mean reaction times the predictions for responses to accompanied stimuli were promising. However, the mean reaction times to un-accompanied stimuli were always underestimated by the model.

Contents

Chapter 1

Introduction

In natural environments, an organism must always fixate on a single target out of a large variety of potential visual targets at any time. What determines which of the stimuli is chosen? There are sensorimotor as well as attentional processes that contribute to this decision.

Traditionally, the sensory modalities have been studied in isolation from each other. There is a large number of behavioral and neurophysiological studies on the visual system that was studied most extensively from all sensory modalities. One main topic has been the investigation of the programming processes of saccadic eye movements. Saccadic eye movements are rapid, short movements of the eye, executed to bring objects of interest on the fovea. Riggs (1971) reported that for practiced observers saccadic eye movements to high-contrast visual stimuli are about 150 ms.

However, in many studies on saccadic eye movements only one target was presented at a time. Since our everyday world contains a huge variety of potential targets at the same time, selection has become a topic of major interest in current eye movement research. An experimental task frequently used to investigate the selection of a target in the visual field is the double target paradigm: Two visual stimuli are presented simultaneously at different locations and the subject's task is to perform an eye movement to any one of them. Lévy-Schoen (1969) showed, by presenting two simultaneous stimuli at opposite sides of a fixation point, that the visual system will decide for one of the two targets and that the reaction times are about 30–40 ms longer than to single control targets. This slowing was interpreted as a result of competitive processes between the two targets, i.e. a decision only can be made if one of the two targets 'wins' against the other. Since it is assumed that the targets mutually inhibit each other the reaction time with two targets might be prolonged compared to only one.

These findings were extended by Findlay (1980, 1982), showing that there are in fact two different response patterns: the described bistable pattern, (one of the two targets is selected by an exactly placed eye movement) and second, that some sort of 'global processing' takes place (the landing position of the eye movement is located somewhere between the targets).

Ottes F.P. & Eggermont (1984) demonstrated that it is the distance between the two stimuli that determines which response pattern will occur. They found that responses become bistable when two horizontally aligned targets are separated by at least 30°. They also observed a bistable response pattern when the two targets were presented at a sufficiently large distance in direction ($\Delta\phi = 90°$). But only in the second case, reaction times were prolonged significantly compared to single control stimuli.

More recent studies by Walker, Kentridge & Findlay (1995) demonstrated that distractors presented to both hemispheres can as well increase saccade latency by about 20–30 ms, and that this increase is largest if the distractor appears at the same time as the target. However, latency was still increased if the distractor was presented within an time period of 100 ms before the target stimulus. Walker, Deubel & Findlay (1997) extended their findings by postulating a reciprocal relationship between latency and amplitude effects: Distractors within a region of 20° of the target axis influence amplitude, but not latency, distractors outside this region increase latency and have no effect on amplitude. Furthermore, they found that the slowing of reaction times was most pronounced if the distractor was presented at fixation. Therefore, they concluded that the underlying processes might be similar to those which cause the so-called *gap effect*. As it was reported on several studies (e.g., Saslow, 1967; Ross & Ross, 1980; Kingstone & Klein, 1993), saccadic reaction times are much shorter if the fixation point disappears 100–200 ms before the target onset. It is supposed the gap effect resulted from two components, a non-specific warning-signal effect and a fixation disengagement-effect.

Neurological studies have provided evidence that processes of competitive inhibition from the rostral pole region of the colliculus superior might be involved in this phenomenon (Munoz & Wurtz, 1993a,b).

The double target task was useful as well to investigate the selection of visual targets. One often used operational term, was ‘visual salience’. The underlying idea was that subjects always chose the more salient target out of two.

Again, Lévy-Schoen (1969) and Lévy-Schoen & Blanc-Garin (1974) were the first to demonstrate that salience was especially influenced by the proximity to the fixation point: The target that was closer to the fovea was more likely to be fixated than the more peripheral one. They tried to compensate for this spatial bias by delaying the onset of the near target.

Findlay (1980) extended these findings to quantitative measures. He presented two visual stimuli with different size and proximity to the fixation point. In most cases he was able to compensate for the effects of proximity by varying the size of the other target. One explanation for these findings was that increasing the size of a target raises cortical activation to a level equivalent to a proximal target. Deubel, Wolf & Hauske (1984) added the finding that eccentricity can as well be compensated by increasing the intensity of a stimulus instead of the size.

Fewer studies were taken to investigate voluntary saccades to auditory stimuli. Riggs (1971) reported latencies of about 110–120 ms for auditory-evoked saccades. Yao & Peck (1997) found that the accuracy of saccades to auditory stimuli at 10° did not differ significantly from those to visual stimuli. Only at eccentricities of 20° or more auditorily elicited saccades were less accurate than visually elicited ones. Furthermore they found that—in contrast to saccades to visual stimuli—reaction times were the shorter the larger the desired change in eye position was: When subjects had to fixate a central point saccades to auditory targets at 30° were faster than to targets at 20° or less. Frens & Van Opstal (1995) investigated auditory-evoked saccades in the two-dimensional frontal plane. They found that localization was good for both azimuth and elevation, if the auditory stimulus was a broad band noise of long (500 ms) duration. Furthermore they found that the latencies depended on the saccadic amplitude and not on the direction of the eye movement. This was already observed by Zahn, Abel, Dell'Osso & Daroff (1995) and has been interpreted as evidence for a occulocentric representation of auditory localization.

Recently, Heuermann & Colonius (1999) studied the localization in virtual environments compared to free field conditions with saccadic eye movements. They found that localization in the horizontal plane under virtual conditions was as good as under free field conditions.

While the findings reported so far refer to only *one* modality, in the last decade interest on the integration of the senses has grown. It was criticized on the traditional research that, since on natural environments organisms use information from different sensory modalities, studying one modality in isolation could lead "to only partial understanding of everyday perceptual experience" (Welch & Warren, 1986, p. 25-2). Therefore, it was suggested to take into account interaction processes between the different modalities. Welch & Warren defined *intersensory interaction* operationally as 'situation in which the perception of an event as measured in terms of one sensory modality is changed in some way by the concurrent stimulation of one or more other sensory modalities'. Stein & Meredith (1993) provide a good overview on intersensory effects. Several studies have shown that presenting multimodal stimuli leads to better results than presenting only unimodal stimuli. This is called the *intersensory facilitation effect.* An often used paradigm to investigate the intersensory facilitation effect is the focused attention paradigm. In this task a reaction to a special stimulus is to be performed, e.g., an eye movement to a small light dot, ignoring all additional stimuli, such as auditory distractors.

By presenting near-threshold visual stimuli to cats, Stein, Huneycutt & Meredith (1988) showed that localization accuracy improved, if an auditory stimulus was added at the location of the visual stimuli. Kurylo, Vimal & Hartline (1992) extended these findings to double stimuli. They trained cats to look at briefly flashed visual or auditory stimuli. After this training period, they presented in some trials also double targets, either two visual, or two auditory, or two disparate bimodal targets. In all double target conditions, cats made saccades to positions intermediate between the two presented stimuli. Therefore, Stein et al. (1988) concluded that the spatial information on all double targets was combined at a common stage in the same way no matter whether presented across modalities or within one modality.

The intersensory facilitation effect was also found in a number of behavioral studies with human observers.

Engelken & Stevens (1989) instructed subjects to track a visual and/ or auditory target as quickly and accurately as possible. Saccades to bimodal stimuli were about 11.3% shorter compared to visual stimuli, but only if the auditory stimulus had an onset synchronous with the visual one. Since this reduction occurred even if the auditory stimulus was presented at an overhead position providing no localization cue, they concluded that the observed reduction can be explained solely as 'warning effect'. However, in most studies the localization of the auditory stimulus with respect to the visual stimulus does have a strong influence on the observed reaction times.

Frens, Van Opstal & Van d. Willungen (1995) asked subjects to perform an eye movement toward a visual target and to completely ignore an auditory co-stimulus. They reported that if the target was spatially aligned with an additional auditory stimulus saccadic eye movements were about 50 ms faster than when of a solely visual stimulus was presented. But this speed-up disappeared when the auditory stimulus was presented in the contralateral hemisphere of the visual stimulus or when subjects could not localize the auditory stimulus properly. No influence was found irrespective of the visual and auditory stimuli were at high or at low intensity. On the other hand, the relative timing of the visual and auditory stimulus had a strong effect on saccadic latency: Latencies were shortest with the auditory stimulus presented 50 ms *before* the visual stimulus. This is surprising, since it is known that the processing times for auditory stimuli are about 40 ms shorter than for visual stimuli. Therefore, both stimuli should reach a common stage if the auditory stimulus was presented about 40 ms *after* the visual one and not before it. So the auditory stimulus might as well have served as an 'alerting cue' in this task.

In a similar task, Hughes, Nelson & Aronchick (1998) found that saccade latencies were reduced in bimodal (visual-auditory) trials, especially if both stimuli were at the same location, but even if the auditory stimulus was presented at a distance of 30° and into the contralateral hemifield. They demonstrated that the observed facilitation was greater than one would expect from the observed unimodal reaction times.

Recently, Colonius & Arndt (2001) have studied the spatial-temporal relationship between visual target and auditory accessory stimulus in more detail. They required subjects to look as fast as possible at a visual target ignoring an irrelevant auditory stimulus. The auditory stimulus was located at a distance of 0°–55° from the visual target and was presented at the same time or with different time intervals before and after the visual target. Reaction times were fastest when the auditory stimulus was presented at the same location as the visual one and about 30 ms before the visual one. Fig.1.1 shows the observed reaction times for different spatial-temporal arrangements between the visual and the auditory stimulus for subject MI.

Presenting an auditory co-stimulus also improved the performance in more complex tasks, e.g., in the visual search paradigm. In this task, subjects are to identify a target

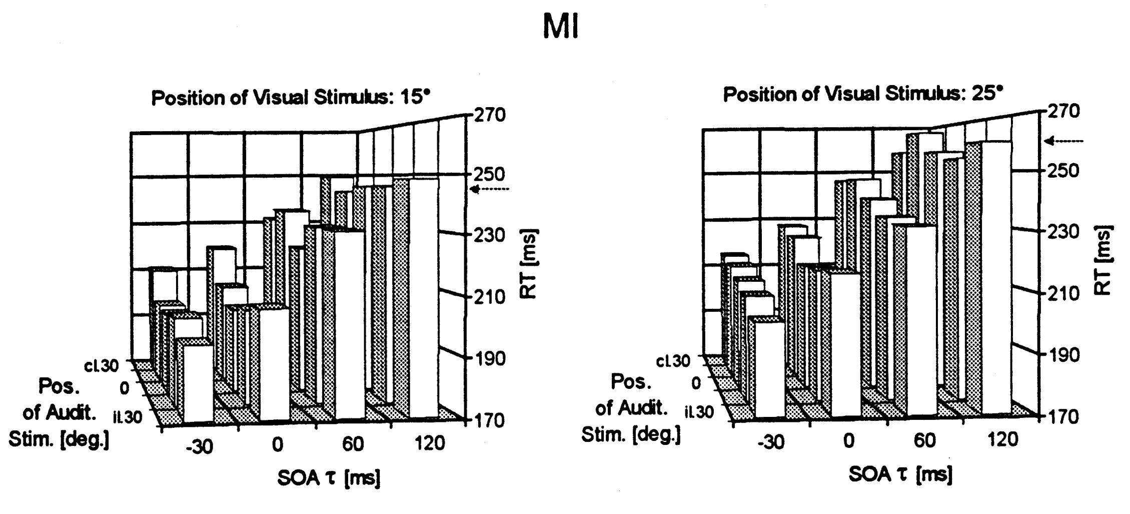

Figure 1.1: Results from Colonius & Arndt (2001): Mean reaction time is shorter if the auditory stimulus precedes the visual stimulus and is presented at the same position.

stimulus within a set of distractor stimuli. Perrott & Cisneros (1996) showed that subjects were able to localize and identify a visual target much better, if this search was aurally aided.

There are two different approaches to model the observed facilitation effect. Early models argued that the speed-up is caused simply by probability summation. They assume that both visual and auditory channel are processed independently and that their reaction latency distributions overlap. As soon as either of the two processes is finished, a reaction is performed. Because of this 'race' between two channels, the term *race models* (Raab, 1962) was coined. The upper limit of facilitation such models can predict is given by the sum of the cumulative reaction latency distributions to the auditory and the visual stimulus alone (Miller, 1982). This is often referred to as *race inequality.* Since the observed facilitation exceeds this boundary in most multimodal studies, the interest in race models has diminished. Furthermore Nickerson (1973) noted that Raab (1962)'s model was developed 'to account for the results obtained in situations in which the subject responds on every trial and is free to adopt the strategy of responding either to the visual or to the auditory stimulus, whichever he detects first.' (p. 493). Therefore, they can not be used to explain the results observed in the focused attention paradigm. However, Hughes, Reuter-Lorentz, Nozawa & Fendrich (1995) observed violations of the race inequality in focussed attention paradigms as well.

As an explanation for these violations as documented in numerous studies, it was argued that some sort of 'energy summation' accross the sensory modalities must occur (Bernstein, Rose & Ashe, 1970). The basic idea of these so called *coactivation models* is that input from different modalities is collected and a response is elicited, if the common activation exceeds a threshold. An implicit consequence of this idea is that increasing the intensity of the visual stimulus is equivalent to adding an auditory accessory stimulus to it. However, this does not resemble the findings observed in the focussed attention paradigm since there are very few errors (reactions to the irrelevant auditory stimulus) in auditory catch trials even if the intensity of the auditory stimulus was increased relative to the intensity of the visual stimulus (Bernstein, Briggs & Schurman, 1973). This problem can be solved by assuming that the contribution of the auditory stimulus to the energy-summation is weighted by the subject. So if the contribution of the auditory stimulus is set very low and the threshold sufficiently high, no response will be elicited in auditory catch trials. One coactivation model that was used successfully to explain the intersensory facilitation with three modalities (visual, auditory and tactile) is the Multi-Channel Diffusion Model by Diederich (1992). It will be described in more detail in Chapter 3 since it was used to model the data of this study.

The original form of coactivation models does not consider any spatial relationships between the visual and the auditory stimulus. Therefore, they can not offer a straightforward explication of why facilitation is greater if the auditory accessory stimulus is presented at the same position as the visual stimulus in contrast to a presentation to the contralateral hemisphere. However, these models can be further worked out to do so. One might assume that the weighting of the auditory stimulus decreases with its distance to the visual stimulus.

The *Two stage model for visual-auditory interaction*, recently published by Colonius & Arndt (2001) assumes such a kind of relationship to account for the observed influence of the spatial arrangement.

In detail, the model suggests two different processing stages with stochastically distributed duration times. In the first stage, both sensory modalities are processed independently from each other. It is assumed that a race between the two modalities takes place and only if the auditory stimulus wins this race, interaction occurs in a subsequent stage. The amount of interaction is a function of the spatial relationship between the visual and the auditory stimulus.

To integrate the various results of studies on stimulus-elicited saccades into a comprehensive framework, Findlay & Walker (1999) have recently presented a model of saccade generation. Their model can be considered as an extension of the model proposed in the late 1970s by Becker & Jürgens (1979). It is based on the idea of parallel processing of spatial and temporal information. The model resembles this duality by maintaining two separate pathways, denoted as WHEN- and WHERE-pathway. Inside each pathway, several levels of processing (cognitive, reflexive etc.) simultaneously influence the decision stage of the respective pathway, thus delaying or accelerating a saccade (temporal) or shifting its landing point in some way (spatial). To determine the endpoint of a saccade, the WHERE-pathway employs a scheme of mutual inhibition among different peripheral locations. This type of interaction is well suited to explain spatial effects such as the 'remote distractor effect' and the 'global effect'.

The mutual inhibition architecture is believed to have a neural substrate in the superior colliculus (SC). The SC is an non-cortical structure of the brain that is thought to play an important role in saccade generation in general and in multimodal interaction in particular (Sparks, Holland & Guthrie, 1976; Sparks, 1978; Wurtz & Optican, 1994).

Several researchers assume that during visual fixation so called 'fixation neurons' in the rostral pole of the SC are active (see, e.g. Munoz & Wurtz, 1993a). When a new target appears, these neurons are inhibited. Before an eye movement is executed, activity occurs at the location in the SC where the new target is represented.

The SC is divided into the superficial (I–III) and the deep layers (IV–VII). Fig. 1.2 provides a schema of the cat SC.

While the superficial layers only receive visual input, the deep layers process also multimodal inputs (Meredith & Stein, 1986; Sparks & Nelson, 1987).

There are many neurons that respond to auditory, somatosensory and/or visual stimulation. Meredith & Stein (1986) measured the activity of neurons in cats and found neurons that responded only if they were stimulated by inputs in two different sensory modalities. Furthermore it was found that the receptive fields of the multisensory neurons are large and respond foremost simply to the presence of a stimulus. Besides this, it is assumed that there is a topographical representation for visual and tactile as well as for auditory stimuli (Stein, Magalhaes-Castro & Kruger, 1976; Gordon, 1973). This is surprising since it is known that the location of a stimulus is encoded differently for the sensory modalities. The localization of a visual target is, for example, provided by retinotopic coordinates whereas the localization of an auditory stimulus is first tonotopic and then makes use of head-centered cues (e.g., interaural differences in timing and intensity). However, Gordon (1973)'s experiments in paralyzed cats suggest that these representations are aligned. The activity of a lot of the collicular neurons is enhanced, if there is an additional stimulus in another modality at the same location. On the contrary, many collicular neurons show reduced activity relative to the activity in unimodal trials if the bimodal stimuli are spatially separated. Stein & Meredith (1993) provide a good

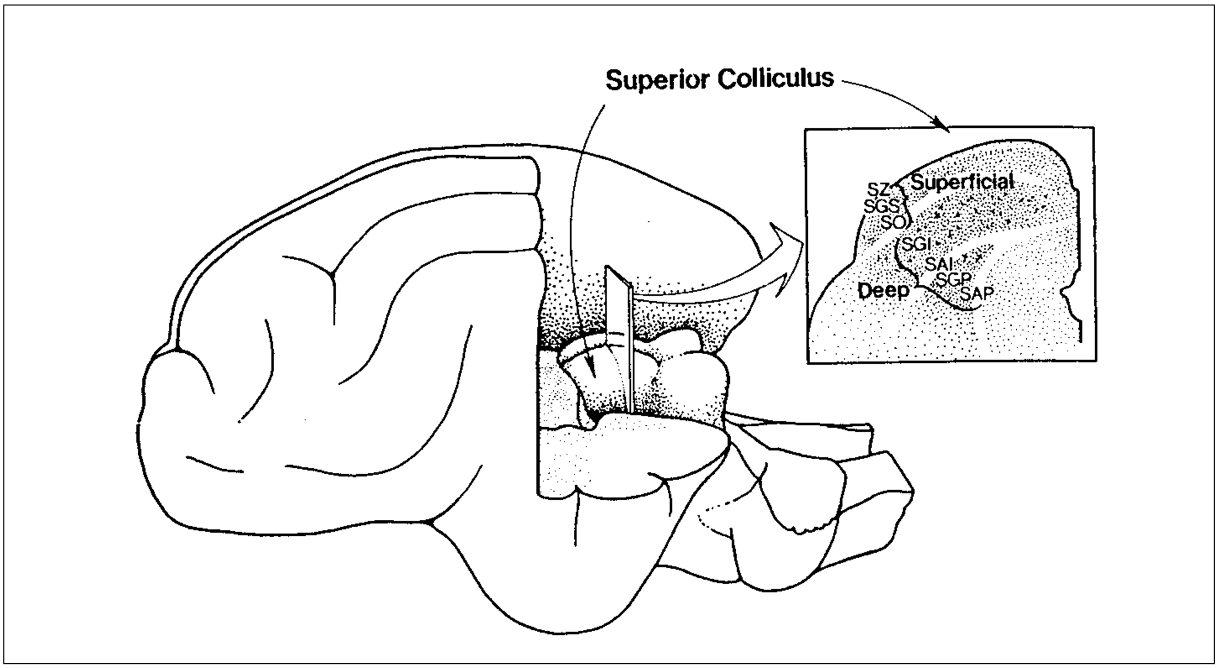

Figure 1.2: Schema of the location and laminar pattern of the cat superior colliculus (SC) (from Stein & Meredith, 1993, p. 42)

summary of single-cell studies on multimodal neurons.

Jay & Sparks (1987) suggested that the sensory maps might be organized in motor coordinates. They found in monkeys that the receptive fields of sound-sensitive neurons in the SC shifted with changes in the eye position. However, such a shift was not found in all experiments (e.g., Harris, Blakemore & Donaghy, 1980) and it is still not clear how the different modalities are transferred in a common reference system.

Meredith, Nemitz & Stein (1987) investigated the influence of the timing between the visual and auditory stimuli on multisensory interaction. From cell studies in cats, they concluded that interaction might be produced not by overlapping onsets of the stimuli but by overlapping discharge trains since the observed enhancement or depression was often greatest when the two stimuli were presented temporally disparate.

The aim of this study is to investigate the influence of an auditory stimulus on the selection between two visual stimuli. Whereas previous studies concerned on target selection in only the visual modality, I expand the paradigm to a bimodal design. This study intends to quantify the effects of visual-auditory interaction. The main questions are: Does an auditory stimulus increase the selection probability of a visual target at the same location? And second, are the reaction times to a visual target shorter if an auditory stimulus is present?

In Chapter 2, five experiments are reported. In two experiments (Experiment 1 and Experiment 4), subjects had to select one of two visual stimuli, ignoring an additional auditory stimulus. Whereas in Experiment 1 the inner stimulus was delayed in time, in Experiment 4, the intensity of the more eccentric was increased relative to the other stimulus.

Experiments 2 and 3 were designed to investigate subjects' performance in localizing the auditory stimulus.

The last experiment reported here, is a control study to learn about subjects' ability to ignore an auditory stimulus. In this experiment only one visual stimulus was presented and the task was again to gaze at the visual stimulus ignoring the auditory stimulus. But unlike as in the former experiments, the auditory stimulus was presented not only at the same location as the visual one. Therefore, subjects were able to make 'errors' by looking at the auditory stimulus instead of the visual stimulus.

In Chapter 3, a model to explain the observed data is presented. The Multi-Channel Diffusion Model proposed by Diederich (1992, 1995, 1997) was already successfully used to predict simple reaction times to multi-sensory stimuli. Since it also provides predictions of choice probabilities in selection tasks, it provides a promising approach for modeling the data observed in this study.

In Chapter 4, I present predictions on reaction times and choice probabilities for two exemplary subjects. Therefore, I first estimate parameters for the Multi-Channel Diffusion Model from conditions with only one visual or auditory-visual target (*single target condition*). In a second step, I use these values to make quantitative predictions for the conditions with two visual targets (*double target condition*).

The last chapter summarizes the main findings and provides a short discussion. In Appendix A a short theoretical background information for the Multi-Channel Diffusion Model is presented. The Appendices B through C.2.4 provide the data for all the subjects not presented in the text.

Chapter 2

Experiments

Five experiments are reported. While Experiment 1 and Experiment 4 study the effects of an auditory accessory stimulus on reaction time and choice frequency with two visual stimuli, Experiment 2 and Experiment 3 were conducted to investigate the ability to localize the auditory stimuli used in all experiments. Experiment 5 studies subjects' ability to ignore the auditory stimulus.

2.1 General methods

This section describes the experimental setup as far as it was identical for all experiments reported here.

2.1.1 Apparatus

Fig. 2.1 shows the experimental setup. Subjects were seated in a dark, sound attenuated chamber (1.0 m × 1.2 m × 1.9 m). To prevent subjects from moving their heads, they were fixated by a bite bar. At a distance of 57 cm, behind a window (74.5 cm × 59 cm), there was a 37 inch monitor (NEC, Multisync XP-3778G(A)) on which all visual stimuli were displayed. Auditory stimuli were presented via headphones (AKG K 1000) by a high performance sound card (Tahiti, Turtle Beach). Eye movements were recorded by an infrared light reflecting system (IRIS, Skalar Medicals) which provides linear signals in the range between $-25°$ and $25°$ in the horizontal plane. Taking into account the errors due to calibration and digitalization of the signal the spatial accuracy was about 12 min of arc. All experiments were controlled by computers: A 486 Personal Computer served for stimulus presentation and a Pentium-PC for data recording (sampling rate: 1 kHz). Both PCs were synchronized with the onset of the visual stimulus determined by the monitor update rate (13.3 ms) to guarantee the exact temporal presentation of the stimuli.

2.1.2 Stimuli

Visual stimuli. The visual stimuli were white dots (diameter: 0.1°, intensity: 11 cd/m^2) presented against a dark background at eccentricities of 8° right, 24° right, 8° left and 24° left of the fixation point.
Auditory stimuli. The auditory stimuli were white noise signals with a sharp rise in

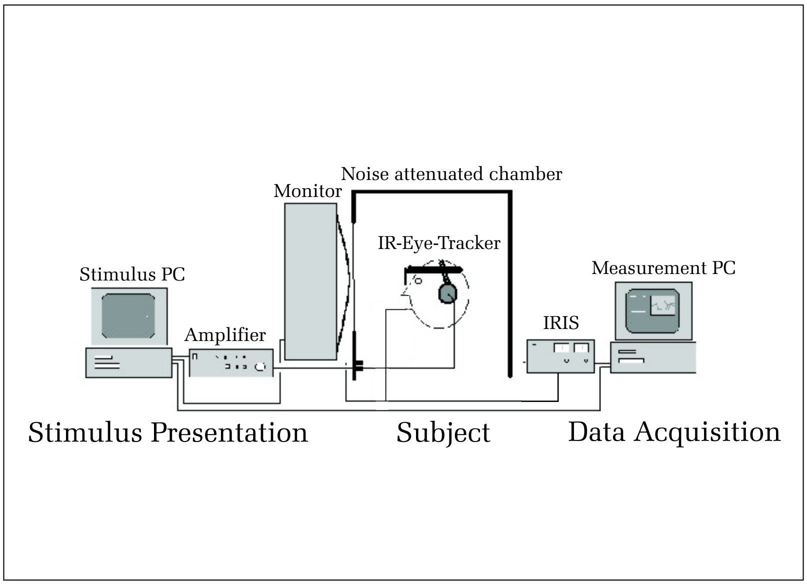

Figure 2.1: Schematic diagram of the apparatus used in all experiments.

energy (5 ms), generated from HRTFs and headphone transfer functions of a dummy head (Oldenburger Kunstkopf). They were produced for four eccentricities: 8° right, 24° right, 8° left and 24° left of the fixation point and had an intensity of 59 dB SPL. This intensity level was used since it was found in a pretest that subjects on average perceived the auditory stimulus as intensive as the visual stimulus.[1]

2.1.3 Data analysis

Data were analyzed off-line using a Matlab program. All trials were checked visually by the experimenter and were excluded from further analysis if fixation was not held correctly or subjects performed blinks. In order to determine the beginning and the end of a saccade I used velocity and acceleration criteria.[2] Reaction time was defined as the time between the onset of the visual stimulus and the beginning of the eye movement. Since only saccades that began between 80 and 500 ms after the onset of the visual target stimulus were judged as being evoked by the presented stimulus arrangement, saccades outside this time window were disregarded. The saccadic amplitude was calculated as the visual angle between the start position and the end position of the eye movement.[3] When the stimulus appeared at 24°, some subjects often performed two very fast subsequent saccades to reach the visual target. For these saccades, I defined the end position as follows: If the second movement started within a time interval of 60 ms after the end of

---

[1] For the pretest, I asked four subjects to adjust the intensity of the auditory stimuli at 8° and at 24° manually to match that of the visual stimulus (intensity: 11 cd/m^2) presented at the same position. During this task subjects always had to gaze at the fixation point.

[2] The criteria for the onset of the saccade defined for each subject ranged from 45°/ms to 65°/ms, for the off-set from 20°/ms to 40°/ms

[3] Data were standardized on data samples to controlled positions made in a calibration procedure. The calibration procedure was conducted before and after each experimental block. If the amplitudes of saccades to stimuli at 24° calculated with the two calibrations deviated more than 5° from each other, the whole block was repeated.

the first, it was considered as *one* movement, and the amplitude was calculated as the distance from the start position before the first movement to the end position of the second movement (type I). If the second movement appeared more than 80 ms after finishing the first movement, the saccades were treated as two separate saccades and therefore, the amplitude was calculated as the visual angle between the starting and endpoint of the primary saccade (type II). If the second movement set in somewhere in between 60 and 80 ms after the first one, I discarded the trial, since I could not decide to which of the two types the saccade belonged. Saccadic eye movements were classified into one of four possible orientations of gaze, i.e. 8° left or right or 24° left or right. The maximum allowed deviation from either of these positions was ±2 standard errors of the amplitude to that visual stimulus when presented alone.[4] Saccades whose amplitudes fell outside this region were excluded from further analysis. These strict criteria for accepting a saccade lead to rather high drop out rates ranging from 12% to 19% in Experiment 1 and from 6% to 29% in Experiment 4.

2.2 Experiment 1: The influence of an auditory accessory stimulus on target choice and reaction time with two visual stimuli

In this experiment, I investigated the influence of an auditory accessory stimulus on the selection of one out of two visual targets with the same intensity. Subjects were asked to gaze at any one out of two visual target stimuli and to ignore the auditory stimulus. However, I had observed in a pretest that subjects nearly always looked at the visual stimulus closer to the fixation point. To avoid ending up with an extremely poor database for gazes at stimuli at 24°, I decided to compensate for the effects of eccentricity. Therefore, the stimulus at 24° was presented 2 monitor cycles (26.6 ms) before the one at 8°.[5]

2.2.1 Subjects

Five subjects (*mi*, *ld*, *rv*, *cs*, *cp*), aged 15 to 26 years, with normal (or corrected to normal) auditory and oculomotor function participated in this experiment. All subjects were well-trained in this task but naïve with respect to the specific aim of the study.

2.2.2 Stimulus arrangement

Visual stimuli were presented either as a stimulus pair (= experimental condition) or as a single stimulus (= control condition). As mentioned above, if the visual stimulus pair

---

[4] Because the amplitudes in the presentation of purely visual trials were not significantly different from the amplitudes performed in audio-visual trials, I pooled these data to gain a greater data base.

[5] In a pretest presentation of the visual stimulus pair 8° right/24° left or 8° left/24° right, most subjects gazed at the 24°-stimulus when the stimulus at 8° was presented with a delay of 3 monitor cycles or 39.9 ms. Because of technical restrictions no finer temporal spacing than in monitor cycles was possible. So I decided to present the 24°-stimulus only 2 monitor cycles (26.6 ms) earlier than the 8°-stimulus, since this was still the ‘natural reaction’ but somewhat more balanced.

consisted of one stimulus at 8° and one at 24°, the presentation of the stimulus at 8° was delayed 26.6 ms relative to that of the stimulus at 24°. The auditory stimulus was presented at the same location as one of the two visual stimuli either 50 ms before, after or at the same time as the visual stimulus. I refer to this temporal visual-auditory relationship as *Stimulus Onset Asynchrony (SOA)*. Positive values indicate in which amount of time (in ms) the auditory stimulus was presented *after* the visual stimulus and negative values in which amount of time (in ms) the auditory stimulus was presented *before* the visual stimulus. In the audio-visual trials, the fixation point disappeared simultaneously with the auditorily accompanied stimulus.

All configurations were presented in a single experiment (9 sessions, 3 blocks each). Every stimulus condition was measured 54 × for each audio-visual condition and 81 × for each purely visual condition. So the total number of trials was 2997 trials (9 × 81 purely visual trials + 42 × 54 audio-visual trials) for each subject.

Table 2.1 shows the presented stimulus combinations and their abbreviations used in the following for trials with one visual stimulus or with two stimuli. For simplicity, only one possibility is illustrated for each visual stimulus pair, although the symmetrically reversed stimulus constellation was presented as well, e.g., the visual stimulus pair 24° right/8° left also includes the visual stimulus pair 8° right/24° left.

2.2.3 Procedure

Each trial started with the presentation of a small fixation point in the centre of the screen (diameter: 0.1°, intensity: 11 cd/m^2). After a random time interval of 850 to 3990 ms, the fixation point disappeared and one (*single target condition*) or two visual stimuli (*double target condition*) were displayed simultaneously. In some trials, there was also an auditory accessory stimulus presented with one out of three SOAs at the same location as the visual one or—if *two* visual stimuli appeared—as *one* of them.[6]

The SOA between the auditory and the visual stimulus was always computed with respect to the particular visual stimulus at whose location it was presented (*accompanied stimulus*). Reaction time was defined as the time between the onset of the *chosen* visual stimulus and the beginning of the eye movement to this stimulus.

2.2.4 Differences in reaction times of saccades to single versus double visual stimuli

Generally, saccadic reaction time averaged over all subjects for single stimuli was shorter for saccades to stimuli at 8° than to stimuli at 24° (8° left: 195 ms, 8° right: 192 ms, 24° left: 222 ms, 24° right: 224 ms).

To test for differences in reaction times to single versus double visual stimuli, repeated measurement ANOVAs with the within factors *number of visual stimuli* (one or two) and

---

[6] In the trials in which the two visual stimuli were presented at different times, the fixation point was switched off by the auditorily accompanied stimulus. In the purely visual trials, the fixation point disappeared in the stimulus conditions 8° right/24° left and 8° left/24° left when the stimulus at 24° was presented, and in the stimulus conditions 8° left/24° right and 8° right/24° right when the stimulus at 8° was presented. However, I tested in a control study whether reaction times differed if the fixation point was switched off by the first appearing stimulus. I found the same tendency, but—under this condition—the influence of the auditory stimulus seemed weaker in the stimulus constellation 8° right/24° right.

Table 2.1: Stimulus conditions for Experiment 1.

Visual stimulus pair:	**Position of stimuli**	**SOA**	**abbreviation**
8° **right**/8° **left**	visual stimulus at 8° right		8V
	+ auditory stimulus at 8° right	−50 ms	8AV-50
	+ auditory stimulus at 8° right	0 ms	8AV0
	+ auditory stimulus at 8° right	50 ms	8AV50
	visual stimulus at 8° left		-8V
	+ auditory stimulus at 8° left	−50 ms	-8AV-50
	+ auditory stimulus at 8° left	0 ms	-8AV0
	+ auditory stimulus at 8° left	50 ms	-8AV50
8° **right**/24° **left** 24° **right**/8° **left**	visual stimulus at 8° right		8V
	+ auditory stimulus at 8° right	−50 ms	8AV-50
	+ auditory stimulus at 8° right	0 ms	8AV0
	+ auditory stimulus at 8° right	50 ms	8AV50
	visual stimulus at 24° left		-24V
	+ auditory stimulus at 24° left	−50 ms	-24AV-50
	+ auditory stimulus at 24° left	0 ms	-24AV0
	+ auditory stimulus at 24° left	50 ms	-24AV50
8° **right**/24° **right** 8° **left**/24° **left**	visual stimulus at 8° right		8V
	+ auditory stimulus at 8° right	−50 ms	8AV-50
	+ auditory stimulus at 8° right	0 ms	8AV0
	+ auditory stimulus at 8° right	50 ms	8AV50
	visual stimulus at 24° right		24V
	+ auditory stimulus at 24° right	−50 ms	24AV-50
	+ auditory stimulus at 24° right	0 ms	24AV0
	+ auditory stimulus at 24° right	50 ms	24AV50

SOA (−50 ms, 0 ms, 50 ms, no auditory stimulus) were performed for each stimulus constellation, separately for reactions to stimuli at 8° right or left and to stimuli at 24° right or left.

For the visual stimulus pair 8° right/8° left (see Fig. 2.2), I found significant main effects and no interaction effect (for the number of visual stimuli: $F(1,4) = 38.49$; $p < 0.01$, for SOA: $F(3,12) = 65.93$; $p < 0.01$): If two visual stimuli were presented, reaction times were prolonged for all SOAs.

For the visual stimulus pairs 24° right/8° left and 8° right/24° left the results had the same overall tendency for saccades to stimuli at 8° (for the number of visual stimuli: $F(1,4) = 27.46$; $p < 0.01$, for SOA: $F(3,12) = 59.65$; $p < 0.01$) as can be seen in Fig. 2.3. For saccades to stimuli at 24° (see Fig. 2.4) I found significant effects for SOA and the interaction between SOA and number of visual stimuli, although they were much smaller than observed with 8°-stimuli. When the auditory stimulus was presented late

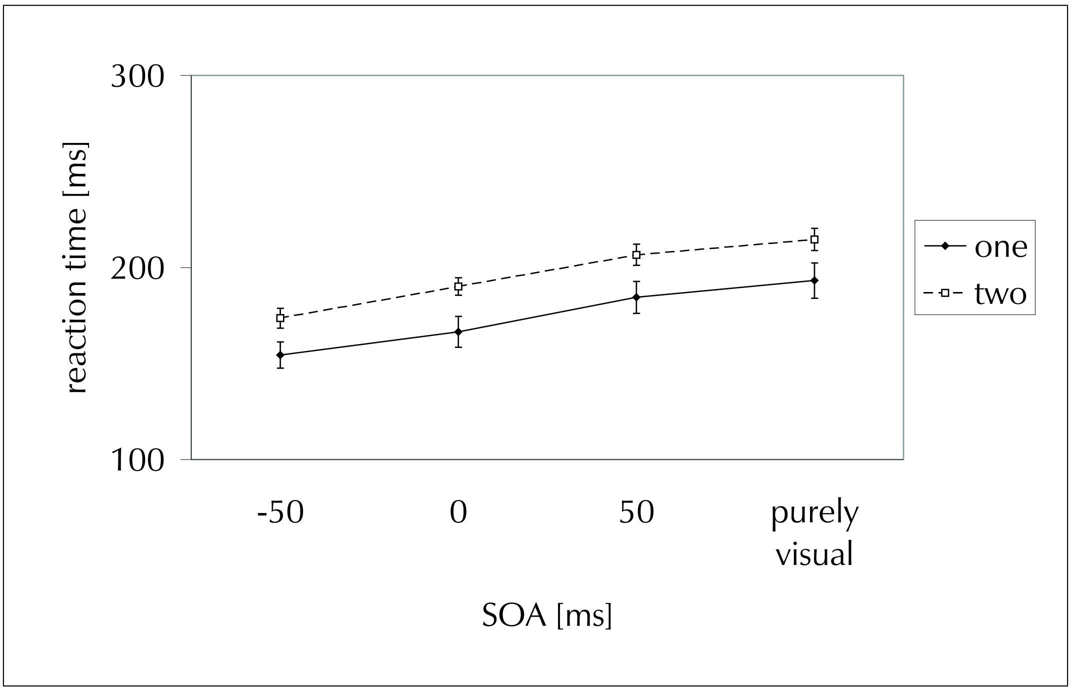

Figure 2.2: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 8° right or left, averaged over five subjects.

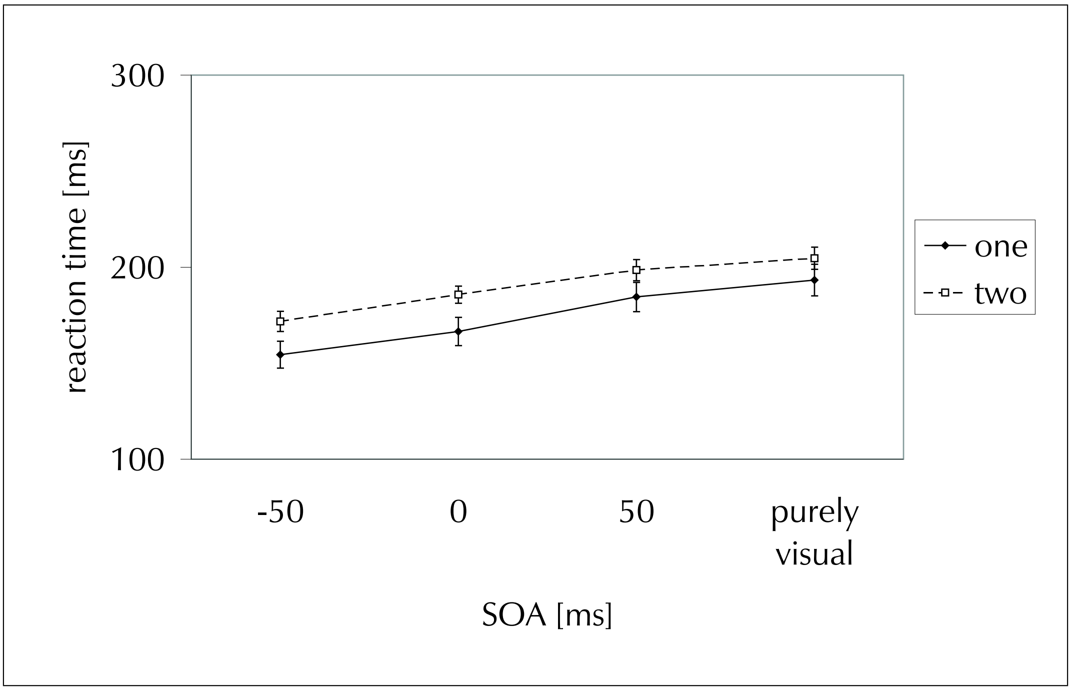

Figure 2.3: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 8° right or left for the visual stimulus pair 24° right/8° left or the visual stimulus pair 8° right/24° left, averaged over five subjects.

(SOA = 50 ms) or not at all, reaction times were more prolonged than when the auditory stimulus was presented at the same time or even earlier than the visual stimulus (for SOA: $F(3,12) = 52.44$, $p < 0.01$, for $SOA \times Number$: $F(3,12) = 3.63$, $p < 0.05$).

If the visual stimuli appeared within the same hemisphere (visual stimulus pair 8°/24° left or right, only the SOA became significant, for both saccades to stimuli at 8° (see Fig. 2.5) as well as to stimuli at 24° (see Fig. 2.6) (for saccades to stimuli at 8°: $F(3,12) = 44.69$, $p < 0.01$, for saccades to stimuli at 24°: $F(3,6) = 23.28$, $p < 0.01$). In this stimulus constellation, no slowing down of reactions with two visual stimuli was observed.

2.2.5 The influence of the auditory stimulus on visual stimulus pairs

In an investigation on the influence of an auditory stimulus on visual stimuli one might ask two questions:

1. Is the response faster to a visual target stimulus if it is accompanied by an auditory stimulus?
2. Is the gaze frequency to a visual target stimulus higher if it is accompanied by an auditory stimulus?

I will try to provide answers to both questions in the next sections.

2.2.5.1 Gaze frequency

When comparing the gaze frequencies to purely visual stimuli, it became obvious, that all subjects had a preference for one hemisphere (*bias*).Three of the subjects (*mi, ld, cp*) were biased to the right hemisphere and two (*rv, cs*) to the left hemisphere. Therefore, this bias seemed not due to errors in the experimental design but to some individual preference.

To test whether the auditory stimulus had an influence on gaze frequency a Pearson 2×3-χ^2-Test was performed separately for each subject and each visual stimulus pair. For the visual stimulus pair 8° right/8° left three out of five subjects showed significant shifts of gaze (*ld*: $\chi^2 = 23.16$, $p < 0.001$; *cs*: $\chi^2 = 7.32$, $p < 0.05$; *cp*: $\chi^2 = 60.74$, $p < 0.001$).
If the two visual stimuli appeared at a distance of 32° from each other, i.e. the visual stimulus pair 24° right/8° left or the visual stimulus pair 8° right/24° left, I found significant differences for all subjects (*mi*: $\chi^2 = 71.64$, $p < 0.001$; *ld*: $\chi^2 = 101.89$, $p < 0.001$; *rv*: $\chi^2 = 21.07$, $p < 0.001$; *cs*: $\chi^2 = 54.79$, $p < 0.001$; *cp*: $\chi^2 = 154.93$, $p < 0.001$). Furthermore, for stimuli at 24° there was a greater shift of gaze frequency than for stimuli at 8°. One reason for this is that stimuli at 8° were still much more frequently selected than stimuli at 24° and so had a much smaller ‘potential for gain’.
When the visual stimulus pair appeared within one hemisphere, all but one subject (*cp*) showed significant differences between observed and expected frequencies (*mi*: $\chi^2 = 10.69$, $p < 0.01$; *ld*: $\chi^2 = 23.74$, $p < 0.001$; *rv*: $\chi^2 = 10.26$, $p < 0.01$; *cs* for stimuli at

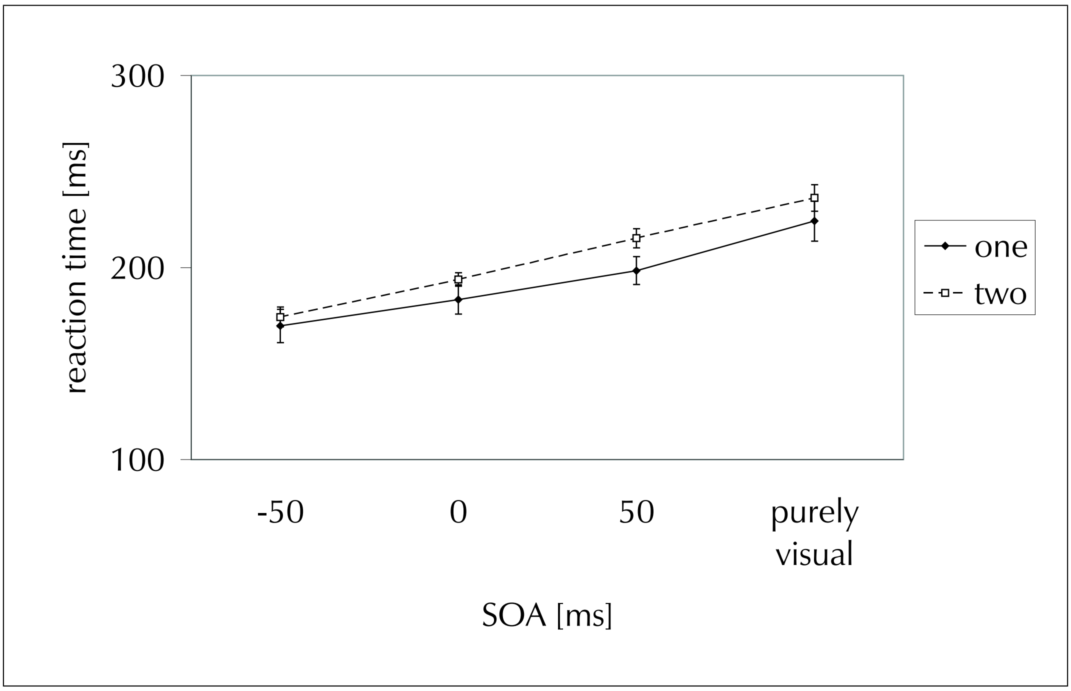

Figure 2.4: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 24° right or left for the visual stimulus pair 24° right/8° left or the visual stimulus pair 8° right/24° left, averaged over five subjects.

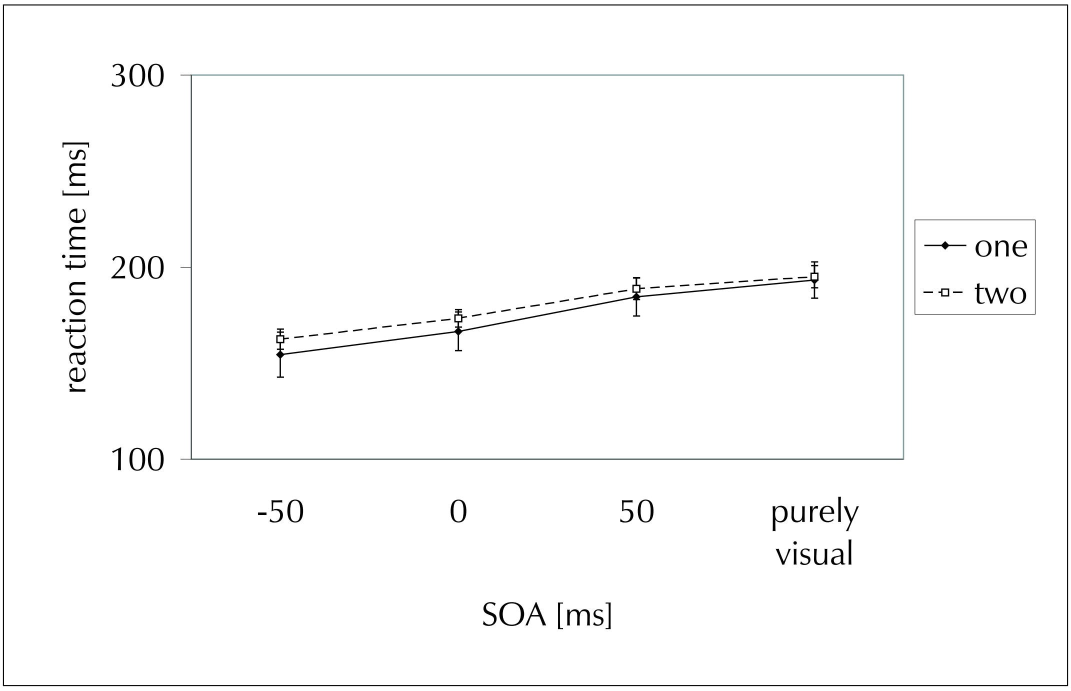

Figure 2.5: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 8° right or left for the visual stimulus pair 8° right/24° right or the visual stimulus pair 8° left/24° left, averaged over five subjects.

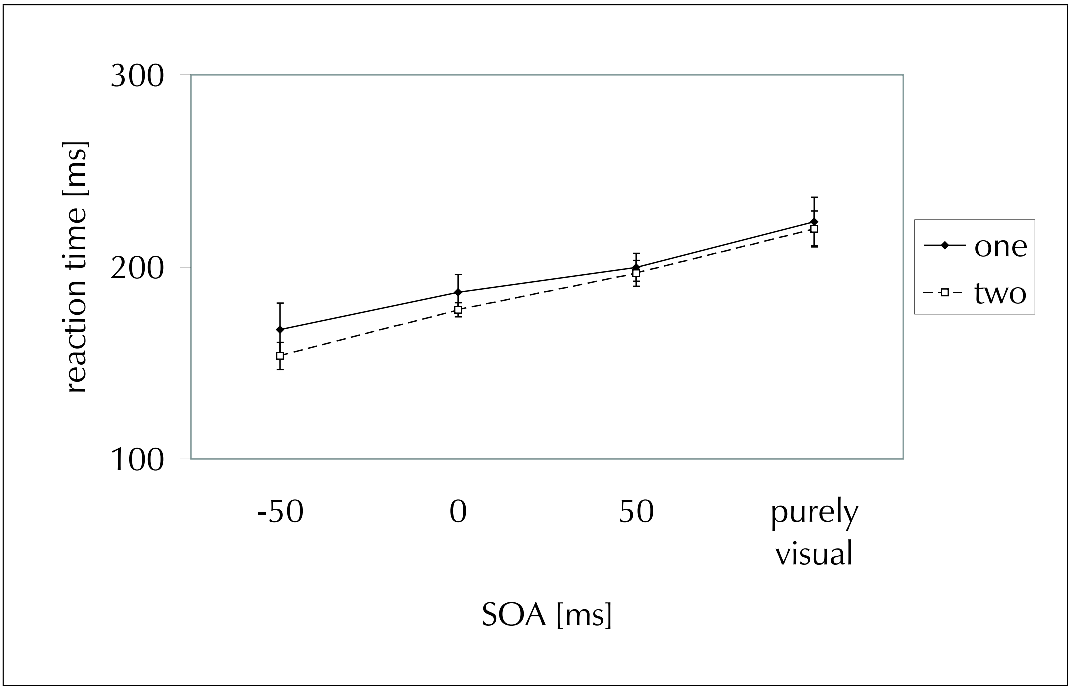

Figure 2.6: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 24° right or left for the visual stimulus pair 8° right/24° right or the visual stimulus pair 8° left/24° left, averaged over five subjects.

24°: $\chi^2 = 8.14$, $p < 0.01$).[7] Furthermore, orthogonal comparisons revealed that this was due to the shift to auditorily accompanied stimuli at 24°.

2.2.5.2 Reaction times

To investigate the influence of the auditory stimulus on reaction times, repeated measurement ANOVAs were performed.[8] Since the effects were the same for both hemispheres, stimuli at 8° left and right as well as stimuli at 24° left and right were pooled. Data were also pooled over the three SOAs, since otherwise the data base would have been too small.[9]

Therefore, two factors *preference of bimodal stimulus* and *stimulus constellation* were included in analysis. For the factor *preference of bimodal stimulus* the levels were

1. gazing at an auditorily accompanied stimulus, and

---

[7] Since for the subjects *cs* and *cp* the expected cell frequencies were below 5 datapoints, I used Fisher's exact statistics to analyze the following two 2 × 2 crosstabs:

1. Frequency of gaze to auditorily accompanied stimuli vs. un-accompanied stimuli at 8°.
2. Frequency of gaze to auditorily accompanied stimuli vs. un-accompanied stimuli at 24°.

[8] I decided for a repeated measurement design (and not for individual ANOVAs) for two reasons: First, I was interested in a 'tendency over all subjects' and second, by pooling the reactions of all subjects the data base was much greater which was especially important to provide enough observations for saccades to un-accompanied stimuli.

[9] However, for the SOA always the same response pattern was observed:
The earlier the auditory stimulus was presented, the faster were the reactions.

2. gazing at an auditorily un-accompanied stimulus,

for the factor *stimulus constellation* the levels were

1. visual stimulus pair 8° right/8° left,
2. visual stimulus pair 24° right/8° left or visual stimulus pair 8° right/24° left, and
3. visual stimulus pair 8° right/24° right or visual stimulus pair 8° left/24° left.

I tested the effects separately for reactions to stimuli at 8° and stimuli at 24°.

For saccades to visual stimuli at 8°, there was a significant effect for *stimulus constellation* ($F(2,8) = 8.04$, $p < 0.05$) and the interaction of *preference of bimodal stimulus* and *stimulus constellation* ($F(2,8) = 28.25$, $p < 0.001$). Reaction times were fastest, when the visual stimulus pair was presented within one hemisphere. But interestingly, only when the visual stimuli were presented in both hemispheres, saccades to auditorily accompanied stimuli were faster than those to un-accompanied ones. When the stimuli were presented within the same hemisphere, the opposite was true.

For saccades to visual stimuli at 24°, only the main effects became significant (for *stimulus constellation*: $F(1,3) = 96.21$; $p < 0.01$, for *preference of bimodal stimulus*: $F(1,3) = 69.75$, $p < 0.01$). Again, reaction times were faster when the two stimuli appeared within one hemisphere than when they appeared in both hemispheres. In both cases, auditorily accompanied stimuli evoked faster reactions than un-accompanied ones.

2.2.6 Summary and discussion

Figures 2.7 to 2.9 show the relationship between the shift of frequency and the facilitation that occurs when an auditory stimulus is presented, plotted for the three different stimulus conditions. Data to stimuli at the same eccentricity were pooled over the right and the left hemisphere and averaged over all subjects.[10] Data were normalized on the gaze frequencies and reaction times observed for the same subject in the purely visual trials. If the visual stimuli were presented to *both* hemispheres, the same response pattern can be observed for reactions to all stimuli:

Auditorily accompanied stimuli are both responded to faster and selected more frequently than auditorily un-accompanied ones.

However, if the visual stimulus pair appears within *one* hemisphere, this only holds for eye movements to stimuli at 24°.

For eye movements to stimuli at 8°, there is no shift of frequency for auditorily accompanied stimuli and reaction times are even longer than for auditorily un-accompanied stimuli.

An explanation for the different effects for saccades to stimuli at 8° versus at 24° might be well-founded in the experimental design: Since the 24°-stimulus was presented 26.6 ms before the 8°-stimulus, an accessory auditory stimulus at 24° simply appeared 26.6 ms earlier than an accessory stimulus at 8°. The reaction times might therefore be shorter for the first case, since the interval for visual-auditory interaction might be longer. However, even for saccades to 24°-stimuli, effects are smaller when stimuli were

---

[10] Data points whose observed frequency was below 3 were discarded, since the resulting mean reaction times seemed unreliable.

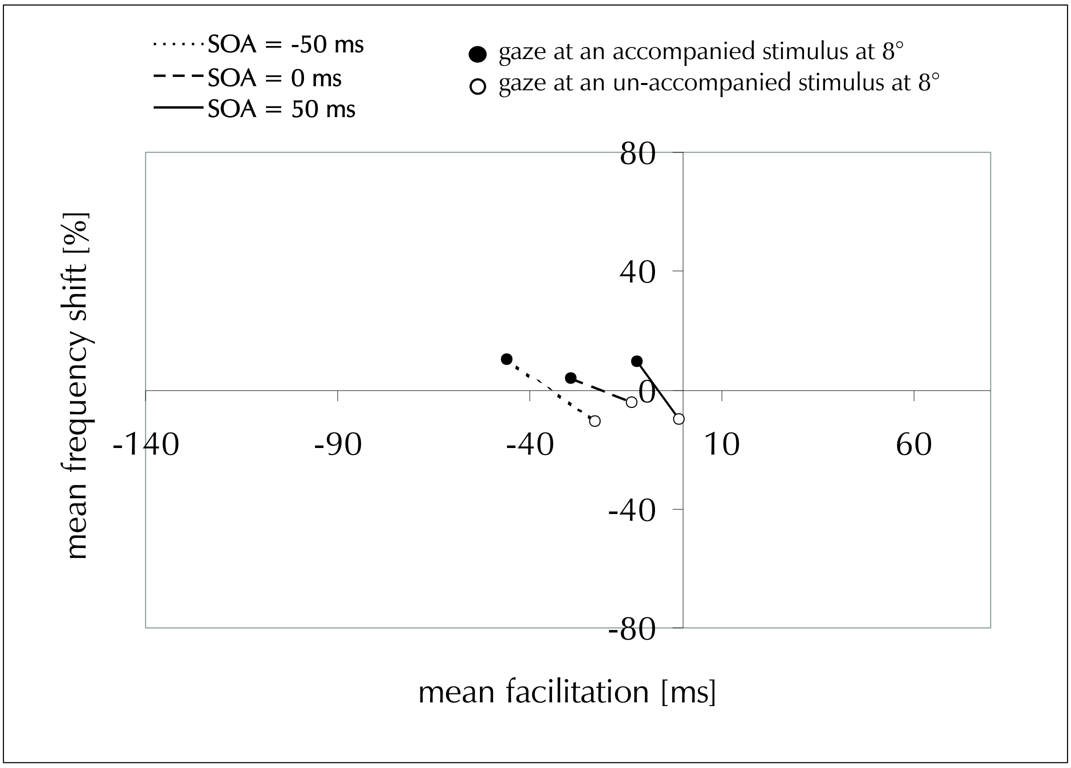

Figure 2.7: Shift of gaze frequency and facilitation or inhibition provided for auditorily accompanied stimuli and un-accompanied stimuli for visual stimulus pair 8° right/8° left, averaged over five subjects.

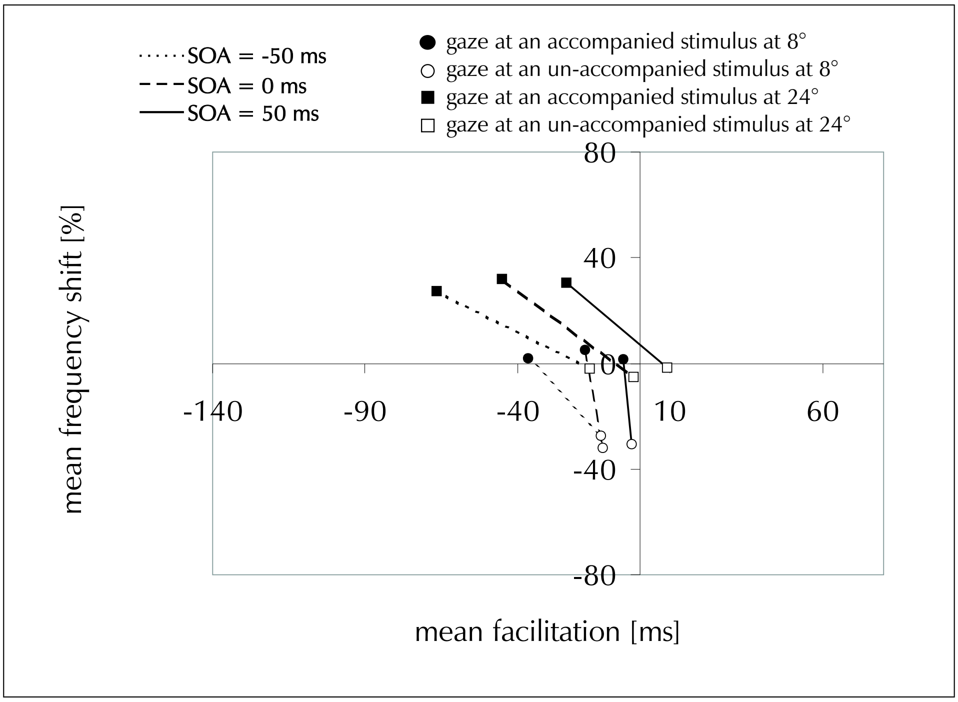

Figure 2.8: Shift of gaze frequency and facilitation or inhibition provided for auditorily accompanied stimuli and un-accompanied stimuli for visual stimulus pair 24° right/8° left or visual stimulus pair 8° right/24° left, averaged over five subjects.

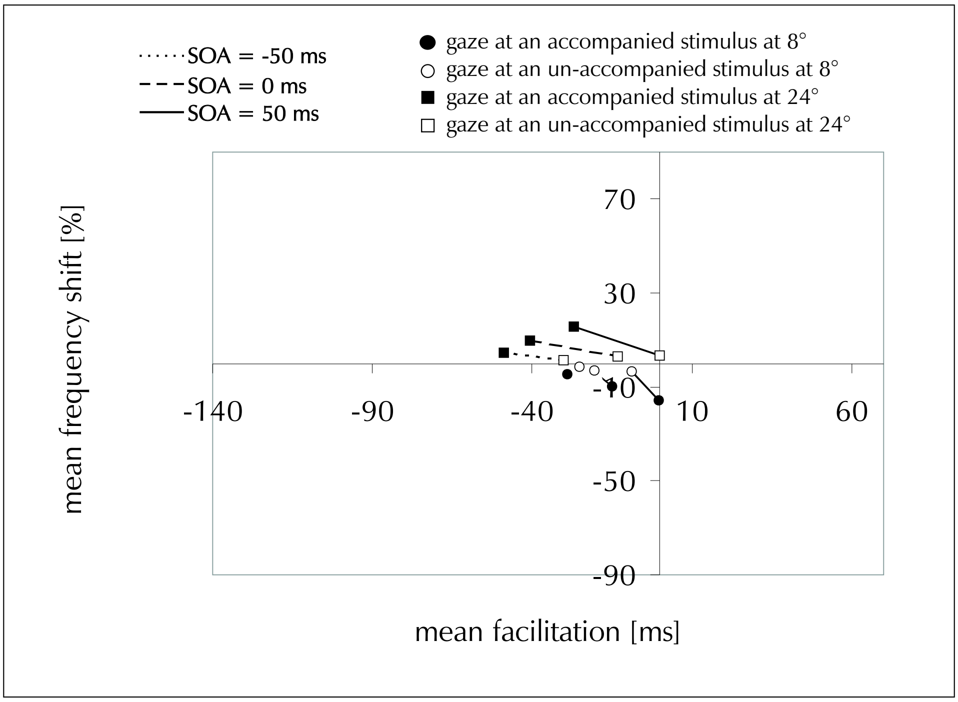

Figure 2.9: Shift of gaze frequency and facilitation or inhibition provided for auditorily accompanied stimuli and un-accompanied stimuli for visual stimulus pair 8° right/24° right or visual stimulus pair 8° left/24° left, averaged over five subjects.

presented within one hemisphere. One straightforward explanation for this might be that subjects were not able to discriminate between auditory stimuli within one hemisphere. So Experiment 2 was conducted to find out whether the subjects were able to localize the presented auditory stimuli correctly.

2.3 Experiment 2: Localization of auditory stimuli in a mixed design

The main purpose of Experiment 2 was to investigate subjects' ability to localize the auditory stimuli used in the former experiment. In general, it is assumed that localization in the horizontal plane is quite good with virtual acoustics (see Heuermann & Colonius, 1999). In the majority of the experiments on localization, the focus of interest was subjects' general ability to localize an auditory target. Therefore, subjects were allowed a long time interval (up to 1 s) to choose their target of gaze. However, in my experiments I was interested in the very *first reaction* evoked immediately by the auditory stimulus, since this might be the contribution of the auditory stimulus to audio-visual interaction. So I only considered primary saccades to study subjects' performance on localization. Since in Experiment 1 I presented all stimulus conditions in a single experiment, I did so as well in this experiment. The task was to gaze, after the fixation point had disappeared, at that point in space at which the displayed auditory stimulus was perceived.

2.3.1 Subjects

All five subjects who participated in Experiment 1 completed this experiment as well. Conventional audiometry testified them normal hearing.

2.3.2 Stimulus arrangement

The auditory stimuli were the same ones as used in Experiment 1 and were displayed at eccentricities of 8° right, 24° right, 8° left and 24° left.

2.3.3 Procedure

Each trial started with the presentation of a small fixation point in the centre of the screen (diameter: 0.1°, intensity: 11 cd/m^2). After a random time interval of 850 to 3990 ms, the fixation point disappeared and, simultaneously, one of four possible auditory stimuli was displayed.

2.3.4 Reaction times and amplitudes

Reaction time was defined as the time between the onset of the auditory stimulus and the beginning of the eye movement to this stimulus. Saccadic amplitudes were calculated for primary saccades only.

2.3.5 Results and discussion

2.3.5.1 Reaction times

Fig. 2.10 shows the mean reaction times and standard errors for all subjects. There was a great individual variability of mean reaction times. All subjects but one (*rv*) showed faster eye movements when the auditory stimulus was presented at 24°. Therefore, one might conclude that the influence of the auditory stimulus at 24° is stronger because an auditory stimulus at 24° is processed faster than one at 8°. But one cannot decide whether the stronger influence for auditory stimuli at 24°, as evident in Experiment 1, is caused by this faster processing *only* or also by the temporal advantage included in the experimental design. Remember that the auditory stimulus was always presented together with the visual stimulus it accompanied. This means when it accompanied a visual stimulus at 24°, it was as well presented 26.6 ms earlier than when it was accessory to a visual stimulus at 8°. To answer this question, both visual targets are presented at the same time in the next experiment.

2.3.5.2 Amplitudes

Fig. 2.11 shows the mean amplitudes for primary saccades to the four auditory stimuli. As one can see, standard deviations[11] are rather high, especially for the subjects *ld*, *rv* and *cs*. Therefore, one might argue that these subjects can correctly discriminate the auditory stimulus only with respect to the hemisphere it was presented to. However, within *one* hemisphere, auditory stimuli at 8° were confounded with those at 24°. This provides evidence for the hypothesis that the auditory stimulus had no effect in presentations of two visual stimuli to the same hemisphere, because its localization was too poor. One way to improve localization might be to simplify the task by reducing the number of possible auditory stimuli. So I decided to split the experiment up into four sub-experiments with only one stimulus pair (and its respective auditory stimulus) presented in each trial.

2.4 Experiment 3: Localization of auditory stimuli measured in a blocked design

In this experiment I presented only two auditory stimuli within a block to simplify the task. This yielded the following four sub-experiments:

1. Localization of auditory stimuli at 8° right versus 8° left,
2. Localization of auditory stimuli at 8° right versus 24° left or 8° left versus 24° right,
3. Localization of auditory stimuli at 8° right versus 24° right or 8° left versus 24° left, and
4. Localization of auditory stimuli at 24° right versus 24° left

Each subject completed four sub-experiments. For the second and the third sub-experiment one half of the subjects had to localize auditory stimuli at 8° right versus 24° left and 8° right versus 24° right, and the other half 8° left versus 24° right and 8° left versus 24° left.

---

[11] Since I was interested in the variance of eye movements in localizing an auditory target and not in the reliability of the mean, here the standard deviations instead of the standard errors are shown.

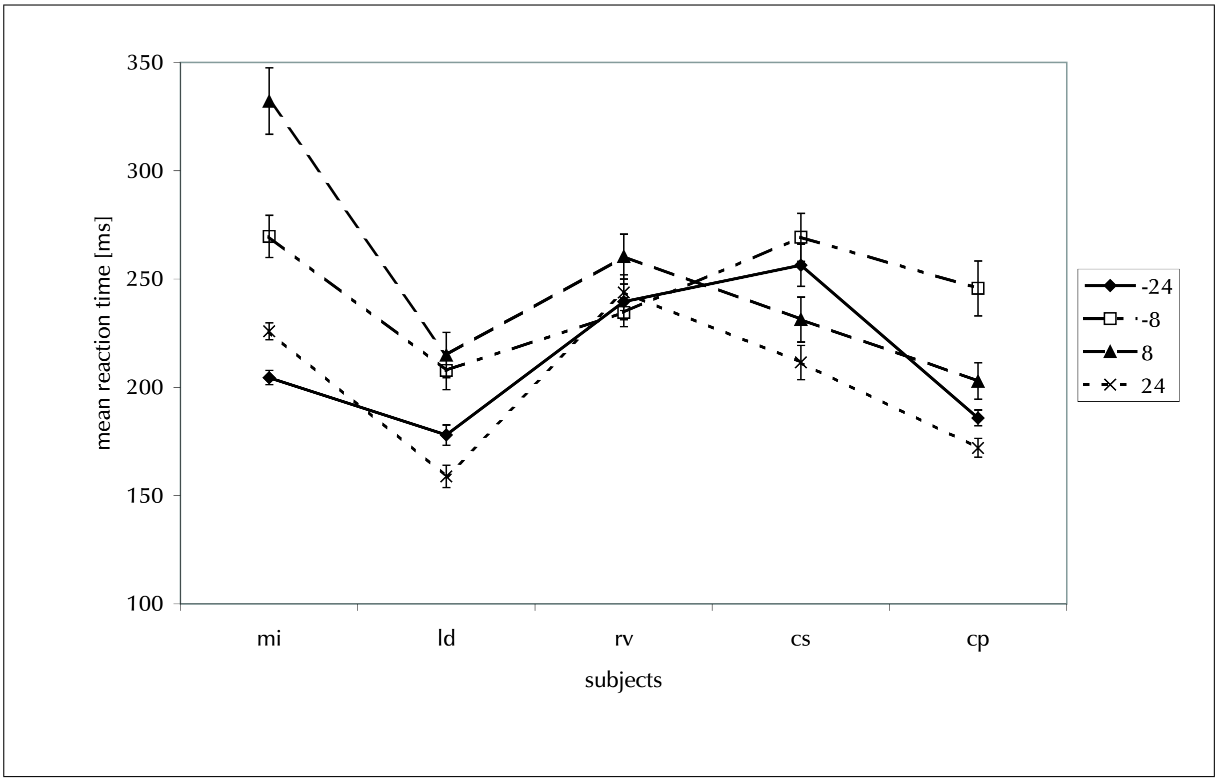

Figure 2.10: Mean reaction times and standard errors of saccades to auditory stimuli for five subjects.

2.4.1 Subjects

Eight subjects participated in this study. Three of them (*mi*, *rv*, *cp*) had already taken part in Experiment 1, the others have never taken part in any localization experiment so far. All subjects had normal hearing as tested by conventional audiometry.

2.4.2 Stimulus arrangement

In each sub-experiment only two auditory stimuli were presented. Apart from that, the stimulus arrangement was the same as in the former experiment.

2.4.3 Procedure

Before each sub-experiment, there was a training session (100 trials) in which the auditory stimuli were presented together with a visual stimulus at the same location. This served to familiarize the subjects with virtual acoustics. Subjects conducted, if time permitted, at least two experimental blocks (100 trials each), on different days.[12] Each trial started with the presentation of a small fixation point in the centre of the screen (diameter: 0.1°, intensity: 11 cd/m^2). After a random time interval of 850 to 3990 ms, the fixation point was removed and, at the same time, one of the two possible auditory stimuli was presented.

---

[12] The first block was carried out before Experiment 4, the second after it . Performance did not differ between the two blocks.

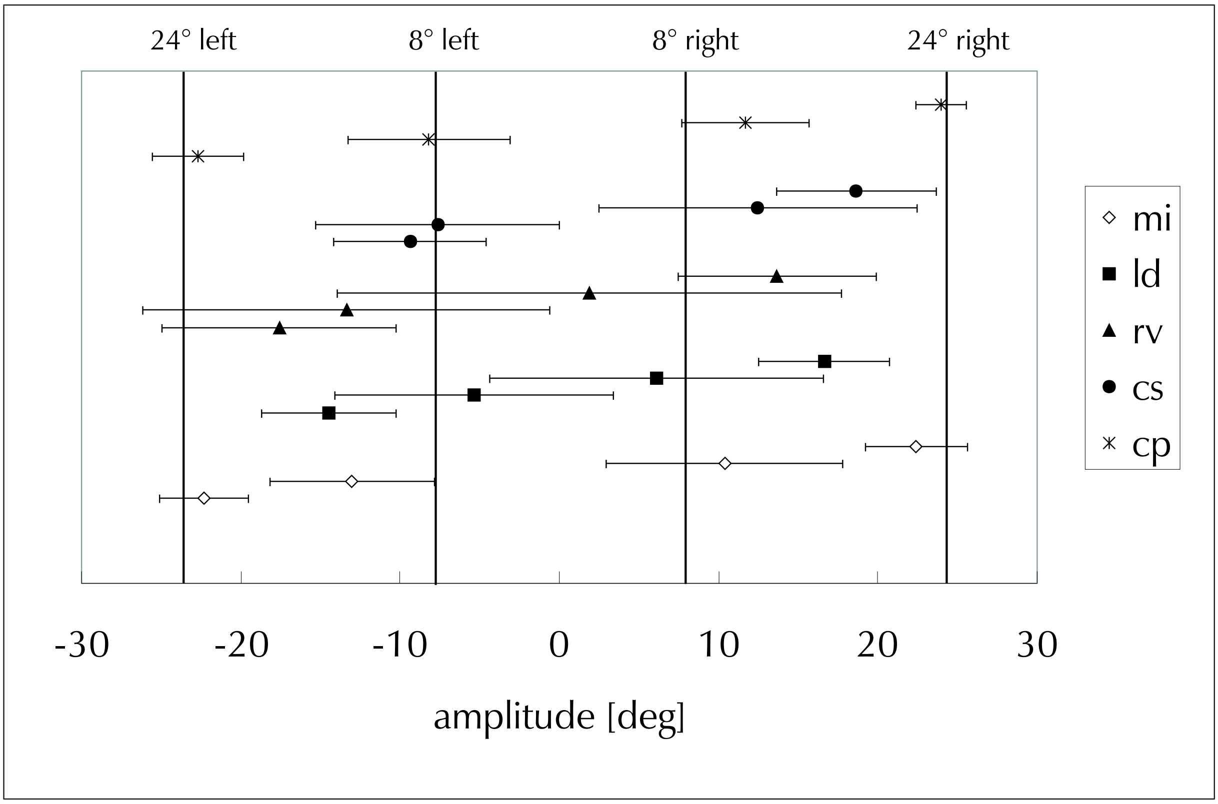

Figure 2.11: Mean amplitudes and standard deviations of the saccades to auditory stimuli for five subjects.

Reaction times and amplitudes

As before, reaction time was defined as the time between the onset of the auditory stimulus and the beginning of the eye movement to this stimulus. Saccadic amplitudes were only calculated for primary saccades.

2.4.4 Results and discussion

2.4.4.1 Reaction times

Fig. 2.12 shows mean reaction times and standard errors for all subjects. Generally, the mean reaction times were faster than in the previous experiment. Whereas the individual variability in terms of standard errors was small, there were large interindividual differences. This might be due to the easier task. Subjects had only to decide for one out of two instead of four possible stimulus locations. However, the latencies of saccades to auditory stimuli at 24° were still shorter than those to auditory stimuli at 8°. One explanation for this difference might be that the processing time of the stimulus at 24° is shorter because the uncertainty of the target position is smaller.

2.4.4.2 Amplitudes

The mean amplitudes and standard deviations for the primary eye movements to the auditory stimuli are illustrated in Figures 2.13 to 2.16 for the four different sub-experiments.

As one can see, there are individual differences in localization performance. But on general, subjects were able to discriminate the two presented stimuli. Only when the stimuli were presented within one hemisphere, two subjects (*rv*, *th*) confused the auditory stimuli at 8° with those at 24°. Therefore, performance was much better than in Experiment 2. No speed-accuracy-trade-off was observed, i.e. subjects who responded faster to the stimuli did not make more errors in localization. This suggests a rather automatically triggered saccade at the position of the auditory target.

In the next step it is to be investigated whether the same results as in Experiment 1 are found by using stimuli that are easy to discriminate. If differences between stimulus constellations are found also in this task, they are probably not caused by subjects' inability to localize the auditory stimuli correctly.

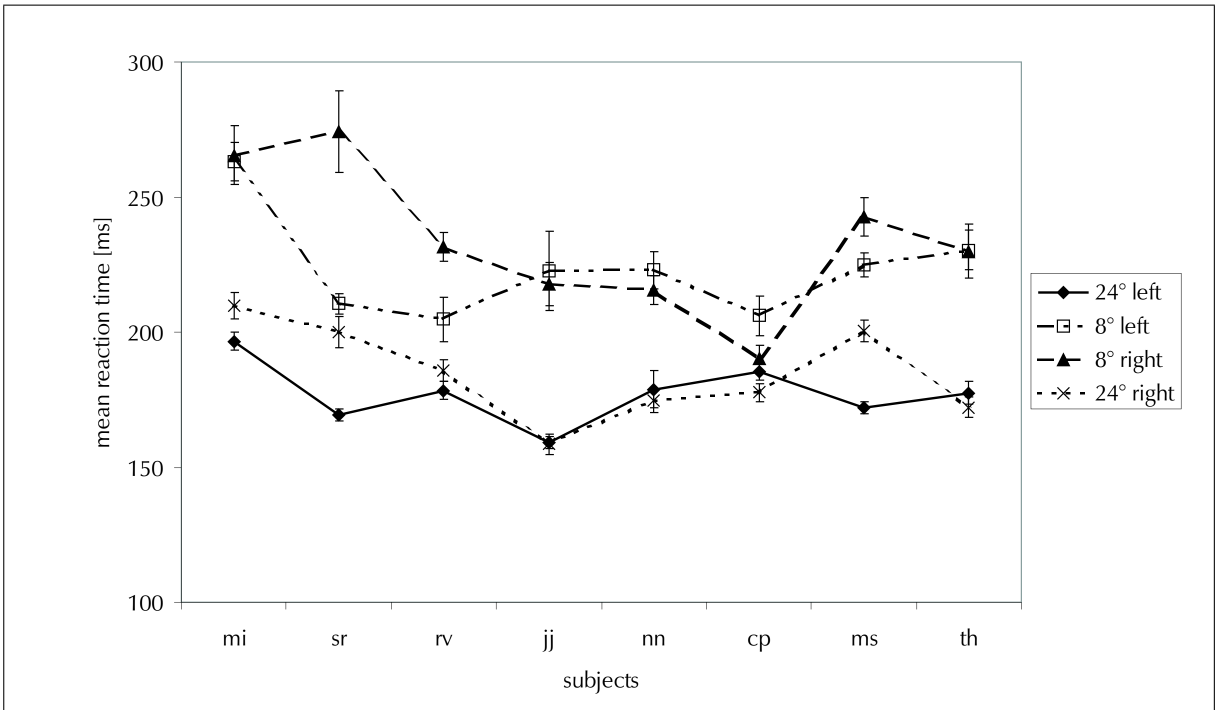

Figure 2.12: Mean reaction times and standard errors of the saccades to auditory stimuli for eight subjects.

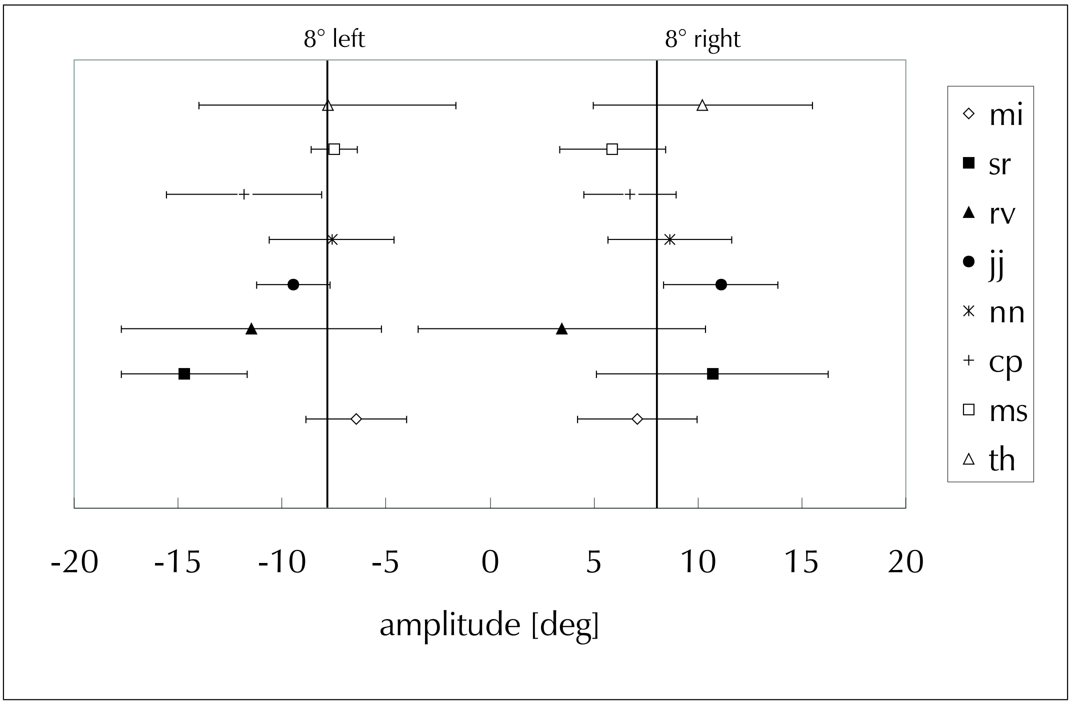

Figure 2.13: Mean amplitudes and standard deviations of the saccades to auditory stimuli at 8° left or right for eight subjects.

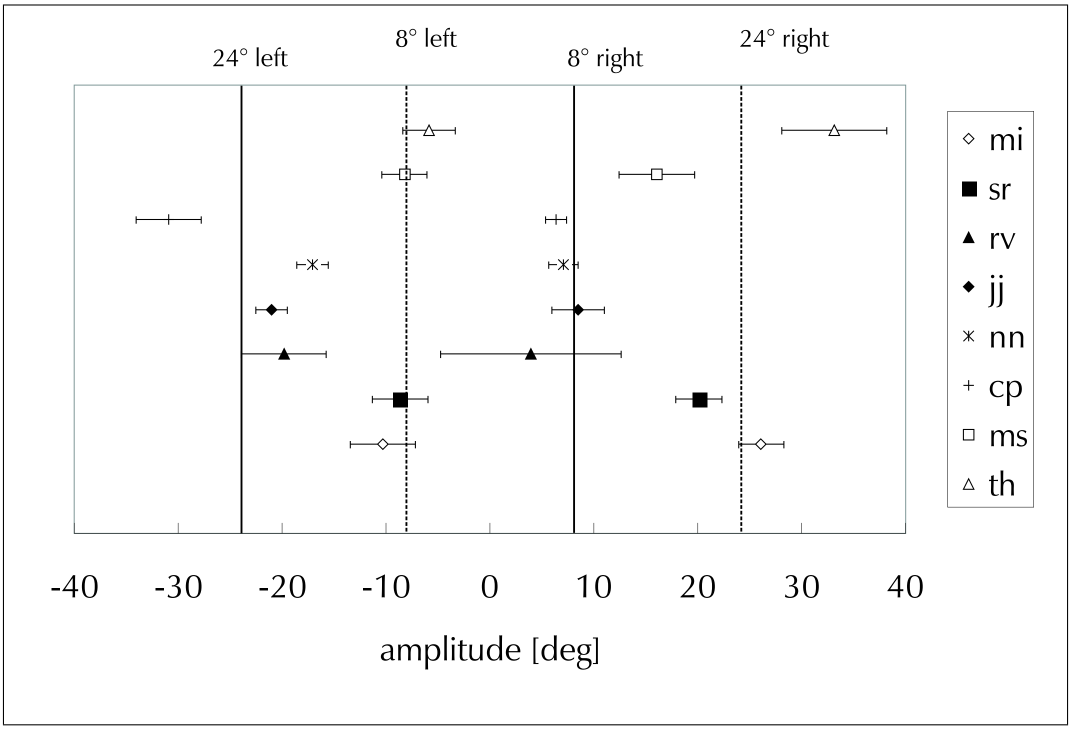

Figure 2.14: Mean amplitudes and standard deviations of the saccades to auditory stimuli at 8° left and 24° right or at 8° right and 24° left for eight subjects.

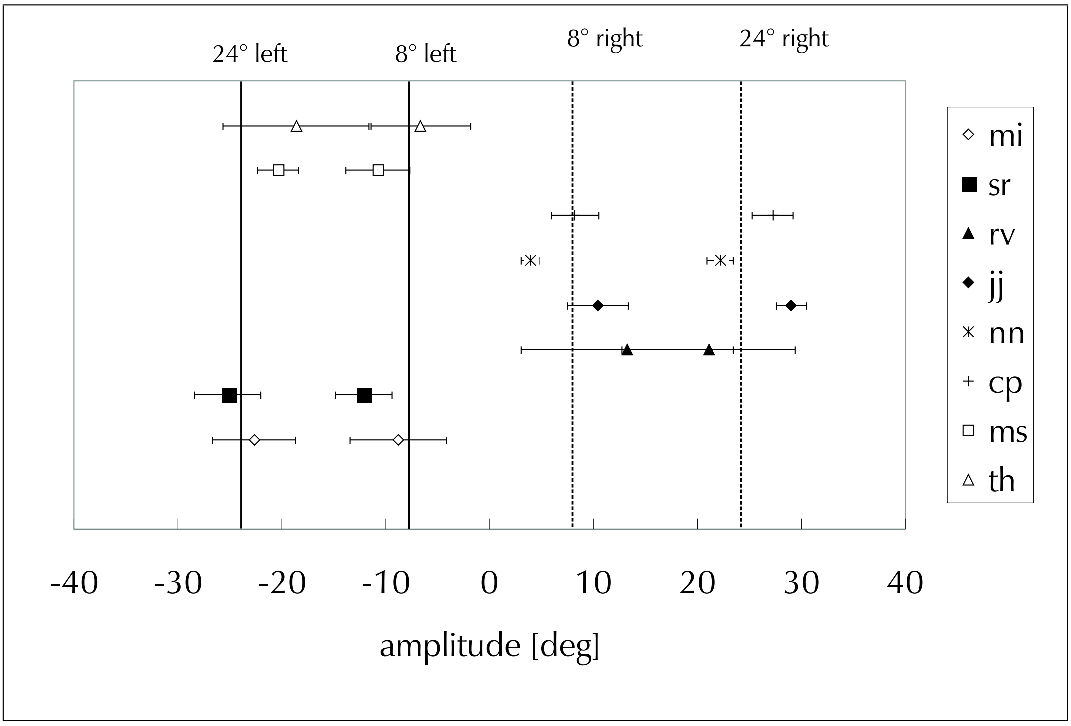

Figure 2.15: Mean amplitudes and standard deviations of the saccades to auditory stimuli at 8° right and 24° right or at 8° left and 24° left for eight subjects.

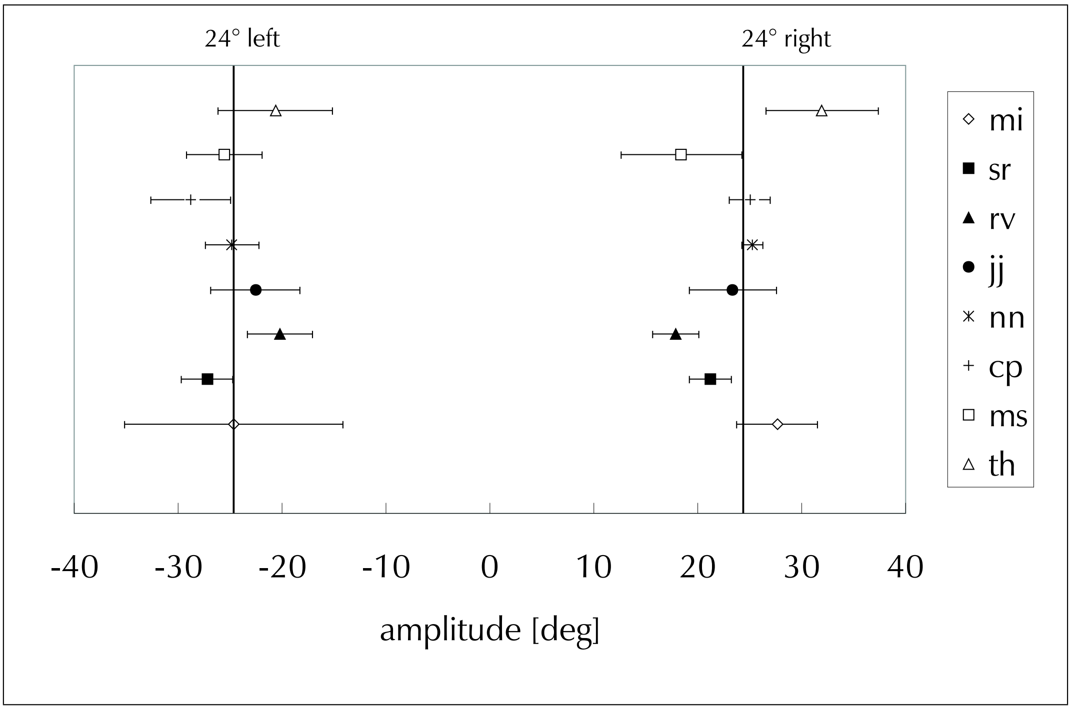

Figure 2.16: Mean amplitudes and standard deviations of the saccades to auditory stimuli at 24° right or left for eight subjects.

2.5 Experiment 4: The influence of an auditory accessory stimulus on target choice and reaction time with two simultaneously presented visual stimuli

As in Experiment 1 (see Section 2.2) I used a focused attention paradigm: subjects were instructed to perform an eye movement to any visual target stimulus that appeared after the fixation point off-set and to ignore the auditory stimulus. In contrast to the first experiment, the stimulus at 8° was now presented at the same time as the one at 24°. To lessen the force of attraction of the 8°-stimulus, its intensity was decreased relative to the 24°-stimuli. Appropriate intensities were determined individually for each subject by a pretest using a 1-step-up/1-step-down adaptive procedure (Levitt, 1971) to make subjects gaze about equally often at each visual stimulus. The stimulus at 24° always served as a reference stimulus and had an intensity of 11 cd/m^2. For all but one subject (*th*), the algorithm succeeded. The provided intensities are shown in Table 2.2. For subject *th* the mean intensity over all other subjects was taken.

Besides these modifications, the experimental setup was exactly the same as described in Experiment 1. Data were analyzed in the same way as in Experiment 1 unless otherwise indicated.

Table 2.2: Presented intensity of the visual stimulus at 8° for eight subjects

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**	**th**
Intensity in cd/m^2	0.16	0.54	1.82	0.83	1.49	0.35	0.54	0.68

2.5.1 Subjects

Eight subjects (*mi*, *sr*, *rv*, *jj*, *nn*, *cp*, *ms*, *th*), aged 16 to 34 years, with normal auditory and oculomotor function participated in this experiment. All of them had taken part in Experiment 3. Three of them (*mi*, *rv* and *cp*) participated also in Experiment 1. Subjects were familiar with this kind of task but were not informed about the specific goal of the study.

2.5.2 Stimulus arrangement

The stimulus arrangement was the same as in Experiment 1 (see Subsection 2.2.2) except for two modifications:

- Visual stimuli at 24° were presented at the same time as stimuli at 8°.
- Each experimental condition and its control condition was presented in a blocked design.[13]

---

[13] A control study with two subjects showed no differences between blocked and mixed design with respect to the influence of the auditory stimulus. However, if the visual stimuli appeared within one

This provided the following four sub-experiments:

1. Visual stimulus pair: 8° right/8° left
2. Visual stimulus pair: 8° right/24° left or 24° right/8° left
   Half of the subjects performed the stimulus condition 8° right/24° left, half of them the stimulus condition 24° right/8° left.
3. Visual stimulus pair: 8° right/24° right or 8° left/24° left
   Half of the subjects performed the stimulus condition 8° right/24° right, half of them the stimulus condition 8° left/24° left.
4. Visual stimulus pair: 24° right/24° left

Each sub-experiment consisted of 2 to 3 sessions, 3 blocks each, which resulted in 54 presentations for every stimulus and every control condition, so that the total number of trials per subject performed in this experiment was 3240 (60 × 54). For each sub-experiment, a list of all stimulus combinations and their abbreviations which are used in the following is presented in Table 2.3. To prevent any order effects, subjects completed these sub-experiments in a different order.

2.5.3 Differences in reaction times to single versus double visual stimuli

As in Experiment 1, saccades to single stimuli at 8° were faster than saccades to 24°-stimuli (8° left: 218 ms, 8° right: 223 ms, 24° left: 223 ms, 24° right: 233 ms). Note that the overall reaction times were shorter for stimuli in the left hemisphere than in the right hemisphere. Therefore, one has to compare e.g., the reaction times to the stimulus at 8° right with those to the stimulus at 24° *right* as well.

Repeated measurement ANOVAs with the within factors *number of visual stimuli* (one or two) and *SOA* (-50 ms, 0 ms, 50 ms, no auditory stimulus) were performed separately for reactions to stimuli at 8° (right or left) and stimuli at 24° (right or left) for each sub-experiment.

In the first sub-experiment, illustrated in Fig. 2.17, (visual stimulus pair 8° right/8° left), significant main effects and no interaction effect were revealed (for *number of visual stimuli*: $F(1,7) = 21.25$, $p < 0.01$, for *SOA*: $F(3,21) = 50.96$, $p < 0.001$): If two visual stimuli were presented, reaction times were about 20 ms longer than with one visual stimulus. Furthermore reaction times were facilitated compared to purely visual stimuli when an auditory stimulus was presented, and facilitation was the larger the earlier the auditory stimulus was presented.

For the visual stimulus pair 24° right/8° left or the visual stimulus pair 8° right/24° left, I detected significant main effects for saccades to stimuli at 8° (see Fig. 2.18) as well as for those to stimuli at 24° (see Fig. 2.19 for reactions to stimuli at 8°: for *number of visual stimuli*: $F(1,7) = 90.84$, $p < 0.001$; for *SOA*: $F(3,21) = 42.12$, $p < 0.001$; for reactions to stimuli at 24°: for *number of visual stimuli*: $F(1,7) = 9.64$, $p < 0.05$, for

---

hemisphere only, the reaction times were significantly faster in the blocked design than in the mixed design.

Table 2.3: Stimulus conditions for four sub-experiments.

Visual stimulus pair:	Position of stimuli	SOA	abbreviation
8° **right/**8° **left**	visual stimulus at 8° right		8V
	+ auditory stimulus at 8° right	−50 ms	8AV-50
	+ auditory stimulus at 8° right	0 ms	8AV0
	+ auditory stimulus at 8° right	50 ms	8AV50
	visual stimulus at 8° left		-8V
	+ auditory stimulus at 8° left	−50 ms	-8AV-50
	+ auditory stimulus at 8° left	0 ms	-8AV0
	+ auditory stimulus at 8° left	50 ms	-8AV50
8° **right/**24° **left** 24° **right/**8° **left**	visual stimulus at 8° right		8V
	+ auditory stimulus at 8° right	−50 ms	8AV-50
	+ auditory stimulus at 8° right	0 ms	8AV0
	+ auditory stimulus at 8° right	50 ms	8AV50
	visual stimulus at 24° left		-24V
	+ auditory stimulus at 24° left	−50 ms	-24AV-50
	+ auditory stimulus at 24° left	0 ms	-24AV0
	+ auditory stimulus at 24° left	50 ms	-24AV50
8° **right/**24° **right** 8° **left/**24° **left**	visual stimulus at 8° right		8V
	+ auditory stimulus at 8° right	−50 ms	8AV-50
	+ auditory stimulus at 8° right	0 ms	8AV0
	+ auditory stimulus at 8° right	50 ms	8AV50
	visual stimulus at 24° right		24V
	+ auditory stimulus at 24° right	−50 ms	24AV-50
	+ auditory stimulus at 24° right	0 ms	24AV0
	+ auditory stimulus at 24° right	50 ms	24AV50
24° **right/**24° **left**	visual stimulus at 24° right		24V
	+ auditory stimulus at 24° right	−50 ms	24AV-50
	+ auditory stimulus at 24° right	0 ms	24AV0
	+ auditory stimulus at 24° right	50 ms	24AV50
	visual stimulus at 24° left		-24V
	+ auditory stimulus at 24° left	−50 ms	-24AV-50
	+ auditory stimulus at 24° left	0 ms	-24AV0
	+ auditory stimulus at 24° left	50 ms	-24AV50

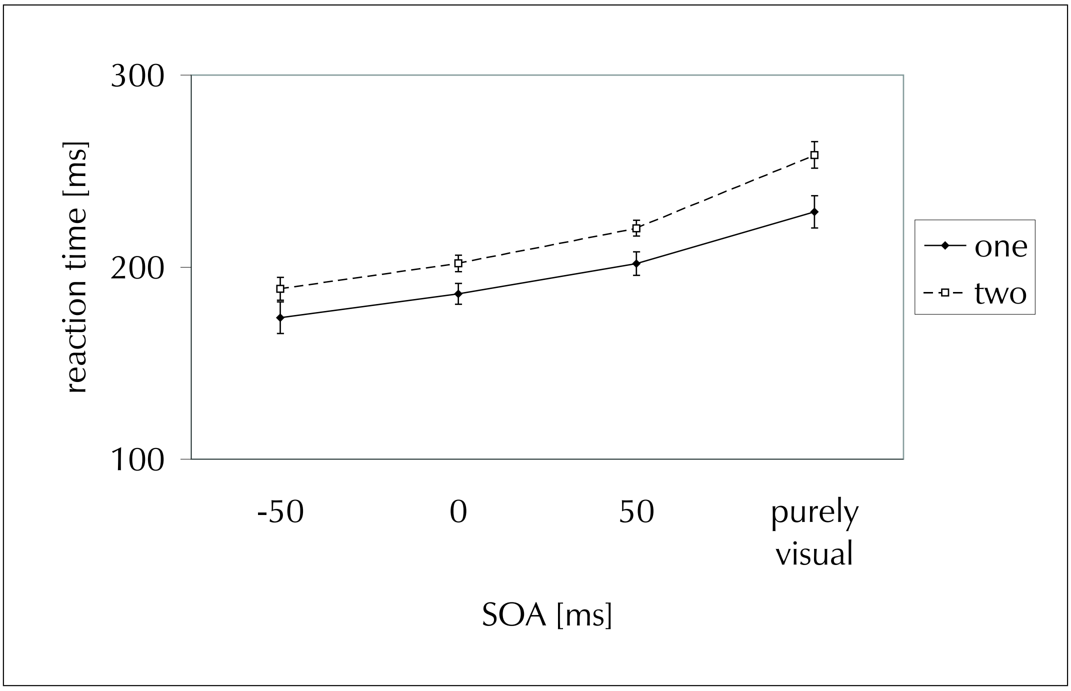

Figure 2.17: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 8° right or left for the visual stimulus pair 8° right/8° left, averaged over eight subjects.

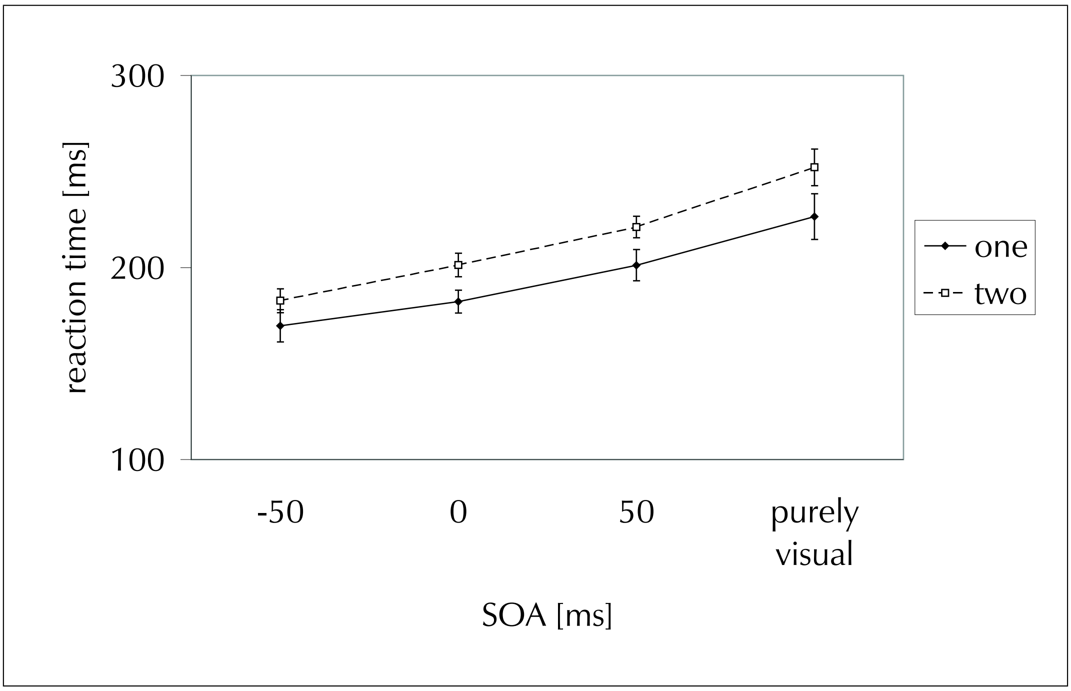

Figure 2.18: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 8° right or left for the visual stimulus pair 8° right/24° left or the visual stimulus pair 8° left/24° right, averaged over eight subjects.

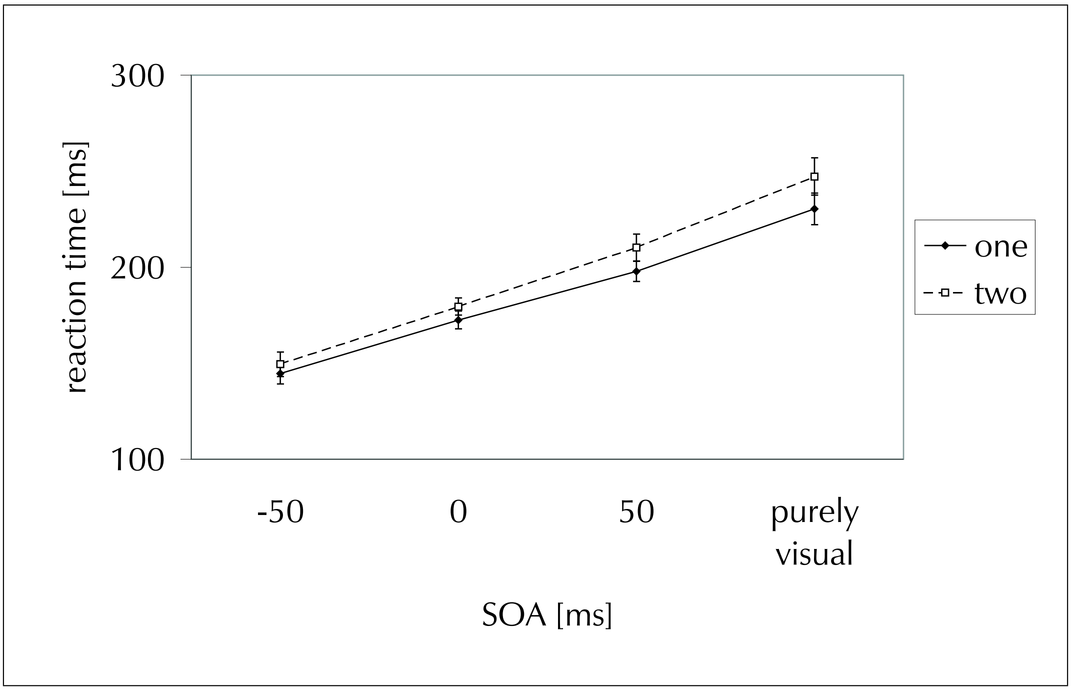

Figure 2.19: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 24° right or left for the visual stimulus pair 8° right/24° left or the visual stimulus pair 8° left/24° right, averaged over eight subjects.

SOA: $F(3, 21) = 71.41$; $p < 0.001$). Reaction times were about 10 to 20 ms shorter when only one visual stimulus was presented than when two visual stimuli were presented. The facilitation effect was the greater the earlier the auditory stimulus was presented and the reaction times were the longest when no auditory stimulus was presented at all.

An ANOVA for saccades to stimuli at 8° (see Fig. 2.20) for the visual stimulus pair 8° right/24° right or visual stimulus pair 8° left/24° left only revealed significant effects for the factor *SOA* ($F(3, 12) = 66.71$, $p < 0.001$). Facilitation was the greater the earlier the auditory stimulus was given. For saccades to stimuli at 24° (see Fig. 2.21) there was as well a small interaction effect:
If there was no auditory stimulus, reaction times to single visual stimuli were about 10 ms longer than those to double stimuli (SOA: $F(3, 15) = 72.41$, $p < 0.001$, *SOA* × *number of visual stimuli*: $F(3, 15) = 4.17$, $p < 0.05$). However, one reason for the fact that the number of visual stimuli had no significant influence is that the prolonging of the reaction times observed for visual stimulus pairs is mainly due to the additional time needed to decide at which hemisphere to look. If the visual stimuli appear within one hemisphere, no such decision has to be made and therefore the reaction times do not differ from those to single visual stimuli.

For the visual stimulus pair 24° left/24° right, illustrated in Fig. 2.22, I found highly significant main effects of *SOA*, *number of visual stimuli* and a weak interaction effect (*SOA*: $F(3, 21) = 79.61$, $p < 0.001$, *number of visual stimuli*: $F(1, 7) = 43.00$, $p < 0.001$, *SOA*×*number of visual stimuli*: $F(3, 21) = 3.99$, $p < 0.05$). Reaction times to double stimuli were about 14 ms longer than those to single stimuli. For SOA I found again the following relationship: The earlier the auditory stimulus was presented the shorter were the observed reaction times.

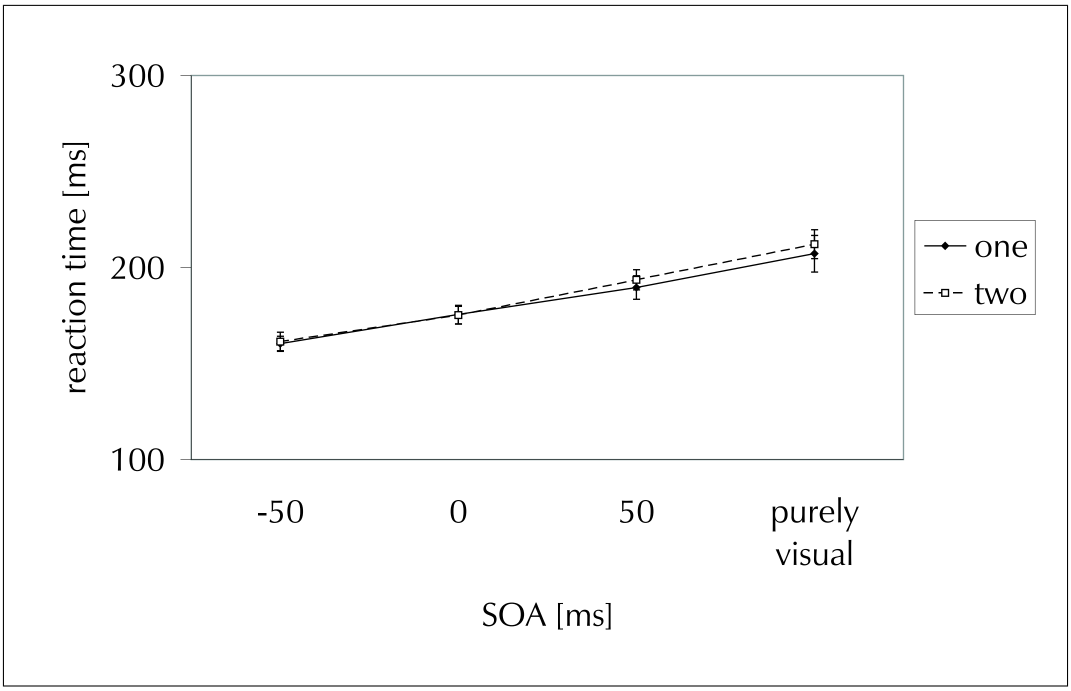

Figure 2.20: Mean reaction time and standard errors for the saccades to one versus two visual stimuli at 8° right or left for the visual stimulus pair 8° right/24° right or the visual stimulus pair 8° left/24° left, averaged over eight subjects.

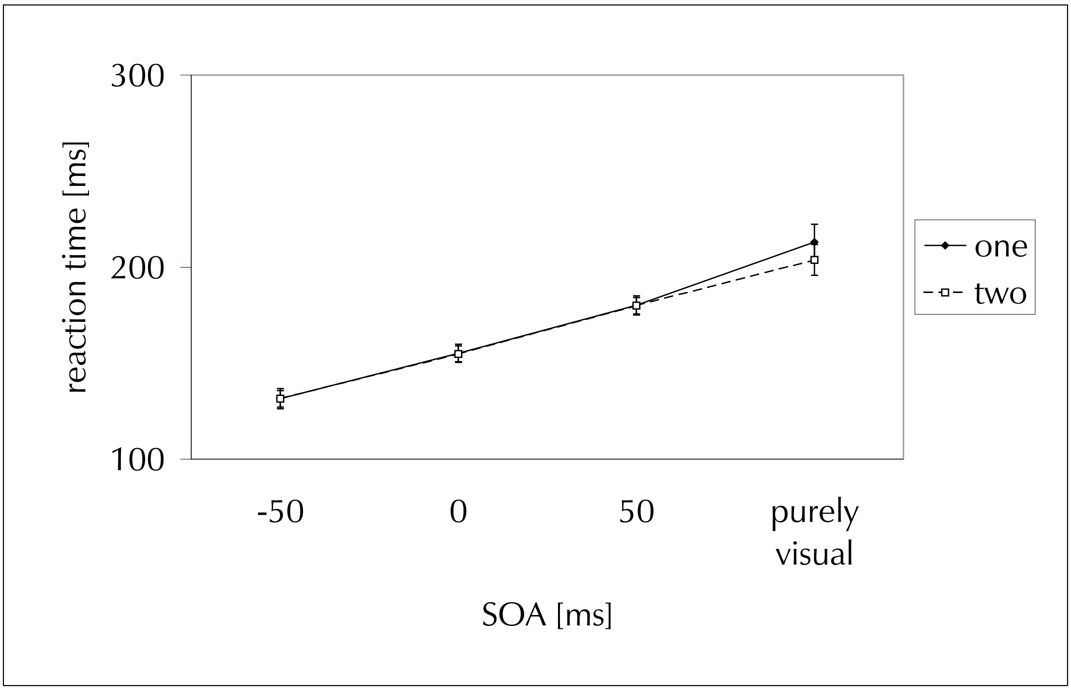

Figure 2.21: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 24° right or left for the visual stimulus pair 8° right/24° right or the visual stimulus pair 8° left/24° left, averaged over eight subjects.

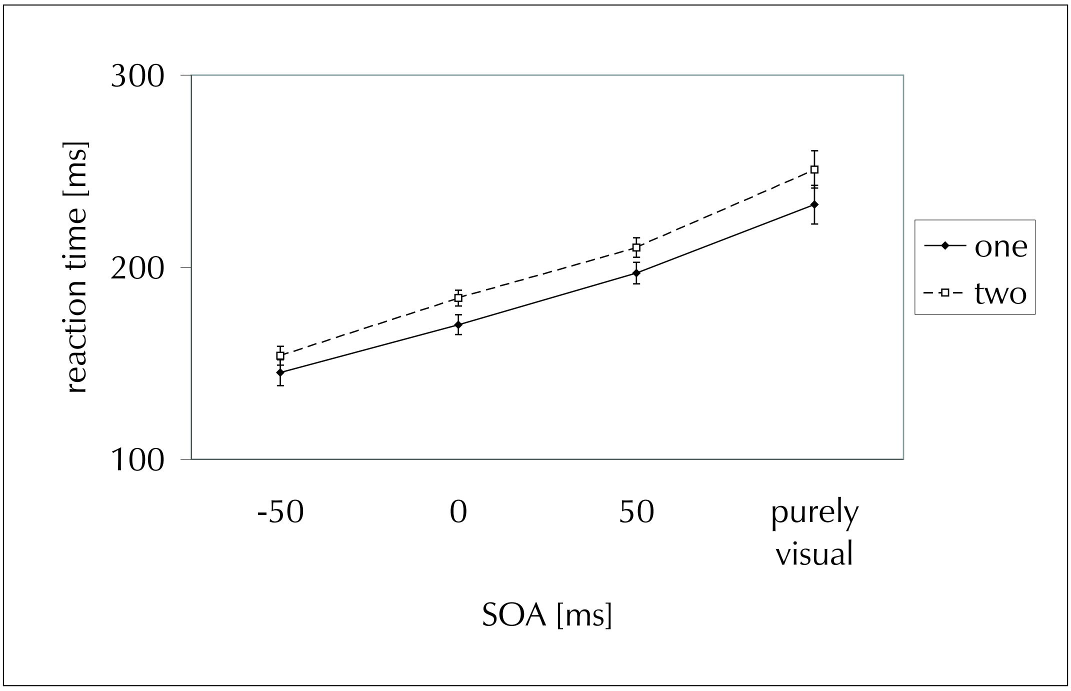

Figure 2.22: Mean reaction time and standard errors for saccades to visual single versus double stimuli at 24° right or left for the visual stimulus pair 24° right/24° left, averaged over eight subjects.

To summarize, Experiment 4 shows that presenting a second visual stimulus prolongs reaction times significantly. In fact, this finding replicates the ‘remote distractor effect’ known from literature (see Findlay, 1982).

2.5.4 The influence of the auditory stimulus for visual stimulus pairs

As in Experiment 1, the influence of the auditory stimulus on ‘gaze frequency’ and ‘reaction times’, will be analyzed.

2.5.4.1 Gaze frequency

Comparing the gaze frequencies for the purely visual, symmetrical stimulus pairs (8° right/8° left and 24° right/24° left), it strikes out that most subjects had a more or less strong preference for one hemisphere (bias for the left hemisphere: *jj, mi, ms, th*, bias for the right hemisphere: *cp*). Interestingly, this individual bias remained the same direction irrespective of the eccentricity at which the stimuli were presented (8° or 24°).

To test whether the frequencies of gaze were influenced by the auditory stimulus in a characteristic manner, $3 \times 2 - \chi^2$-Tests were performed, separately for each subject and each sub-experiment. For the visual stimulus pair 8° right/8° left the shift of frequency was significant for all subjects (*mi*: $\chi^2 = 20.88$, $p < 0.001$; *sr*: $\chi^2 = 172.59$, $p < 0.001$; *rv*: $\chi^2 = 8.71$, $p < 0.05$; *jj*: $\chi^2 = 254.74$, $p < 0.001$; *nn*: $\chi^2 = 44.95$, $p < 0.001$; *cp*: $\chi^2 = 123.61$, $p < 0.001$; *ms*: $\chi^2 = 119.25$, $p < 0.001$; *th*: $\chi^2 = 32.10$, $p < 0.001$).

By analyzing the visual stimulus pairs 24° right/8° left or 8° right/24° left, I found the same result: χ^2-Tests showed significant shifts in frequency of gaze for all subjects (*mi*: $\chi^2 = 39.62$, $p < 0.001$; *sr*: $\chi^2 = 206.57$, $p < 0.001$; *rv*: $\chi^2 = 72.49$, $p < 0.001$; *jj*: $\chi^2 = 239.27$, $p < 0.001$; *nn*: $\chi^2 = 154.66$, $p < 0.001$; *cp*: $\chi^2 = 125.71$, $p < 0.001$; *ms*: $\chi^2 = 139.88$, $p < 0.001$; *th*: $\chi^2 = 113.78$, $p < 0.001$). However, $2 \times 2 - \chi^2$-Tests revealed that the gaze shift, induced by the auditory stimulus, was more pronounced when the auditory stimulus was presented at 24° than when it was presented at 8°.

When the visual stimuli were displayed at 8° and 24° within one hemisphere, all but one subject (*cp*) gazed significantly more frequently to auditorily accompanied stimuli than to un-accompanied ones (*mi*: $\chi^2 = 20.25$, $p < 0.001$; *sr*: $\chi^2 = 124.92$, $p < 0.001$; *rv*: $\chi^2 = 18.43$, $p < 0.001$; *jj*[14]:for stimuli at 24° : $\chi^2 = 7.92$; $p < 0.01$, *nn*: $\chi^2 = 46.23$; $p < 0.001$, *cp*: $\chi^2 = 49.39$; $p < 0.001$, *ms*: $\chi^2 = 102.59$; $p < 0.001$, *th*: $\chi^2 = 43.61$; $p < 0.001$). By performing orthogonal comparisons it became obvious that the significant values, again, were caused by a much greater amount of gaze shifts to auditorily accompanied stimuli at 24° than to those at 8°.

For the visual stimulus pair 24° right/24° left χ^2-Tests revealed significant shifts of gaze frequency for all subjects (*mi*: $\chi^2 = 91.23$, $p < 0.001$; *sr*: $\chi^2 = 214.30$, $p < 0.001$; *rv*: $\chi^2 = 123.31$, $p < 0.001$; *jj*: $\chi^2 = 313.05$, $p < 0.001$; *nn*: $\chi^2 = 34.14$, $p < 0.001$; *cp*: $\chi^2 = 163.30$, $p < 0.001$; *ms*: $\chi^2 = 163.14$, $p < 0.001$; *th*: $\chi^2 = 83.71$, $p < 0.001$).

2.5.4.2 Reaction times

As in Experiment 1, I tested the influence of the auditory stimulus on reaction times with repeated measurement ANOVAs, performed separately for reactions to stimuli at 8° and stimuli at 24°.

For saccades to visual stimuli at 8°, all main effects and the interaction effect were significant (for *stimulus constellation*: $F(2,12) = 12.19$, $p < 0.01$; for *preference of bimodal stimulus*: $F(1,6) = 21.85$, $p < 0.01$, for *stimulus constellation* × *preference of bimodal stimulus*: $F(2,12) = 14.22$; $p < 0.01$).

Reaction times were significantly faster, if the visual stimulus pair was presented within one hemisphere than in the other conditions (about 34 *ms*). Again, as in Experiment 1, reaction times to accompanied stimuli were faster compared to un-accompanied ones, only if the visual stimuli were displayed to both hemispheres. If they appeared in one hemisphere only, the auditory stimulus did not reduce the mean latency of saccades to visual targets at the same position.

The results for saccades to visual stimuli at 24° are very similar: A repeated measurement-ANOVA revealed both significant main and interaction effects (for *stimulus constellation*: $F(2,12) = 22.80$, $p < 0.01$; for *preference of bimodal stimulus*: $F(1,6) = 31.34$, $p < 0.01$, for *stimulus constellation* × *preference of bimodal stimulus*: $F(2,12) = 15.10$; $p < 0.01$). As seen before, reaction times were significantly faster if the two stimuli appeared within one hemisphere than when presented to both hemispheres (about 42 ms). But, only if the visual stimuli were presented to both hemispheres mean reaction times were significantly

---

[14] For subject *jj* the expected cell frequencies were below 5, so I had to calculate Fisher's exact statistic to analyze the following two 2 × 2 crosstabs:

1. Frequency of gaze to auditorily accompanied stimuli at 8° versus un-accompanied stimuli at 8°.
2. Frequency of gaze to auditorily accompanied stimuli at 24° versus un-accompanied stimuli at 24°.

I found significant effects only for the second case.

faster for saccades to auditorily accompanied stimuli than to un-accompanied ones.

2.5.5 Summary and discussion

Important results of Experiment 4 are summarized in Figures 2.23 to 2.26. As in Experiment 1, data to stimuli at the same eccentricity were pooled for the right and the left hemisphere and averaged over all subjects.[15] In summary, the data show that there is a difference in whether visual stimuli are presented to one or to both hemispheres: If the two visual stimuli appear in both hemispheres, auditorily accompanied stimuli are both selected more frequently and responded to faster than auditorily un-accompanied ones. This is true for saccades to stimuli at 8° as well as for saccades to stimuli at 24°.

On the other hand, if the visual stimulus pair appears within one hemisphere, auditorily accompanied stimuli at 8° or 24° are still selected more frequently than auditorily un-accompanied ones. In contrast the reaction times remain basically unchanged, irrespective of the selected stimulus (accompanied or un-accompanied). Notice that reaction times are generally much faster (about 30 to 40 ms) if visual stimuli are presented to one hemisphere only. One might assume that, at least in a first stage, presenting an accessory auditory stimulus facilitates the processing of stimuli for the whole hemisphere. Assuming that a saccade is elicited as soon as this activation reaches a threshold, saccades to stimuli at 8° might be as fast as those to 24°. But why are the auditorily accompanied stimuli selected more frequently than the un-accompanied ones when presented to the same hemisphere? It might be assumed—as e.g., the model proposed by Findlay & Walker (1999) does—that the amplitude of the saccade is computed on a different pathway than its triggering. And that the saccade, if once triggered, simply lands with a higher probability at that point in space at which the information is actually highest. Since the auditory stimulus provides better information on the displayed location, the accompanied stimulus might be selected more often than the un-accompanied one, although reaction times to both are equal.

---

[15] Data points whose observed frequency was below 3 were disregarded, since the resulting mean reaction times seemed unreliable.

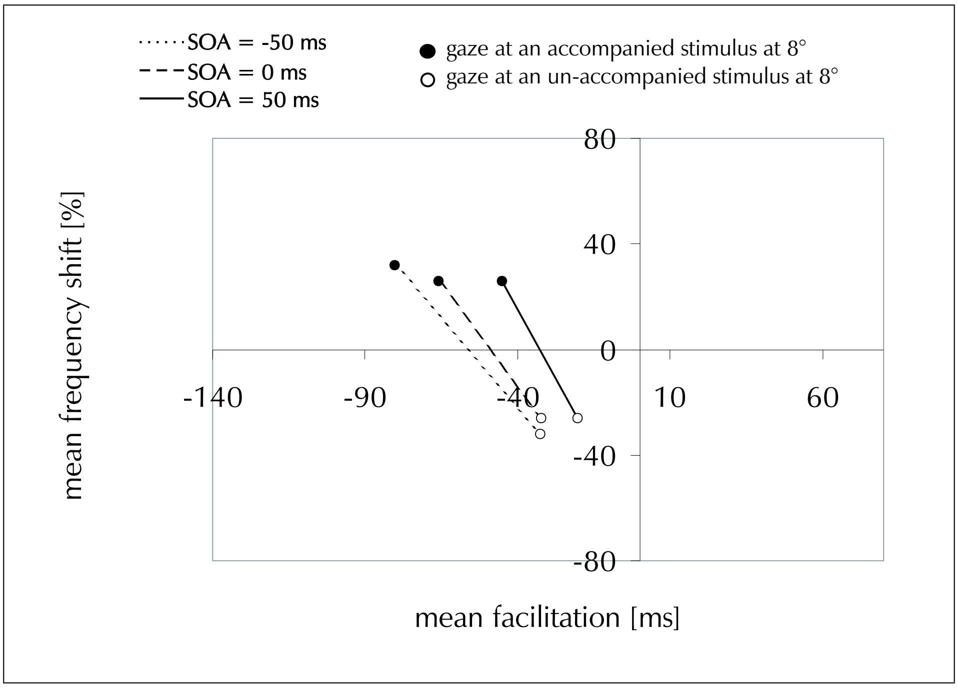

Figure 2.23: Mean difference of gaze frequency and mean facilitation for accompanied and un-accompanied stimuli for the visual stimulus pair 8° right/8° left for three SOAs.

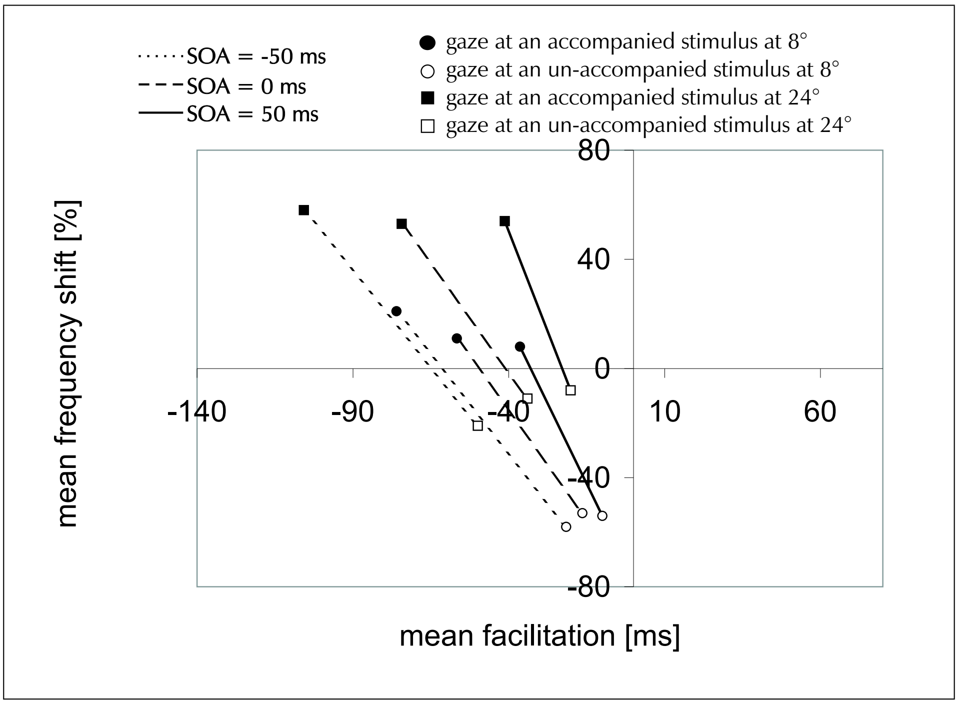

Figure 2.24: Mean difference of gaze frequency and mean facilitation for accompanied and un-accompanied stimuli for the visual stimulus pair 8° right/24° left or visual stimulus pair 8° left/24° right for three SOAs.

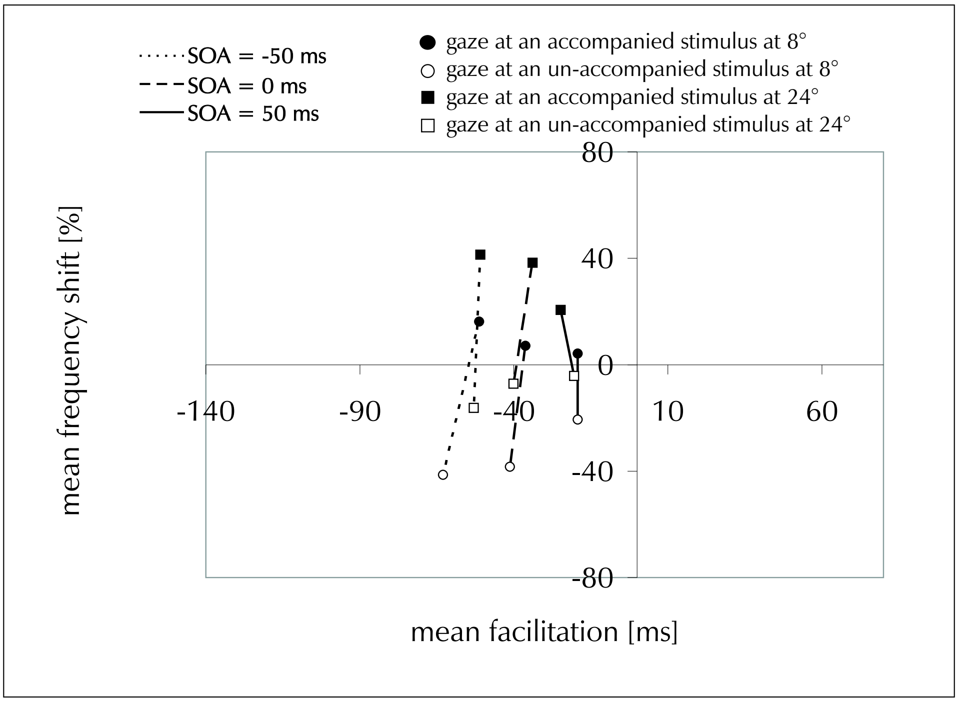

Figure 2.25: Mean difference of gaze frequency and mean facilitation for accompanied and un-accompanied stimuli for the visual stimulus pair 8° right/24° right or visual stimulus pair 8° left/24° left for three SOAs.

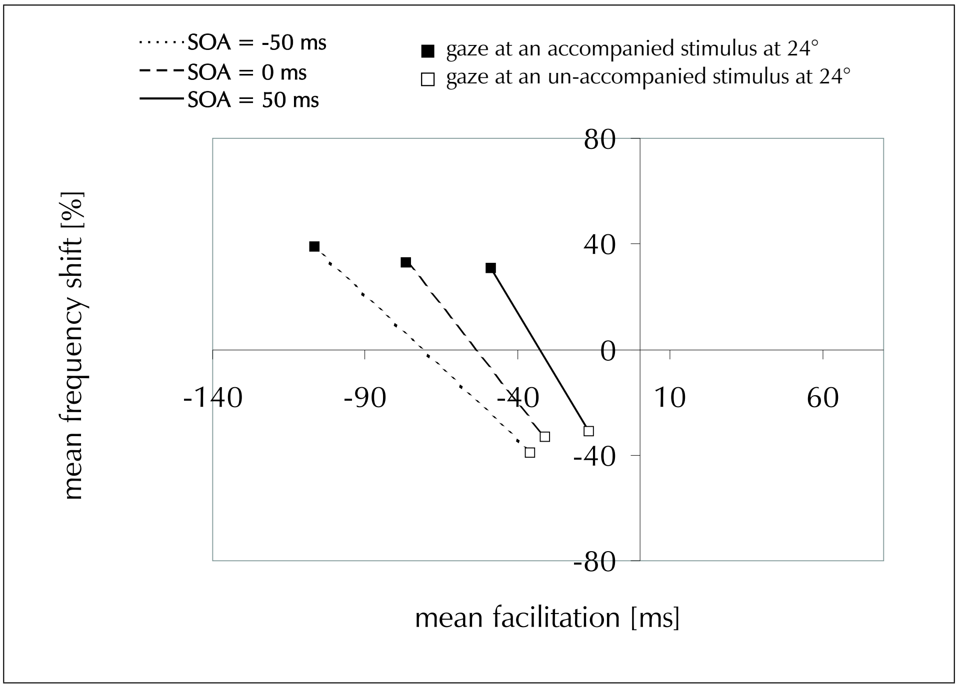

Figure 2.26: Mean difference of gaze frequency and mean facilitation for accompanied and un-accompanied stimuli for the visual stimulus pair 24° right/24° left for three SOAs

2.6 Experiment 5: Errors caused by an auditory accessory stimulus

The last experiment was a control study to determine the influence of instructions. In Experiment 1 and Experiment 4, I had asked subjects to gaze at the visual stimulus and to ignore the auditory stimulus. But is this possible at all? At a very early processing stage, it is likely that orientation reactions are caused by any stimulus, as well by the auditory stimulus. Since the auditory stimulus was always presented at the same location as one of the two visual stimuli, I could not answer this question at this point. Therefore, I conducted a fifth experiment to investigate the errors that might be evoked, if the auditory stimulus was not presented spatially coincident with the visual stimulus. As in Experiment 4 subjects were instructed to gaze at the visual stimulus and to ignore the auditory stimulus. They were not informed about any spatial relationships between the auditory and visual stimulus.

2.6.1 Subjects

All eight subjects[16] who had taken part in Experiment 4 participated also in this experiment. Subjects were not informed about the specific goal of the study.

2.6.2 Stimulus arrangement and experimental design

In this task, I presented only *one* visual stimulus. As in Experiment 4 (see Section 2.5), the stimuli were presented in four sub-experiments:

1. The visual stimulus was presented at 8° right or 8° left.
2. For half of the subjects the visual stimulus was presented at 8° right or 24° left, or, for the other half it was presented at 8° right or 24° left.
3. For half of the subjects the visual stimulus was presented at 8° right or 24° right, or, for the other half it was presented at 8° left or 24° left.
4. The visual stimulus was presented at 24° right or 24° left

In about 14 % of the trials there was a sole visual stimulus. The remaining trials were audio-visual trials. In 50 % of the remaining trials the auditory stimulus was at the same location as the visual stimulus. In the other cases, it was presented at the other stimulus position possible in this sub-experiment. As in the former experiments, the auditory stimulus was presented with one of three possible SOAs: −50, 0 or 50 ms. Each sub-experiment (n=168) consisted of 2 blocks that were conducted on different days.

2.6.3 Results and discussion

To determine the relative frequency of errors only those trials were regarded in which the auditory and the visual stimulus were presented at different locations. When the stimuli

---

[16] In the first two sub-experiments only seven subjects were able to take part.

appeared in both hemispheres, the reaction was counted as an error if the subject made a primary saccade to the wrong direction. When the stimuli were displayed within one hemisphere, I defined an eye movement as correct, if it deviated no more than ±2 standard deviations from the mean amplitude of saccades made to spatially coincident stimuli.[17]

Tables 2.4 through 2.7 show the relative frequency of errors as a function of SOA separately for each stimulus condition and subject. Error rates are rather high, especially if the stimuli appeared at 24° right/24° left. Although χ^2-Tests on constellation and SOA performed separately for each subject[18] in most cases[19] failed to reach significance, there seems to be an overall tendency: Error rates are the higher the earlier the auditory stimulus was presented. The error rate might be explained in the following way: Presenting an auditory or a visual stimulus evokes automatically an orienting reaction towards the stimulus. Only in a later step more high-level influences such as instructions can be integrated. In the cases in which the auditory stimulus was presented early, the movement generation might already have proceeded too far to be stopped by cognitive influences. Therefore, subjects could not withhold their reactions toward the auditory stimuli. Compared to the data found by other researchers as for example Colonius & Arndt (2001), the percentage of auditorily evoked reactions is surprisingly high. However, the task engaged in their experiments were much more difficult (since subjects not only had to discriminate between two possible stimulus positions within a block as in my experiment). And in fact, the faster mean latency in my experiments provides further evidence for this idea. Moreover, in my experiments on visual-auditory interaction the auditory stimulus was always a valid cue for the position for a visual target. Therefore, subjects might have taken advantage of the provided interstimulus contingency.

In general, Experiment 5 suggests that the auditory stimulus can trigger a reflexive response to its position even if it is to be ignored. At the level of neuronal activation one might conclude that presenting an auditory stimulus initiates an information accumulation process even although the subject is instructed to ignore it. One has to bear this in mind when modeling the observed choice probabilities and reaction times in the following chapters.

---

[17] The amplitude of the eye movement was determined as described in section 2.1.3.

[18] Since the cell frequencies were to low Fisher's exact test (one-tailed with $\alpha = 0.05$ and $\alpha_{corrected} = 0.017$) was performed with the following 2×2 crosstabs:

1. Percent of error for SOA = −50 ms versus SOA = 0 ms.
2. Percent of error for SOA = −0 ms versus SOA = 50 ms.
3. Percent of error for SOA = −50 ms versus SOA = 50 ms.

[19] For stimulus condition 8° right or 8° left the shift of frequency was significant for subject *nn*: for SOA = −50 versus SOA = 0 ms: $\chi^2 = 7.39$, $p < 0.009$; for SOA = −50 versus SOA = 50 ms: $\chi^2 = 12.22$, $p < 0.001$; For stimulus condition 24° right or 24° left the shift of frequency was significant for subject *ms*: for SOA = −50 versus SOA = 0 ms: $\chi^2 = 7.56$, $p < 0.008$; for SOA = −50 versus SOA = 50 ms: $\chi^2 = 7.917$, $p < 0.007$.

Table 2.4: Errors (in %) made in the stimulus condition 8° right/8° left, for different SOAs and subjects.

	SOA		
	$-$50 ms	**0 ms**	**50 ms**
mi	4	0	0
sr	29	19	32
jj	0	0	0
nn	44	8	0
cp	9	13	0
ms	17	17	0
th	0	0	0

Table 2.5: Errors (in %) made in the stimulus condition 8° right/24° left or 8° left/24° right, for different SOAs and subjects.

	SOA		
	$-$50 ms	**0 ms**	**50 ms**
mi	14	0	0
sr	19	12	5
rv	9	0	0
jj	21	0	0
cp	8	0	0
ms	30	5	0
th	4	4	0

Table 2.6: Errors (in %) made in the stimulus condition 8° right/24° right or 8° left/24° left, for different SOAs and subjects.

	SOA		
	−50 ms	**0 ms**	**50 ms**
mi	22	0	0
sr	33	0	0
rv	0	0	0
jj	0	0	0
nn	21	4	0
cp	24	4	0
ms	6	6	0
th	5	0	0

Table 2.7: Errors (in %) made in the stimulus condition 24° right/24° left, for different SOAs and subjects.

	SOA		
	−50 ms	**0 ms**	**50 ms**
mi	14	18	0
sr	5	5	5
rv	9	0	0
jj	25	17	8
nn	70	18	27
cp	29	8	4
ms	33	0	0
th	8	0	0

Chapter 3

The Multi-Channel Diffusion Model

3.1 Description of the model

In this chapter I will first discuss a theoretical concept in which the observed data might be embedded and then introduce a model to explain the observed data. In particular, I propose a sequential sampling approach which has been applied to modeling information processing in various psychological tasks, traditionally to account for response time and accuracy data in identification and discrimination tasks using *choice* response time paradigms (e.g., Ashby, 1983; Edwards, 1965; Heath, 1981; Laming, 1968; Link & Heath, 1975; Stone, 1960; Luce, 1986; Townsend & Ashby, 1983, the last item being a comprehensive review).

More recently, this type of model has been used for classification tasks, see, e.g., the works of Ratcliff (1978) (Memory retrieval model) and Nosofsky & Palmeri (1997) (Exemplar-based random walk model of classification). It has also been applied to decision making tasks, see, e.g., Busemeyer & Townsend (1993) (Decision Field Theory) and Diederich (1995, 1997) (Multiattribute Dynamic Decision Model).

Moreover, it was employed to account for observed response time patterns in detection tasks using *simple* response time paradigms (e.g., Diederich, 1992, 1995; Pacut, 1980, 1982; Smith, 1990, 1995).

The basic idea of this approach is that information in sensory or cognitive systems is accumulated over time until a preset criterion is reached and a response is initiated. That is, a response is initiated when enough information has been obtained. *Information* in this context usually means any changes in the central nervous system that translate perception and cognition into action (Luce, 1986; Smith, 2000). Characteristics of both the stimuli and the subjects might influence the information accumulation process. For example, the higher the intensity of the stimulus the sooner the accumulation process reaches a decision criterion.

Sequential sampling models assume that the information about stimuli can be mapped onto numerical values. Further, they assume some random fluctuation in the process of information accumulation. Therefore, sequential sampling, i.e. the accumulation of information, can be described as a stochastic process.

Stochastic processes may be distinguished according to their assumed *state space* and *index set*. The state space may be discrete or continuous. In this context it contains possible information states of the process (activation states). The index set, often called time space, contains the indices for which the process is defined. Again, the index set may be discrete or continuous. *Random walk models* are stochastic processes with discrete state space and discrete index set, e.g., natural numbers. Discrete amounts of information are accumulated at discrete points in time. *Diffusion processes* have continuous state space and continuous index set, i.e., real numbers. That is, the discrete pieces of information are replaced by the assumption of a continuous growth of information on a continuous time scale.

One prototype of a sequential sampling model is the *Multi-Channel Diffusion Model* developed by Diederich (1992). This model was used successfully to explain the sensory interaction effect in simple reaction times (Diederich, 1995) and decision making tasks (Diederich, 1997).[1] Consider first a simple reaction time task (see Fig. 3.1). The *Multi-Channel Diffusion Model* assumes that as soon as a stimulus is presented to the subject, the nervous system stochastically accumulates very small amounts of information continuously over time. From the point of neurobiology the process of accumulating is equivalent to the gathering of neural action potentials that enter the central sensory system after peripheral stimulus onset. Further, it is assumed that activation never drops below its initial level. That is, the process is reflected on a lower boundary. Finally, the information accumulation process stops and a response is initiated as soon as the preset criterion level is reached. Mathematically, this process will be described as a diffusion process with one absorbing and one reflecting boundary. In particular, a Wiener process, characterized by its drift coefficient λ and its diffusion coefficient σ^2 is utilized. The drift coefficient may be related to the intensity of the stimuli and interpreted as intensity parameter, which differs for different sensory modalities and eccentricity. For example, a bright visual stimulus might provide more information, or a larger drift coefficient, than a less intensive visual stimulus. It is assumed that—at a common processing stage—information of different sensory modalities is taken together to provide a greater amount of information than if collected within only one modality. For convenience, the drift coefficients referring to the visual and auditory stimuli are labelled λ_V and λ_A, respectively. The diffusion coefficient of the process is basically a scaling factor and, for simplicity, set to 1. The process stops, if a *decision criterion* is reached. The *decision criterion* is a criterion, set by the subject, that defines the level of information at which a response is performed. Note that the decision criterion can be manipulated by the experimental design, e.g., by the instruction or the difficulty of the required task.

Let us consider what might happen in terms of the Multi-Channel Diffusion Model in Experiment 1 (for details see Section 2.2) for different stimulus conditions. In the simplest case just *one* visual stimulus was presented (see Fig. 3.1).

There was only one appropriate direction to gaze at, i.e. only one decision criterion, (e.g., to look at a visual stimulus at 8° right), is to be considered. As soon as the visual stimulus appears, the diffusion process is driven to the decision criterion by drift rate λ_V. Since in the *purely visual condition* the stimulation remains the same over the time, the drift rate remains the same as well. When enough information is collected, i.e. the decision criterion is reached, the response is initiated.

The first point in time when the process reaches the criterion is called *first passage time.*

---

[1] Here, I will present the model in a rather descriptive way; for a detailed mathematical description, see (Diederich, 1992).

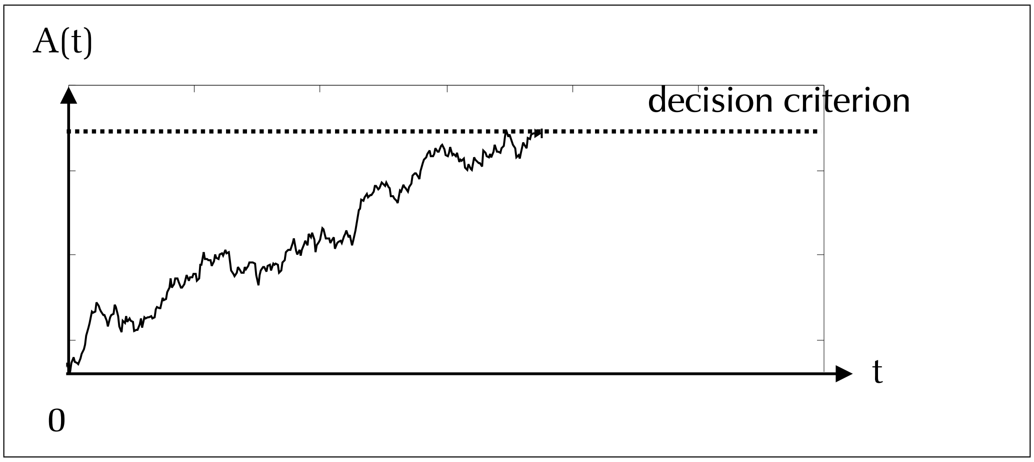

Figure 3.1: A stochastic trajectory for the information accumulation process when one visual stimulus is presented.

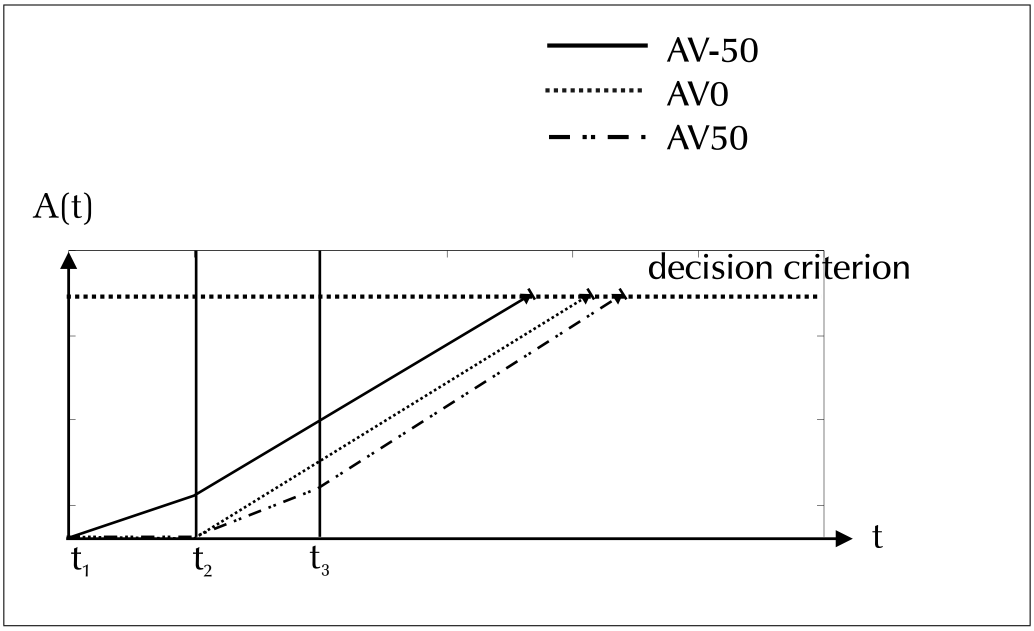

Figure 3.2: Mean drifts for the information accumulation process when one visual and one auditory stimulus is presented with different SOAs.

Fig. 3.2 shows what might happen, when an accessory auditory stimulus is presented τ ms later or earlier than the visual stimulus.

Assume for example the auditory stimulus is presented first (AV-50). Then the process starts at t_1 with drift parameter δ_A. 50 ms later, the visual stimulus is presented. Since it is assumed that the drift rates of both processes are combined, there is a greater amount of information than in the first period. Remember, the moment when the information process reaches the decision criterion determines the first passage time. Because of the additionally presented auditory stimulus, there is more information available than in the first example and so the model predicts shorter mean reaction times. Therefore, the diffusion model could explain the intersensory facilitation effect as a result of just combining visual and auditory information. No further effect such as some kind of warning, is necessary. So one might explain the other conditions in quite the same way: If the auditory stimulus is presented 50 ms after the visual stimulus (AV50), the process only starts at t_2 with the drift parameter for the visual stimulus δ_V till the auditory stimulus is presented and the drift rates are summed up as before.[2] If visual and auditory stimuli were presented at the same time (AV0), the information accumulation process starts at t_2 with the summed drift rate.

Now consider a binary choice response time task.

As before, assume that as soon as a stimulus is presented to the subject, the nervous system stochastically accumulates very small amounts of information continuously over time. However, since two visual stimuli are presented at different spatial locations (e.g., 8° left and 8° right) the process accumulates evidence to initiate a response to one of the two positions.[3] The information accumulation process can be described by a stochastic process with *two absorbing boundaries*, one boundary to initiate a left-response and one boundary to initiate a right-response. Assuming that equally intensive stimuli are presented at the same eccentricity and provided that subjects do not have an a priori tendency (bias) to gaze at a particular direction, the probability to gaze either at the left or at the right stimulus side would be equal. The probability for deciding on one of the two stimuli is denoted as *first passage probability.* The assumption that the drift rates remain the same for single and for double stimuli is called *context independence.* If the subject has a preference for one hemisphere, the diffusion process will not start at zero, but at a starting position that lies somewhere between zero and the decision criterion for the preferred hemisphere. Two exemplary stochastic trajectories for the decision process between two visual stimuli for a subject with bias are shown in Fig. 3.3. Here, the left hemisphere is preferred, so the bias is located between zero and the decision criterion for a left-side decision. As can be seen, the decision criterion for the preferred hemisphere is reached earlier than the one for the other hemisphere.[4] In fact, the model would predict faster reaction times, if the subject gazes at a stimulus along her/his preferred hemisphere. Besides this, since less additional information is necessary to reach the criterion for the stimulus in the preferred hemisphere one might expect that the subject decides for this stimulus more often than for the other one.

---

[2] In the implementation of the diffusion model used here, it is assumed that the drift rates are combined additively. However, this is not a necessary restriction of the model. In fact, there are a lot of possibilities for combining the drift rates.

[3] Note that the same assumptions are made for the ‘ipsilateral’-stimulus condition.

[4] Of course this only holds for the *mean drift*, not for each trajectory.

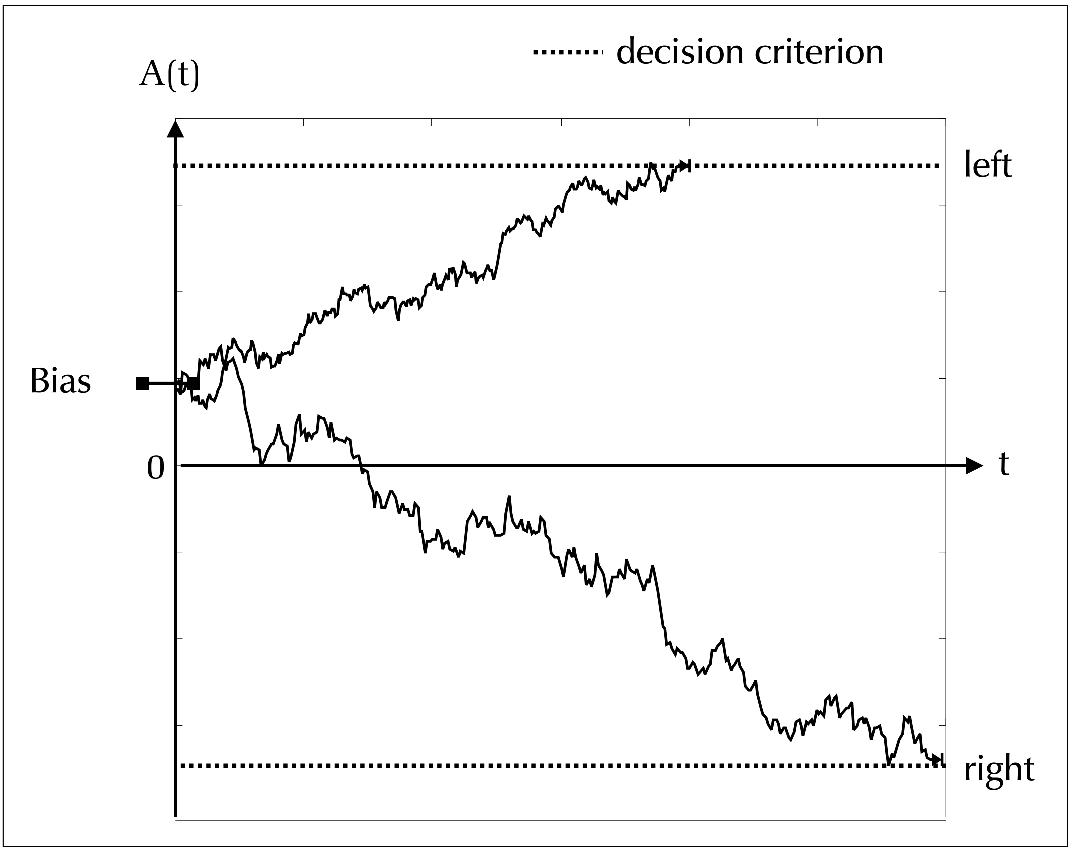

Figure 3.3: Stochastic trajectories and mean drift for the decision process between two visual stimuli.

The application of this model to the Experiments 1 and 4, described in section 2.2 and 2.5, will be presented in the next section.

Chapter 4

Modeling of experimental data

This chapter describes the application of the *Multi-Channel Diffusion Model* to the data gained from Experiment 1 and Experiment 4. Therefore, I first estimated the parameters for the model in terms of mean reaction times for single visual or audio-visual stimuli. My assumption, adopted from Diederich's Model (1992), was that the observed reaction time is composed additively of a random processing time T and a constant residual time r, that includes all remaining processes such as motor preparation and response execution. At the level of expectations, this gives:

$$E[RT] = E[T + r] = E[T] + r \tag{4.1}$$

In detail, the applied model has seven parameters:

1. drift coefficient for visual stimuli at 8° right or left, λ_{V8}
2. drift coefficient for visual stimuli at 24° right or left, λ_{V24}
3. drift coefficient for auditory stimuli at 8° right or left, λ_{A8}
4. drift coefficient for auditory stimuli at 24° right or left, λ_{A24}
5. boundaries of the diffusion process Θ and $-\Theta$
6. individual bias parameter β
7. residual time r

The drift coefficients λ might be interpreted as stimulus intensity parameters. As already mentioned in the previous chapter, it is assumed that the drifts vary for different eccentricities and modalities. The larger the drift, i.e. the greater the amount of information, the earlier the diffusion process will reach the decision criterion set by the subject. In the double target condition, I assume two decision criteria of the same size. So in both cases, I have to estimate one parameter for the decision criterion. If the subject has an inherent preference for one hemisphere—as most of the subjects had—this was modeled by an additional bias parameter β. Due to the experimental setup, small modifications of the model were made, which will be described in the respective sections. All parameters were estimated individually for each subject using the *simplex search method* implemented in Matlab 5.3 to minimize an objective function. As objective function I used the sum-of-squares deviation between predicted and observed data.[1] In the next step, the estimated drift parameters and the residual time r were used to predict choice probabilities and mean reaction times in the double target condition. Boundary and bias parameter were estimated once again. This became necessary due to the additional decision process, the double target condition seemed to be more complicated than the single target condition. This could be reflected by larger criteria. Altering the size of the decision criteria requires fitting the bias parameter to preserve the relationship between these two parameters.

4.1 Modeling the results of Experiment 1

In Experiment 1, each stimulus condition was presented in a random order in every experimental block. So I expected no further context effects, such as advanced practice or momentary fitness, which could have occurred in blocked designs. For that reason, I estimated the parameters from all single target conditions at once to fit the data of all presented double target conditions. Since Experiment 2 has shown that subjects were not able to discriminate stimuli within one hemisphere and because there was no clear pattern in the data (see Section 2.2.6), I decided to omit this condition from my estimations. For the other conditions, I estimated seven parameters to fit 16 averaged data points (observed mean reaction times in the single target condition). Then I kept the estimated drift parameters and the parameter for the residual time r fixed to estimate once again the boundary and the bias parameter and predicted 63 data points (21×2 mean reaction times and 21 choice probabilities in the double target condition) for each subject separately.

4.1.1 Parameter estimations for the single target condition

As can be seen in Table 4.1, the residual times r are in the same range for all five subjects. All but one subject (*mi*) showed a preference for one hemisphere.[2] So for the subject mi, the parameter set reduces to six parameter. Since I artificially slowed the visual stimulus at 8° down by presenting it 26.6 ms later than the visual stimulus at 24°, I supposed, that the visual drift parameters λ_{V8} and λ_{V24} would be estimated to have about the same size. However, this is only true for one subject (*ld*), the correction seemed to be a little too weak or too strong for the other subjects. This is not very surprising, since I did not adjust the correction times individually. Interestingly, the auditory drift coefficients showed the order: $\lambda_{A24} > \lambda_{A8}$ for four subjects (*ld*, rv, *cs*, *cp*).
This is in accordance with the observation that the response to auditory stimuli is faster for 24°-stimuli than for 8°-stimuli. Generally, the data fits are quite good for all subjects.

Figures 4.1 and 4.2 show the observed mean reaction times and the predicted reaction times in an exemplary fashion for two subjects (*mi* and *cp*). The observed standard errors of the means are also shown. But in many cases they were too small to be displayed.

---

[1] Since the probabilities always had a much smaller range than the reaction times, they were multiplied by a weighting factor of 1000. The mean reaction times were weighted with their probabilities of occurrence to take the much greater reliability of some means into account.

[2] For technical reasons I arranged the data to always obtain positive values for the bias parameter β. Anyway, three subjects preferred the right hemisphere whereas two subjects preferred the left hemisphere.

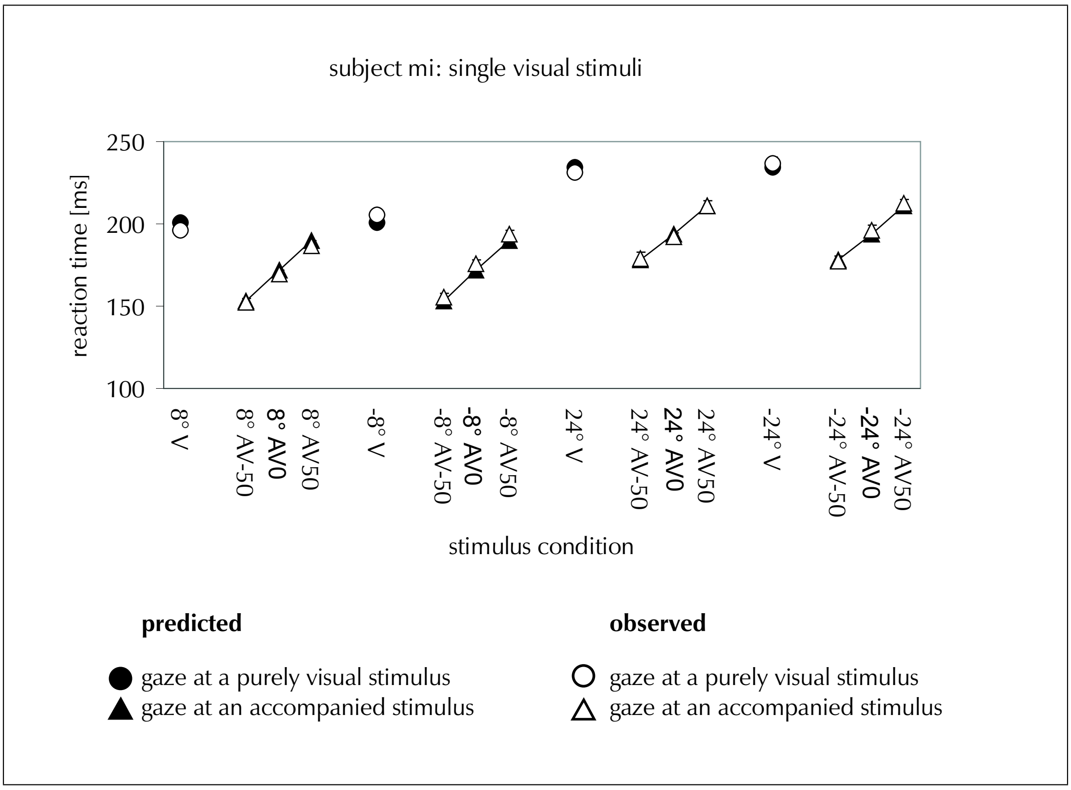

Figure 4.1: Subject *mi*: Single target condition. Given are the predicted and observed mean reaction times and standard errors.

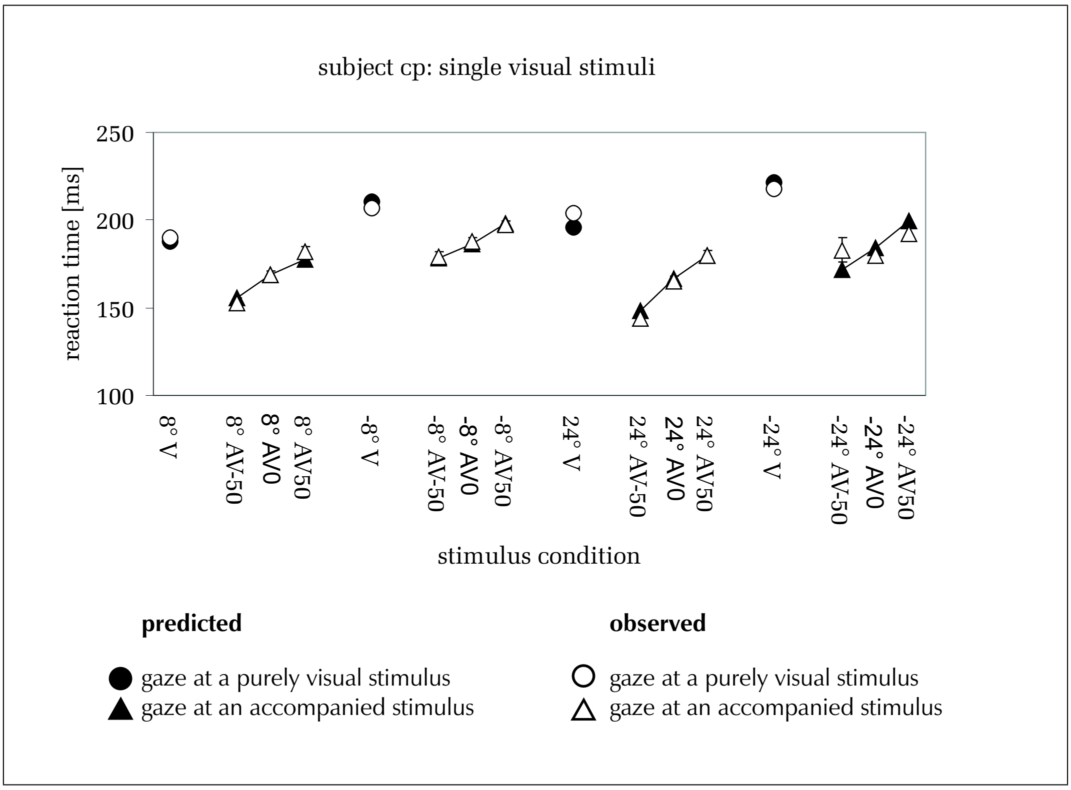

Figure 4.2: Subject *cp*: Single target condition. Given are the predicted and observed mean reaction times and standard errors.

The results of the other subjects can be found in Appendix B.1.

Table 4.1: Estimated parameters of single target condition

	mi	**ld**	**rv**	**cs**	**cp**
λ_{V8}	0.1513	0.0712	0.0768	0.0832	0.1008
λ_{A8}	0.1885	0.088	0.0342	0.0375	0.0565
λ_{V24}	0.0756	0.0724	0.1134	0.0607	0.0843
λ_{A24}	0.1028	0.1325	0.064	0.0787	0.0814
β	0	6	7	4	7
Θ	16	17	18	17	17
r	96	89	79	79	77

4.1.2 Parameter estimations for the double target condition

In the next step, I used the estimated drift parameters and residual times to predict the expected choice probabilities and mean reaction times for the double target condition. Since the model had to be expanded in two decision criteria, one for each target position, I had to re-estimate the parameter for the decision criterion and the size of the bias parameter.[3]

Table 4.2: Parameters estimated on the double target condition

	mi	**ld**	**rv**	**cs**	**cp**
β	1	2	1	1	1
Θ	16	13	14	14	12

Table 4.2 presents the estimated parameters for the bias and the decision criteria for five subjects. The decision criteria are smaller than in the single target condition and their magnitude is about equal for all subjects. For subject *mi* the distance between the bias coefficient and the decision criterion coefficient is the largest, since *mi*—unlike the other subjects—did not show strong hemispheric preferences. This is consistent with the estimation in the single target condition, in which subject *mi* did not show any bias at all. The predicted mean reaction times fit the observed pattern quite well for all subjects.

As it is shown for the subjects *mi* and *cp* in Figures 4.3 and 4.5 (for all the remaining subjects, see Appendix B.2), some mean reaction times are considerably longer or shorter, in absolute figures than those predicted by the model. Furthermore, the fits for the means to un-accompanied stimuli are much poorer than for the accompanied stimuli.

One reason for this might be that there is generally much more scatter in the observed data points to un-accompanied stimuli than to accompanied stimuli since they are based

---

[3] For technical reasons I had to include one modification to the diffusion model described in Chapter 3: The beginning of the process had to be set by the first visual stimulus that was presented, e.g., the visual stimulus at 24°. In the model, this was achieved by the assumption of an additional time interval ι_0. So if a visual stimulus at 24° appeared, the drift rate started in ι_0 to raise towards the boundary. However, if the visual stimulus at 8° was presented first—which means that *only* stimuli at 8° were presented—the drift rate in the time interval ι_0 was set to zero.

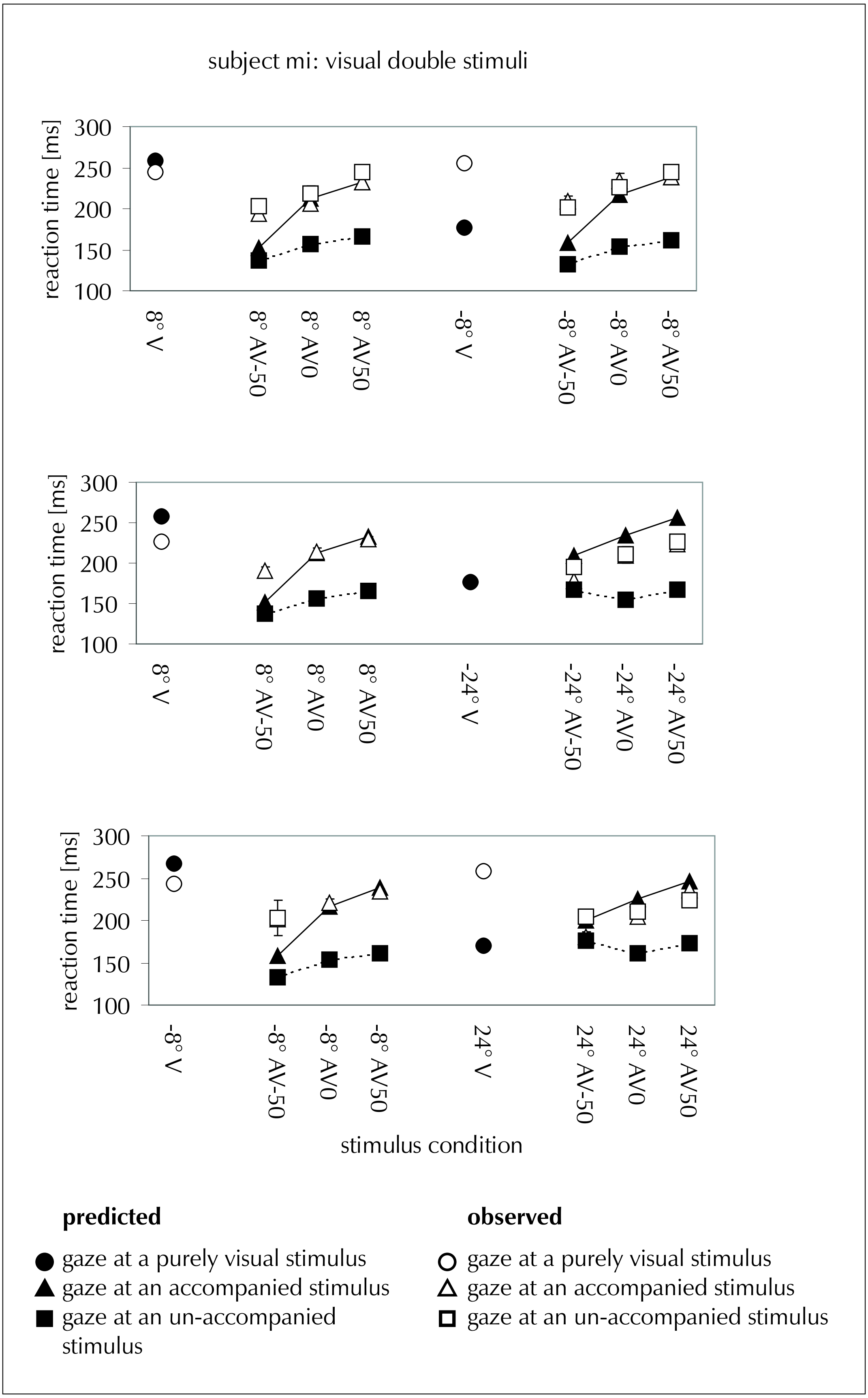

Figure 4.3: Subject *mi*: Three double target conditions. Given are the predicted and observed mean reaction times and standard errors.

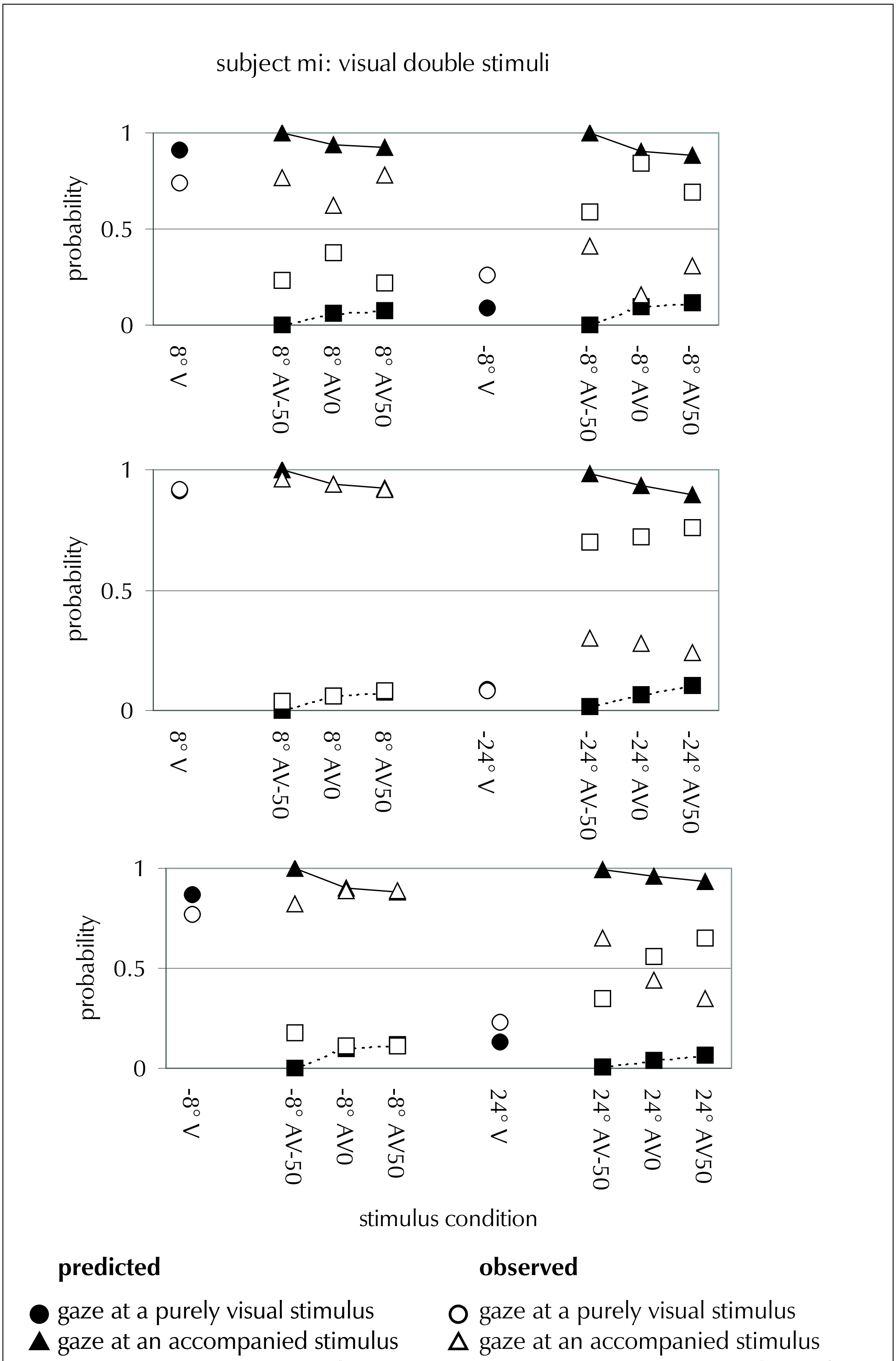

Figure 4.4: Subject *mi*: Three double target conditions. Given are the predicted and observed probabilities.

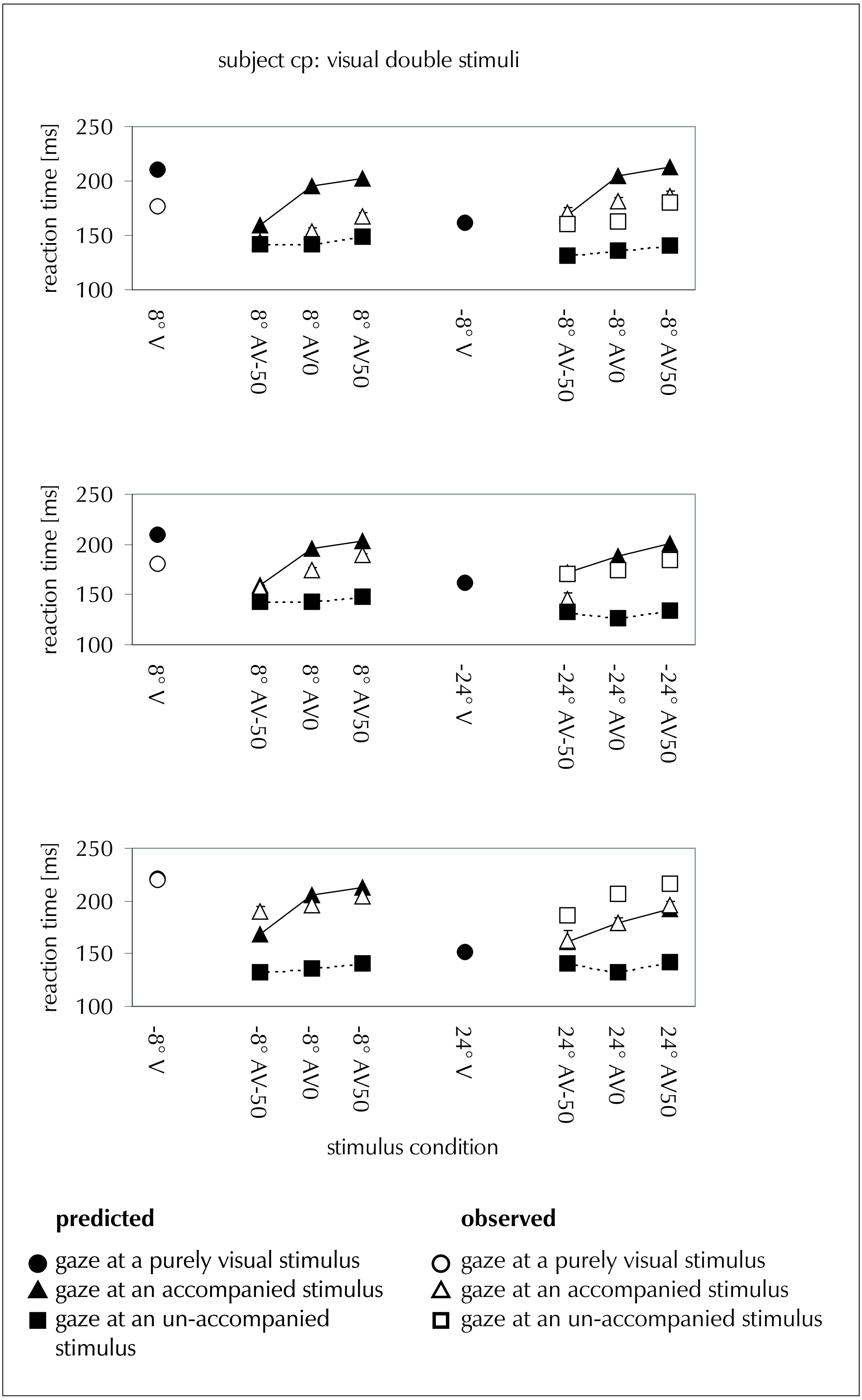

Figure 4.5: Subject *cp*: Three double target conditions. Given are the predicted and observed mean reaction times and standard errors.

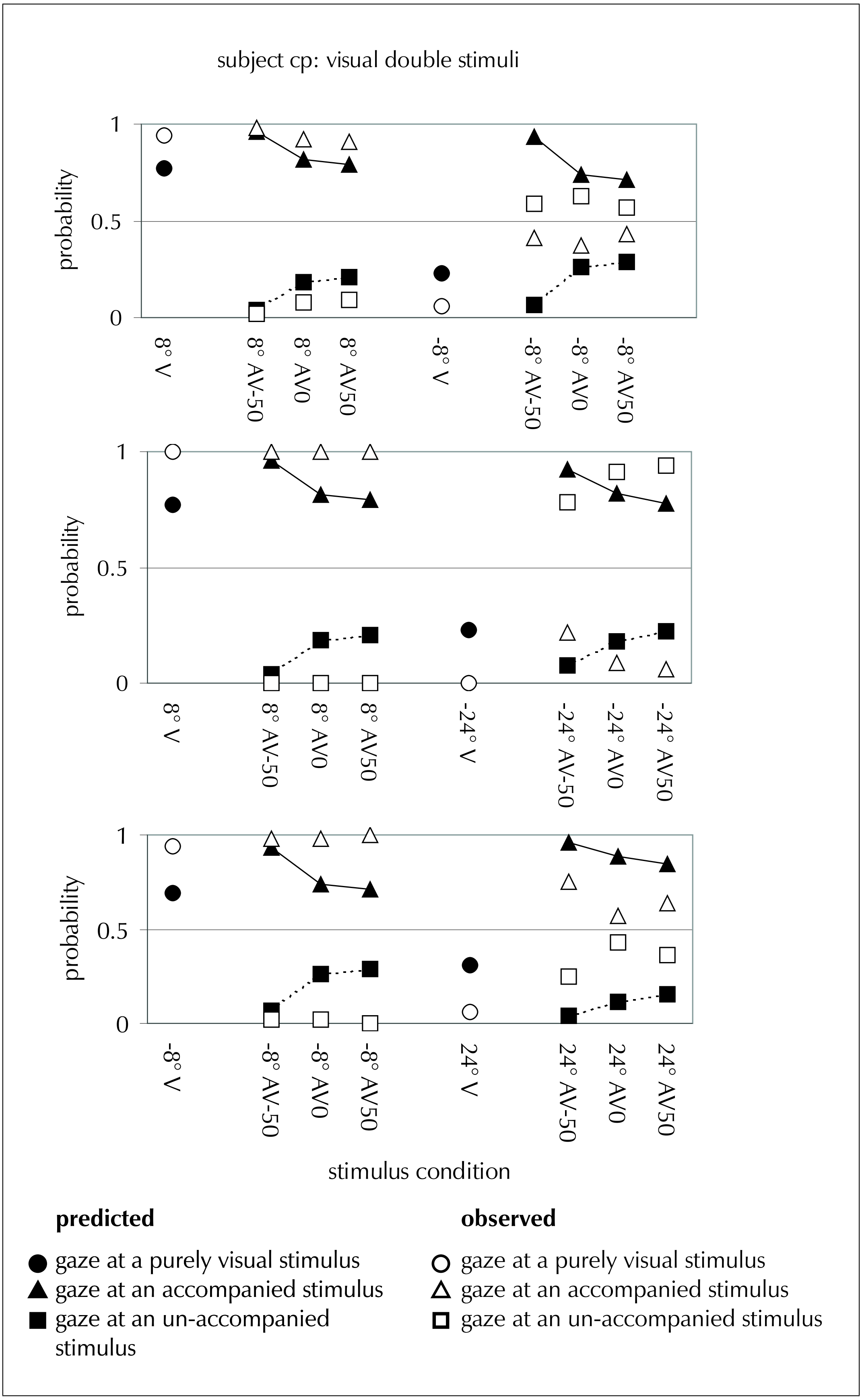

Figure 4.6: Subject *cp*: Three double target conditions. Given are the predicted and observed probabilities.

on less observations. Figures 4.4 and 4.6 show the respective fits of the probabilities for subjects *mi* and *cp* (see Appendix B.2 for the whole sample). Reaction times are ordered according to the SOAs, i.e. an early presentation of the auditory stimulus accelerates the response. In contrast, this is not the case for choice probabilities. For example subject *mi* did not select the accompanied stimuli more often if the auditory stimulus appeared 50 ms before the visual stimulus (SOA = −50 ms) than if it appeared at the same time (SOA = 0 ms) as the model would predict. A possible reason for this might be that the data base is too weak to reveal such a relationship. Just notice that one observation corresponds to a change in probability of 2%. Nevertheless, on some conditions the predicted probabilities deviate characteristically from the observed data for some conditions. If the accompanied stimulus appeared at 24° left or right of the fixation point, the model predicts much higher probabilities for all SOAs than could be observed.[4] This means, the model can not account for a very strong preference for the inner stimulus; instead, it predicts choice probabilities for stimuli at 24° higher than observed. This might be due to the fact that I determined all parameters from the single stimulus conditions. Therefore, no spatial relationship between the two visual stimuli is included. In fact, *context independence* is one necessary requirement of my approach.

4.2 Modeling the results of Experiment 4

In Experiment 4, all visual stimuli were presented at the same time. To overcome the effects of eccentricity, the intensity of the visual stimulus at 8° was adjusted to achieve equal choice frequency as the visual stimulus at 24° (for details see Section 2.5). Since there was no interaction effect between *experimental design* (blocked or not blocked) and *preference of bimodal stimulus* and in order to facilitate the localization of the auditory stimulus, the stimulus conditions were measured separately in four successive experiments (for details see Section 2.5.4). To consider contextual effects, I did not estimate the parameters for all stimulus conditions at once, as I did for Experiment 1, but split them up into four different sections for parameter estimations.

4.2.1 Parameter estimations for the single target condition for the visual stimulus pair 8° right/8° left

I estimated five parameters from eight data points (each mean obtained from on average 46 valid trials). Table 4.3 presents the estimated parameters for 8 subjects.

There is no constant ordering of the estimated drift parameters, neither for the visual nor for the auditory one. This might be due to the fact that the visual stimulus was less bright than in Experiment 1 whereas the intensity of the auditory stimulus was held fixed. Again, subjects showed a more or less strong preference for one hemisphere.[5] The residual times r were between 42 and 73 ms for six of eight subjects (*mi*, *sr*, *rv*, *jj*, *cp*, *ms*). For the subjects *nn* and *th* the estimations of the residual times r were larger (100

---

[4] Of course, the reverse is true for the un-accompanied stimuli since the probabilities must sum up to 1.

[5] For technical reasons I arranged the data to have always positive values for the bias parameter β. Anyway, two subjects preferred the right hemisphere whereas six subjects preferred the left hemisphere.

Table 4.3: Parameters estimated on the single target condition for the visual stimulus pair 8° right/8° left

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**	**th**
λ_{V8}	0.0819	0.0217	0.0412	0.0795	0.0996	0.109	0.03	0.0462
λ_{A8}	0.0314	0.0267	0.0355	0.1211	0.2941	0.0545	0.0456	0.0602
β	1	6	5	1	5	8	7	3
Θ	20	16	16	17	21	22	17	16
r	52	45	57	73	100	42	49	82

and 82 ms). However, the observed reaction times of these subjects were somewhat longer than compared to those of the others. In general, data fits for the mean reaction times are very good for all subjects.

The results of two subjects (*jj* and *cp*) are shown in Figures 4.7 and 4.8. (For the data fits for the other subjects see Appendix C.1.1.)

4.2.2 Parameter estimations for the double target condition for the visual stimulus pair 8° right/8° left

By keeping the estimated drift coefficients and the residual time r constant and estimating only the parameters for decision criterion and bias again, I predicted mean reaction times and choice probabilities for the double target condition. The estimated parameters for all subjects are shown in Table 4.4. The coefficient for the decision criterion, as well as the one for the bias, is smaller than estimated for the single target condition. In fact, the decision criteria are not really comparable since the distance from starting position to criterion in the single target condition might differ from that in the double target condition. The predictions for the mean reaction times are quite good, especially if the subjects gazed at auditorily accompanied stimuli. For the reactions to un-accompanied stimuli, the model still can account for the observed pattern, but predicts much faster reaction times than observed. Although this worse fit might partly have been caused by the much smaller data base for the un-accompanied stimuli than for the accompanied stimuli, it seems to reflect a general difficulty of the model with that kind of reaction. I will address these *'fast errors'* later on in the discussion (see Section 5).

Table 4.4: Parameters estimated on the double target condition for the visual stimulus pair 8° right/8° left

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**	**th**
β	0	0	0	1	1	2	2	3
Θ	16	15	14	16	16	17	13	14

The results of two subjects (*jj* and *cp*) are shown in Figures 4.9 and 4.10. (For the whole sample see Appendix C.2.1.) The predictions for the choice probabilities, depicted for two subjects in Figures 4.11 and 4.12, match the observed pattern in all but one subject (*th*). Since, due to improper fixation or blinks, the data base for this subject was poor, this might have been caused by a greater variance in the observed data. However, for four of eight subjects (*mi*, *sr*, *nn*, *cp*) the model predicts a much higher choice probability for

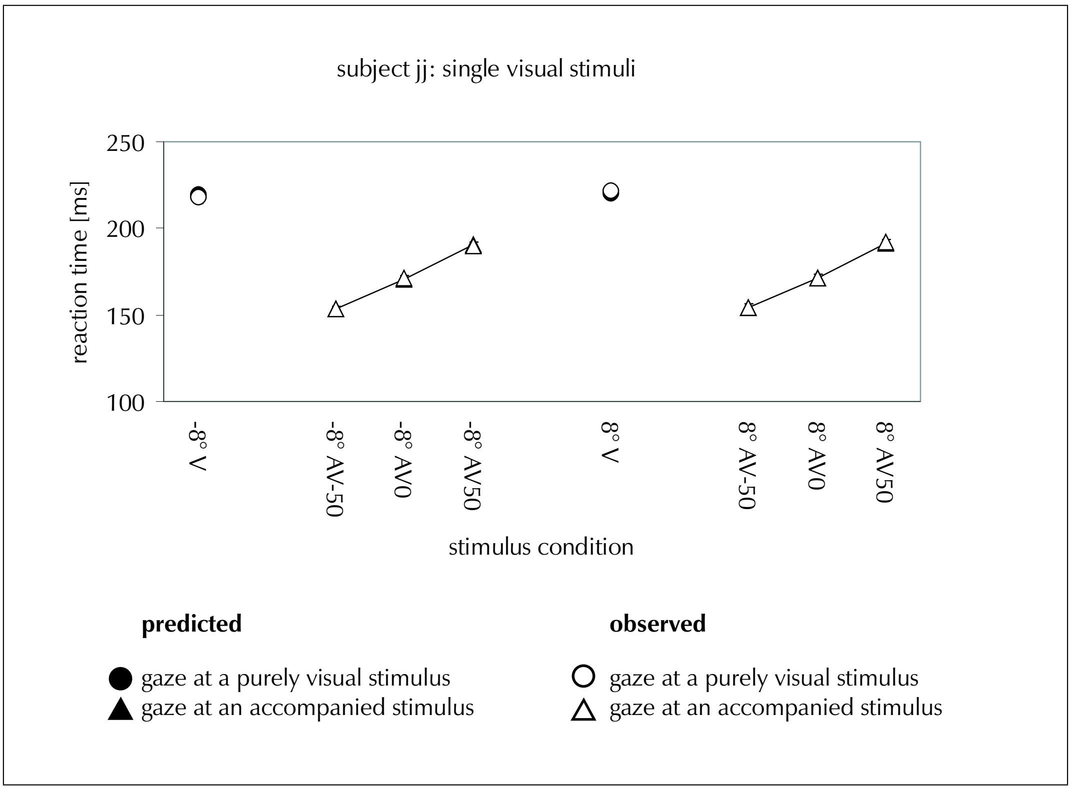

Figure 4.7: Subject *jj*: Single target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

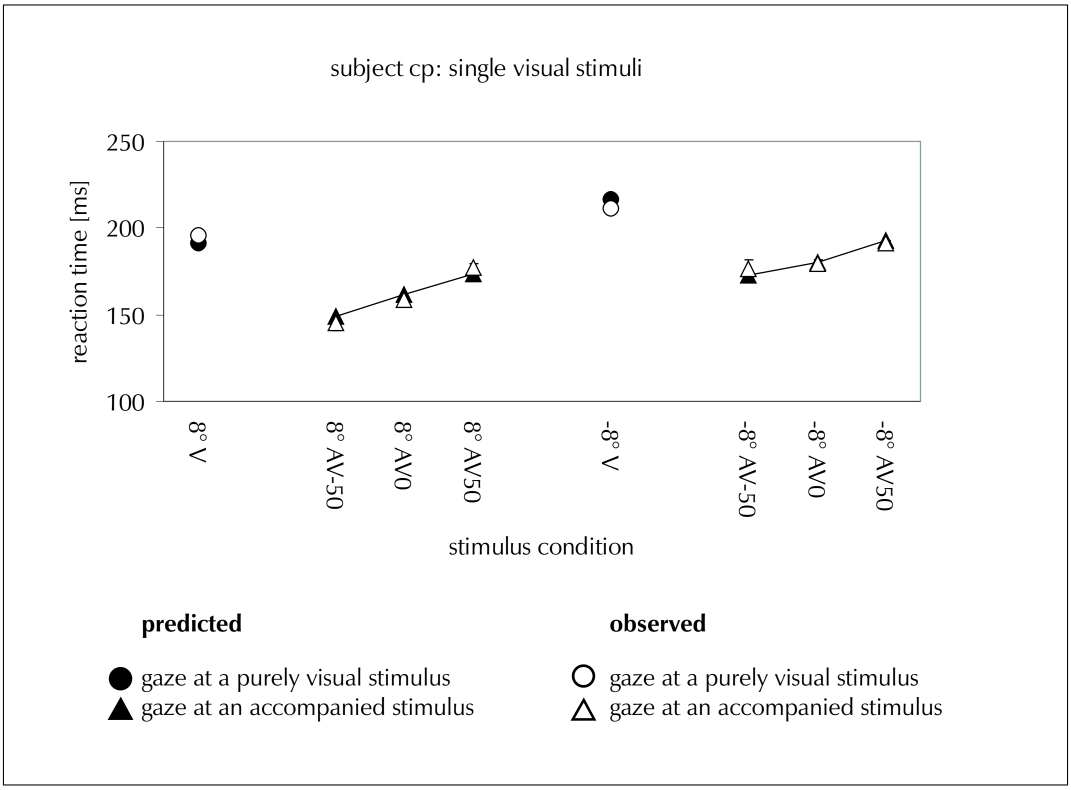

Figure 4.8: Subject *cp*: Single target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

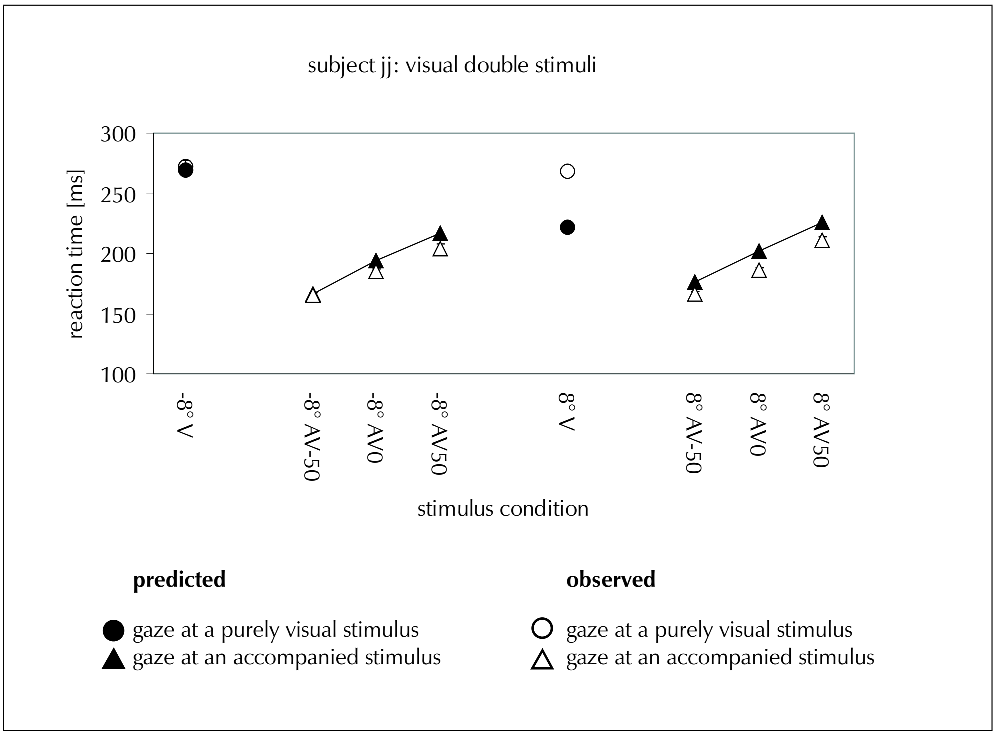

Figure 4.9: Subject *jj*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs. Since the database for saccades to un-accompanied stimuli was too low, only saccades to accompanied stimuli are displayed.

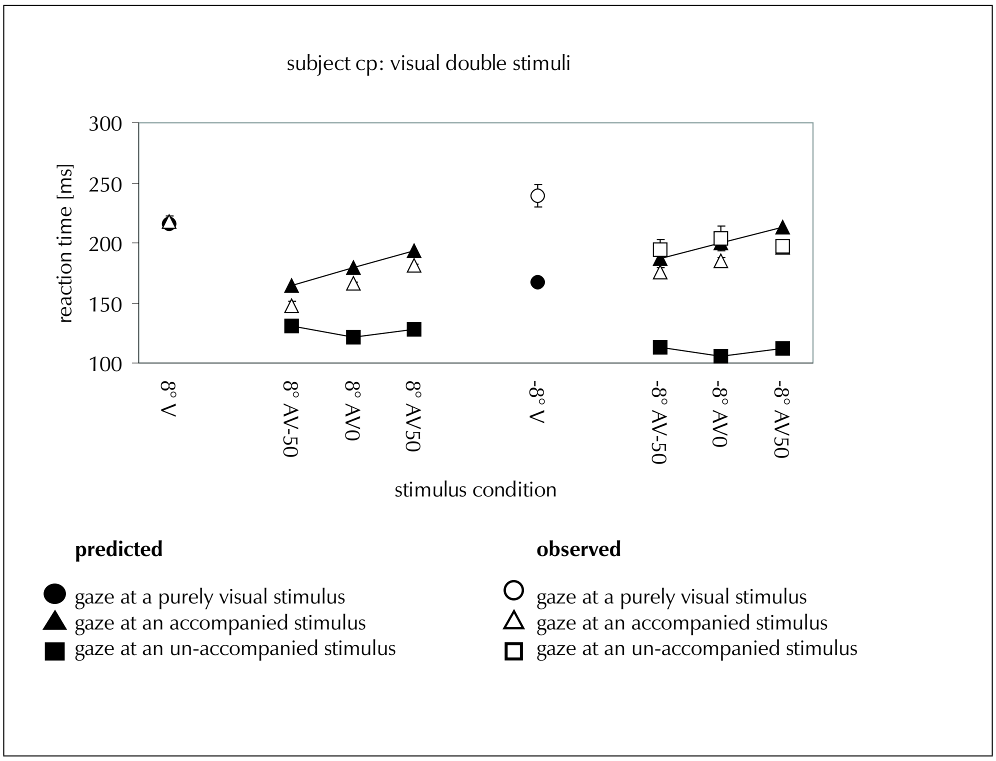

Figure 4.10: Subject *cp*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

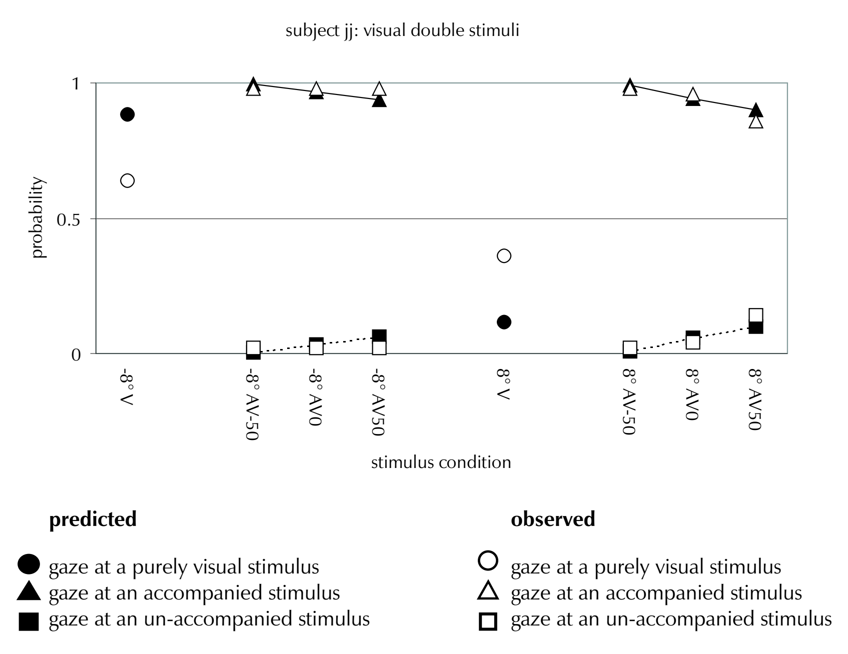

Figure 4.11: Subject *jj*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed probabilities for three SOAs.

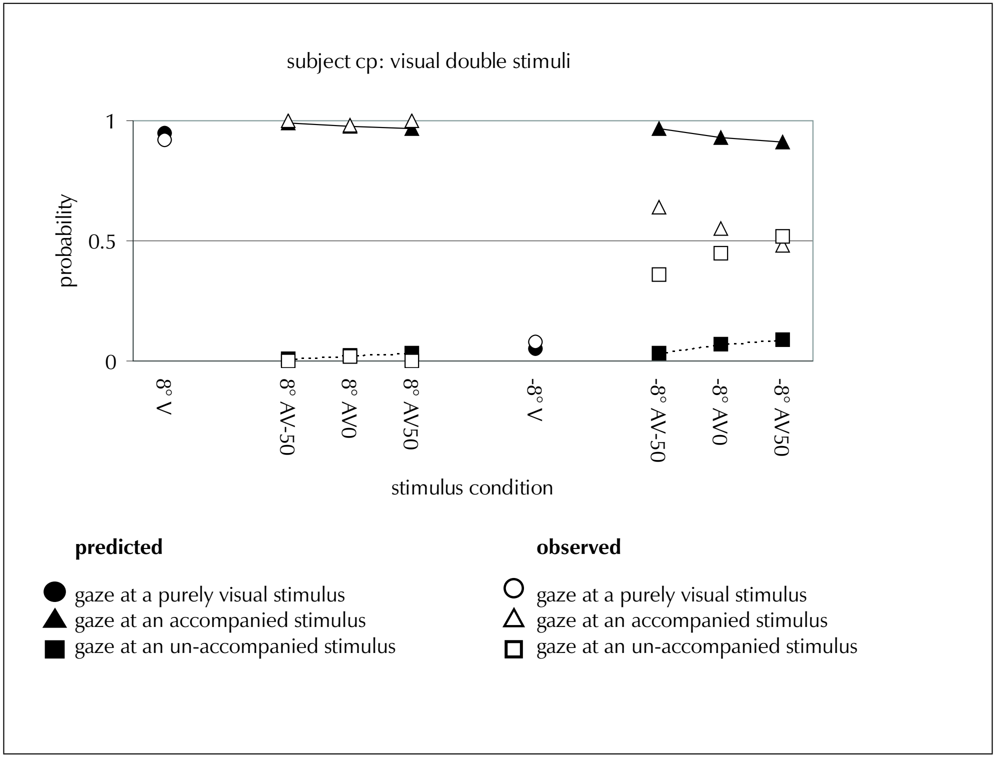

Figure 4.12: Subject *cp*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed probabilities for three SOAs. Note that the predicted values for saccades to 8° left differ remarkable from the observed. This is due to the very strong bias to the right hemisphere of this subject that covers up the influence of the auditory stimulus in a way the model can not account for.

the accompanied stimuli than I could actually observe. This holds for all SOAs. Moreover, if there is no auditory stimulus at all, the model predicts a higher choice probability to a larger bias effect than observed: Five of eight subjects (*mi*, *sr*, *rv*, *jj*, *nn*) did not show such a strong tendency to look at the visual stimulus in the biased hemisphere as predicted by the model.

4.2.2.1 Parameter estimations for the single target condition for visual stimulus pair 24° right/24° left

Five parameters were estimated from eight data points (each mean obtained from on average 48 valid trials).

Table 4.5 shows the Parameter estimations for all eight subjects. For most subjects, the drift coefficient for the auditory stimulus is larger than the one for the visual stimulus. This is quite reasonable since it is known, that auditory stimuli elicit faster responses the more eccentric they are (Yao & Peck, 1997). The residual times vary between 62 and 103 ms. Compared to those of the visual stimulus pair 8° right/8° left, they are a little bit longer. This might reflect a greater amount of time used for the motor component in the more eccentric stimulus constellation. For all subjects a bias parameter was estimated.[6] The direction of the bias remained the same for all but one subject (*th*) as in the previous stimulus constellation (8° right/8° left). Since the direction of the bias was not clear, I decided to exclude the data of subject *th* from further analysis. The data fits for all other subjects are very good.

Table 4.5: Parameters estimated on the double target condition for the visual stimulus pair 24° right/24° left

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**	**th**
λ_{V24}	0.0714	0.056	0.1624	0.0968	0.1029	0.1076	0.1596	0.1499
λ_{A24}	0.1448	0.1751	0.1368	0.3795	0.3275	0.1038	0.5667	0.2029
Θ	17	15	21	22	20	19	25	24
β	5	1	6	6	3	6	6	8
r	99	90	65	103	83	62	85	80

Figures 4.13 and 4.14 show the results for two subjects (*jj* and *cp*) (see Appendix C.1.2 for the whole sample). Note that, as in Experiment 1, the observed standard errors were in many cases too small to be displayed.

4.2.2.2 Parameter estimations for the double target condition for the visual stimulus pair 24° right/24° left

The next step was intended to predict the mean reaction times and choice probabilities for the double target condition with the drift and residual parameters derived from the single target condition. Only the coefficient for the bias and the decision criterion were re-estimated.

---

[6] Again, I arranged the data to have always positive values for the bias parameter β.

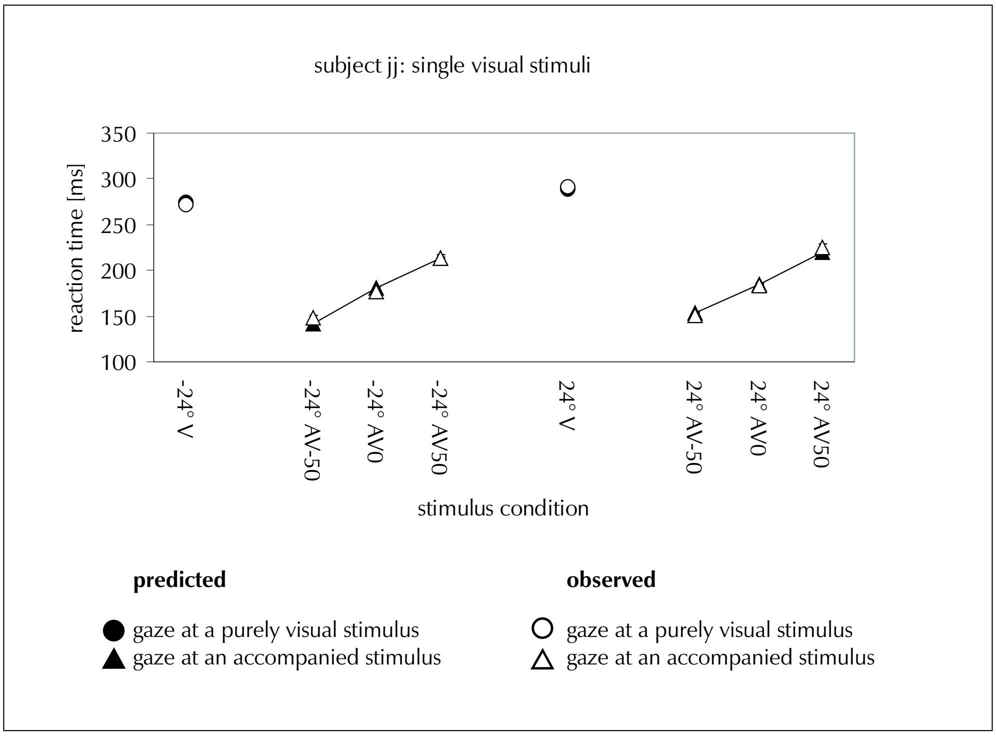

Figure 4.13: Subject *jj*: Single target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

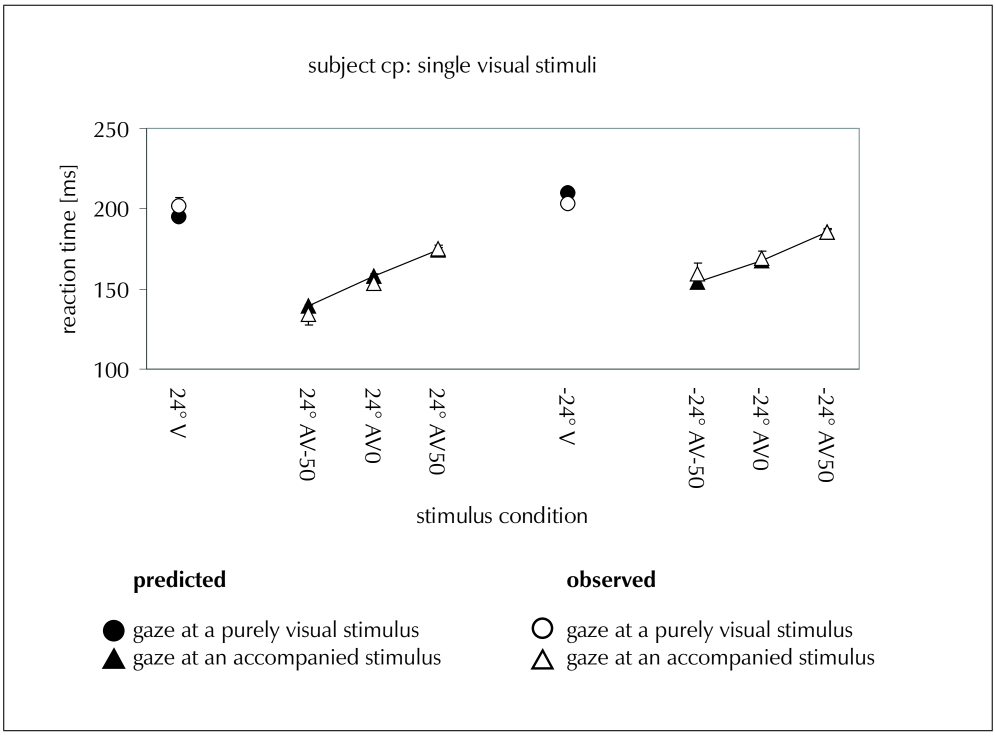

Figure 4.14: Subject *cp*: Single target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

In Table 4.6 estimations of both parameters are given. The numerical ratio between decision criterion and bias coefficient remains about the same as in the single target condition.

Table 4.6: Parameters estimated on the double target condition for the visual stimulus pair 24° right/24° left

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**
β	1	1	1	4	1	1	3
Θ	14	14	18	21	15	15	22

For two subjects (*jj*, *cp*) the mean reaction times and the choice probabilities are shown in Figures 4.15 and 4.16 , and in Figures 4.17 and 4.16, respectively (see Appendix C.2.2 for the whole sample). The patterns for both mean reaction times and choice probabilities can be replicated by the model. However, the data fits for reactions to un-accompanied visual stimuli, again, are rather poor. But, as already mentioned above, the data base for this kind of reaction was also very poor. For example, subject *jj* did not look at un-accompanied stimuli at all. If there are only visual stimuli, the model tends to predict larger choice probabilities for the biased hemisphere than observed.

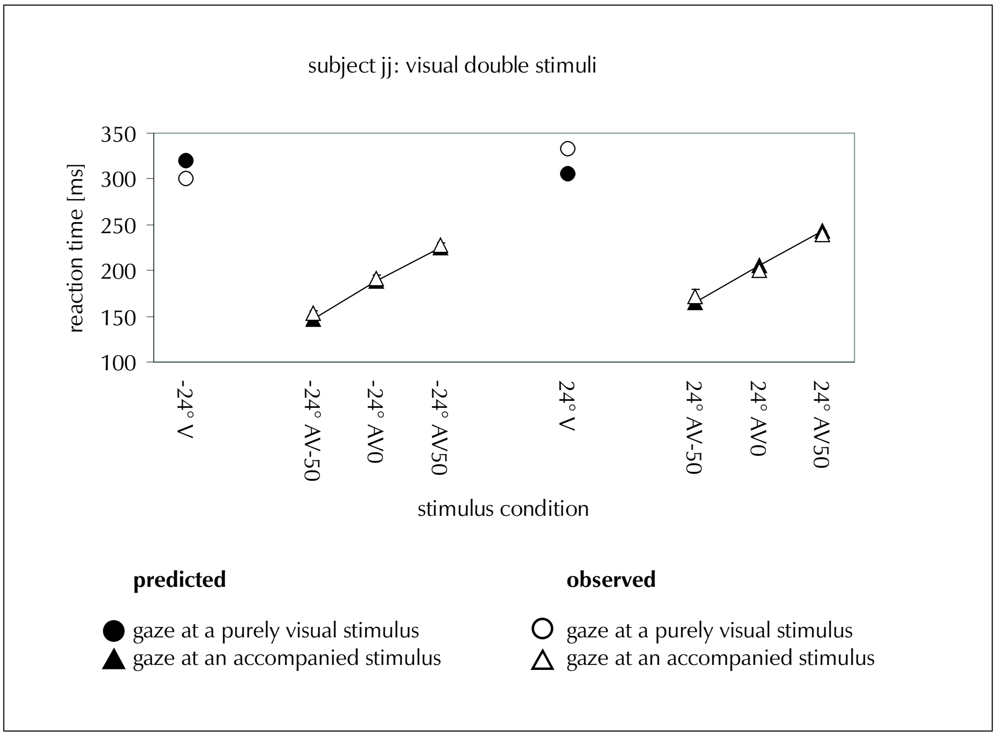

Figure 4.15: Subject *jj*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs. Since saccades to un-accompanied stimuli were almost never observed with this subject, they are not displayed in this figure.

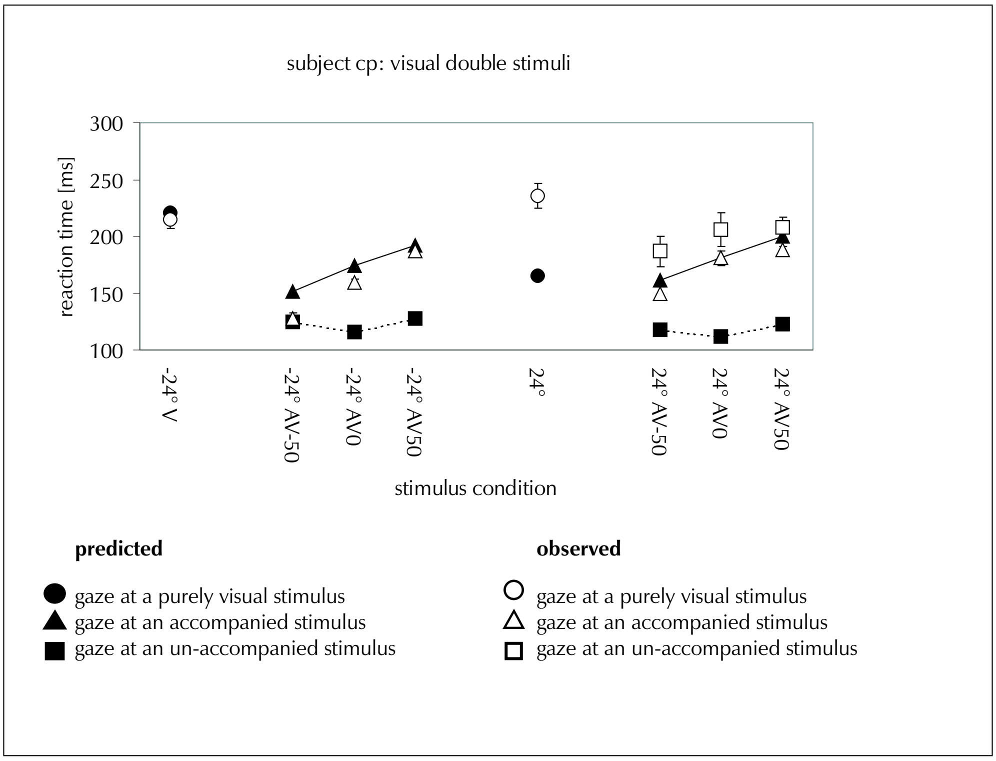

Figure 4.16: Subject *cp*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

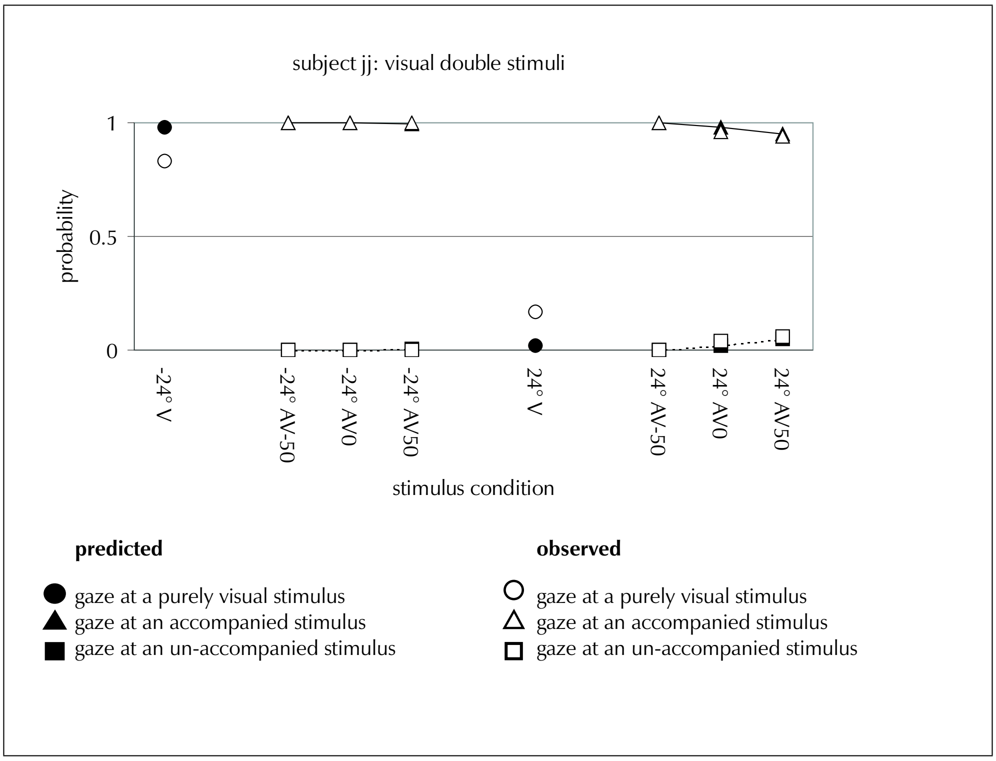

Figure 4.17: Subject *jj*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed probabilities for three SOAs.

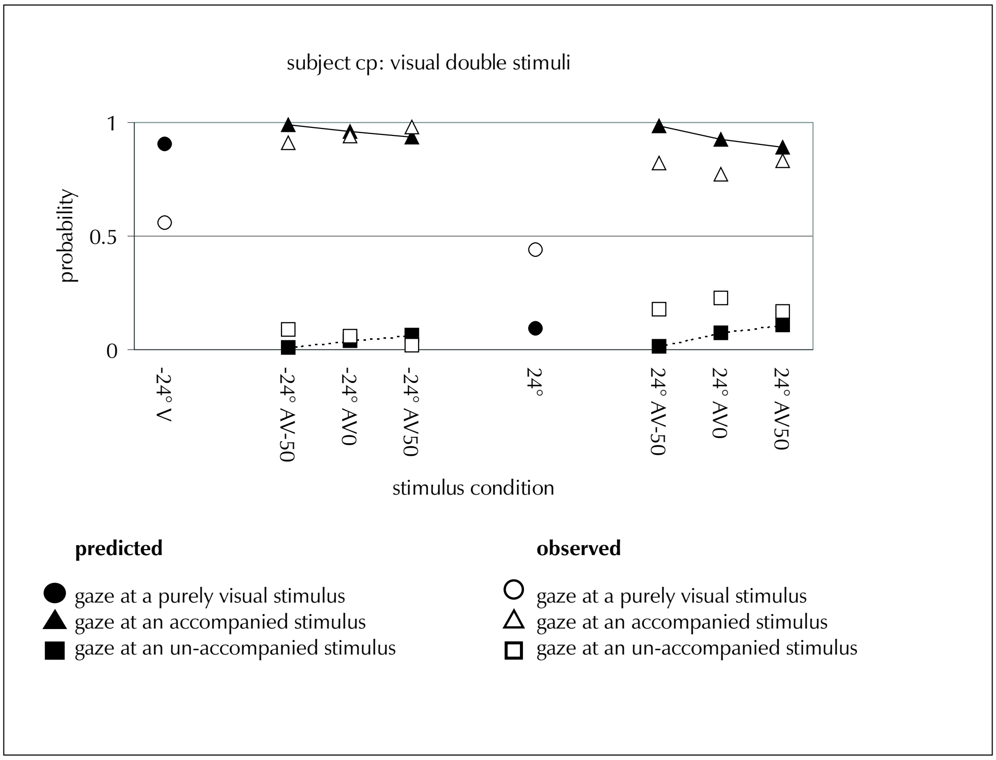

Figure 4.18: Subject *cp*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed probabilities for three SOAs.

4.2.3 Parameter estimations for the single target condition for the visual stimulus pairs 8° right/24° left or 8° left/24° right

For this condition, I had to estimate seven parameters from eight averaged data points (each mean obtained from on average 47 valid trials): one drift parameter for every modality and eccentricity, the parameters for bias and decision criterion and the residual time. I did so in the first approach of modeling (7-Parameter-Version). To reduce the number of free parameters, in a second approach (3-Parameter-Version), I kept the assumed drift parameters as estimated from the former constellations (visual stimulus pairs 8° right/8° left and 24° right/24° left), and fitted only the three remaining parameters β, Θ and r. Since the data fits gained by the estimation of seven rather than three parameters, were better for the single target condition only, but nearly the same for the double target condition, I just present the 3-Parameter-Version. Estimations of both versions for all subjects not shown in text can be found in Appendix C.1.3 for the single target conditions, and in Appendix C.2.3 for the double target conditions. Table 4.7 shows the parameter estimations for seven subjects.

The residual times vary between 68 and 108 ms. Therefore, they are in the range of data for peripheral processing and motor delay documented in literature. For all but one (*nn*) subject, I had to assume a bias parameter.[7] The data fits for the mean reaction times are quite good, taking into account that I assumed the drift parameters to be the same as in the two former stimulus conditions.

Figures 4.19 and 4.20 show the fits for two subjects (for the whole sample, see Ap-

---

[7] For technical reasons I arranged the data to have always positive values for the bias parameter β.

Table 4.7: Parameters estimated on the single target condition for the visual stimulus pairs 24° right/8° left or 8° right/24° left

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**
β	3	7	1	1	0	7	17
Θ	16	16	13	18	20	13	23
r	100	68	94	81	105	108	95

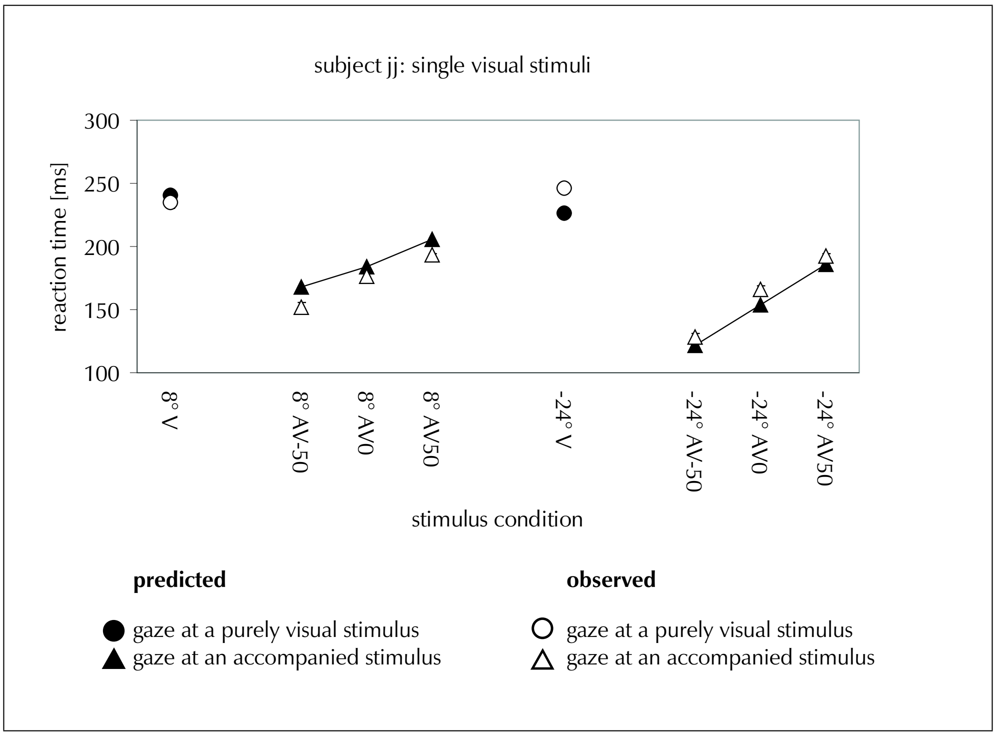

Figure 4.19: Subject *jj*: Single target condition, visual stimulus pair 24° left/8° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

pendix C.1.3.

4.2.4 Parameter estimations for the double target condition for the visual stimulus pair 8° right/24° left or 8° left/24° right

I held the parameters for drift rates and residual times constant and again estimated the coefficients for the bias and the decision criterion to predict the mean reaction times and choice probabilities in this double target condition.[8] The results of the parameter estimations for all subjects are shown in Table 4.8.

Remarkably, for five out of seven subjects (*mi*, *sr*, *rv*, *jj* and *nn*), the bias parameter is estimated to be zero.[9]

---

[8] I restricted the parameter for the bias, so that $\beta \geq 0$. This was necessary to make sure that the preference for one hemisphere would not be reversed by the minimizing algorithm to provide better data fits. In fact, there was no reason to assume a reversal of the bias, since the bias did not change its direction in the former conditions, neither for visual stimuli at 8° nor for visual stimuli at 24°.

[9] If one drops the restriction on the bias parameter, the model would predict negative values for two

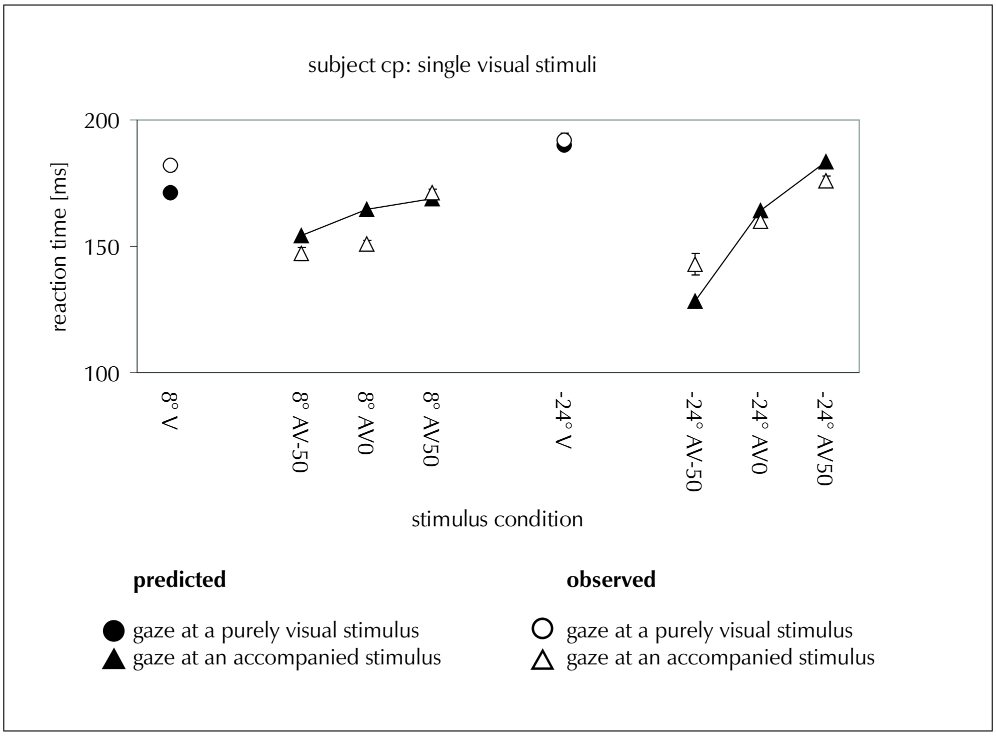

Figure 4.20: Subject *cp*: Single target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

Table 4.8: Parameters estimated on the single target condition for the visual stimulus pairs 24° right/8° left or 8° right/24° left

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**
β	0	0	0	0	0	6	1
Θ	13	13	12	13	18	12	12

The provided data fits for the mean reaction times and for the choice probabilities for two subjects (*jj* and *cp*) are shown in Fig. 4.21 to Fig. 4.24. For the whole sample, see Appendix C.2.3. Again, the predictions reproduce the observed data patterns quite well, at least for responses to accompanied stimuli. However, for subject *cp* the model predicts a greater choice probability for accompanied stimuli at 24° than observed, if the auditory stimulus was presented 50 ms before the visual.

---

of these subjects (*rv*, *jj*). This problem might be due to the strong assumption that the drift rate is the same for single as for double target conditions. If, e.g., the drift parameter for visual stimuli at 8° would have been smaller in the double than in the single target condition, the algorithm might compensate for this by setting the bias parameter to zero.

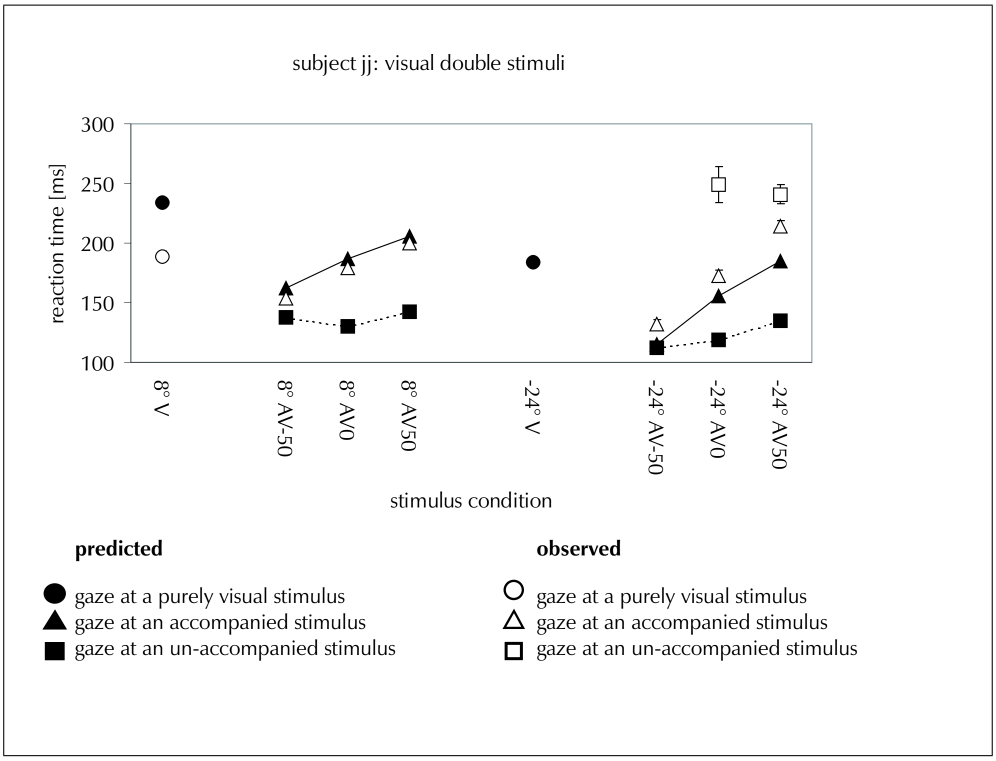

Figure 4.21: Subject *jj*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

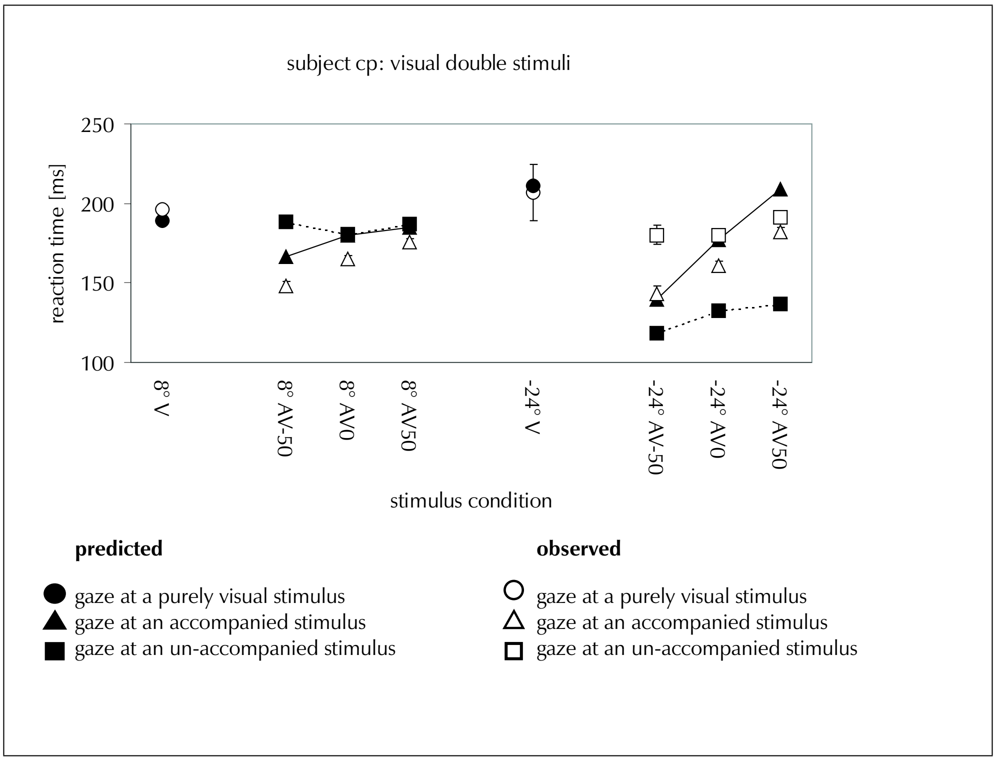

Figure 4.22: Subject *cp*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

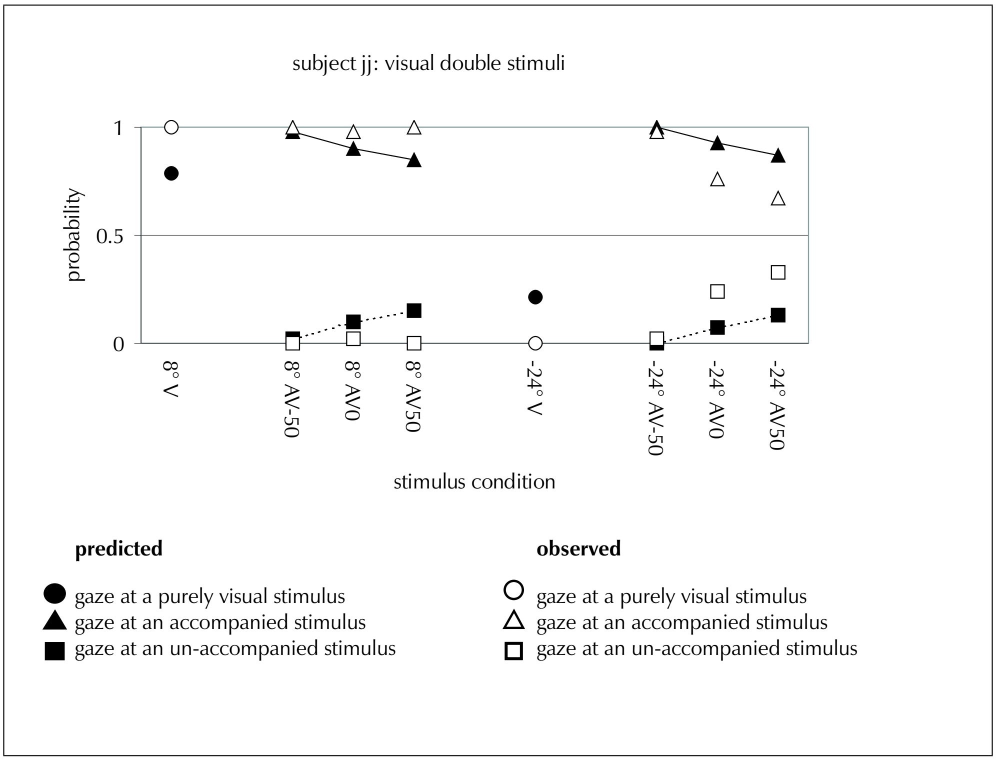

Figure 4.23: Subject *jj*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed probabilities for three SOAs.

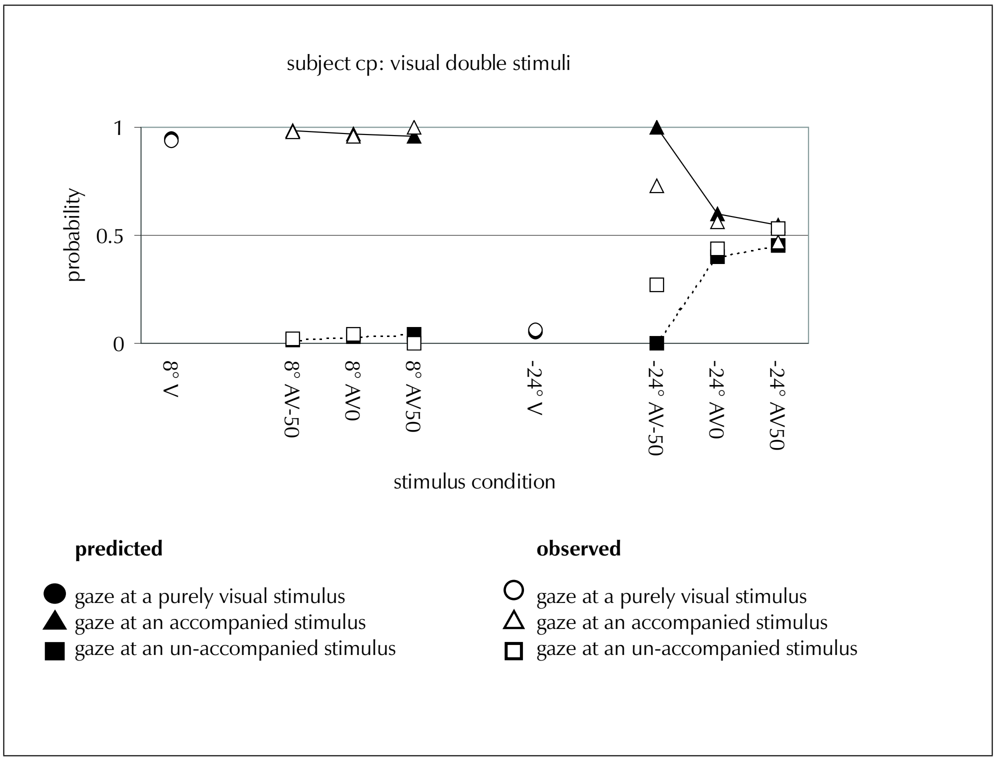

Figure 4.24: Subject *cp*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed probabilities for three SOAs.

4.2.5 Parameter estimations for the single target condition for the visual stimulus pairs 8° right/24° right or 8° left/24° left

Under this stimulus condition, the visual targets were presented in only one hemisphere. Since the bias parameter was only introduced to account for subjects' preference for one hemisphere, it is not needed for the present condition. Again, there are at least two approaches for obtaining estimations:
(1) All parameters are estimated again (6-Parameter-Version), i.e. six parameters are obtained from eight data points (each mean obtained from on average 49 valid trials) or
(2) The same drift parameters as in the former conditions are assumed, and adjusted only the parameters for the boundary and the residual time (2-Parameter-Version) again. The results for both approaches are shown in Appendix C.1.4 for the single target conditions and Appendix C.2.4 for the double target conditions. Of course for the single target condition the data fits are better, if I estimate six instead of two parameters. But for the double target condition the deviations of the estimated data from the observed data are about the same for both versions. So I preferred the 2-Parameter-Version for reasons of parsimony. In Table 4.9 one can see the estimated parameters for seven subjects.

Table 4.9: Parameters estimated on the single target condition for the visual stimulus pair 8° right/24° right or 8° left/24° left

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**
Θ	16	12	11	14	16	12	12
r	78	74	99	109	116	105	100

The coefficients for the residual times are in the same range as in the former conditions whereas the parameters for the decision criterion tend to be smaller. This means that anticipation of the position of a stimulus, e.g., by presenting the stimuli only to one hemisphere, leads to a decrease of the criterion to initiate a response.

The estimated parameters can reproduce the observed pattern for mean reaction times, but the deviations are larger than in the former conditions, especially for purely visual stimuli. Here, the model predicts faster reaction times than observed. The results of two subjects (*jj* and *cp*) are shown in Figures 4.25 and 4.26 (for the whole sample see Appendix C.1.4).

4.2.6 Parameter estimations for the double target condition for the visual stimulus pair 8° right/24° right or 8° left/24° left

In the second step, I predicted the mean reaction times and choice probabilities for the double target conditions by just re-estimating the parameter for the decision criterion. The parameter estimations for all subjects can be seen in Table 4.10.

The mean reaction times to accompanied stimuli can be fitted quite well by the model (see Figures 4.27 and 4.28, for the whole sample see Appendix C.2.4). For the choice probabilities the fits are not too bad, if the visual stimuli can be matched by varying the intensity (for details see Chapter 2.4) to equal choice probability. However, in cases where this attempt at matching did not succeed and the subjects still had a strong preference

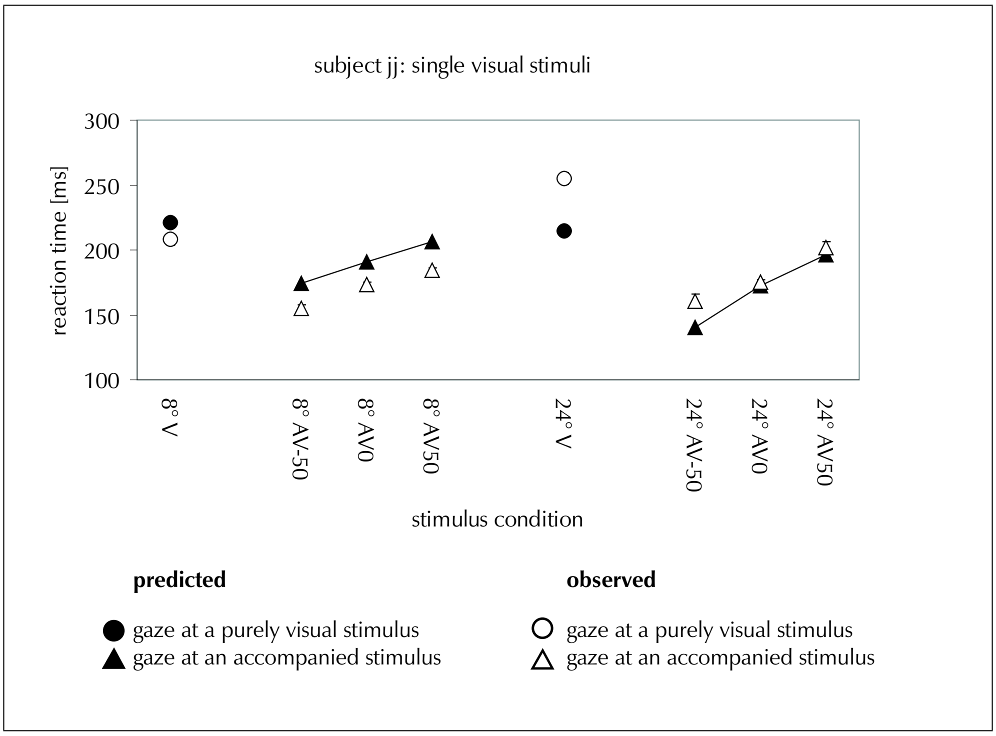

Figure 4.25: Subject *jj*: Single target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

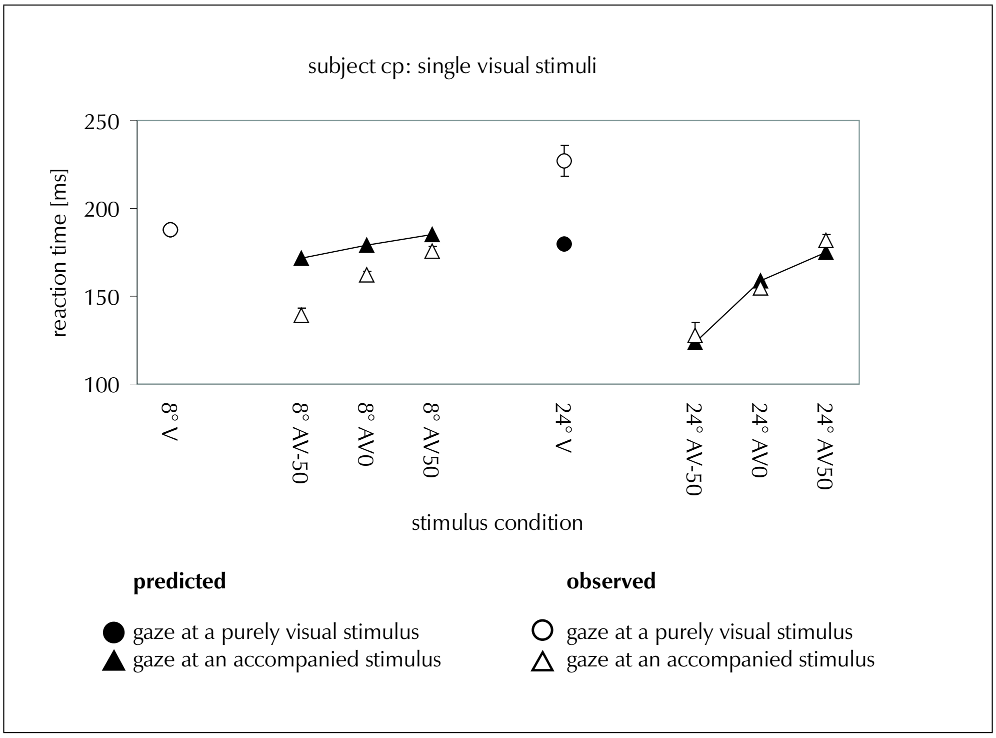

Figure 4.26: Subject *cp*: Single target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

Table 4.10: Parameters estimated on the single target condition for the visual stimulus pair 8° right/24° right or 8° left/24° left

	mi	**sr**	**rv**	**jj**	**nn**	**cp**	**ms**
Θ	12	11	9	10	16	12	9

for one visual stimulus, the model still predicts the accompanied stimulus to be chosen more frequently than the un-accompanied one, irrespective of its eccentricity. Figure 4.30 shows the predicted choice probabilities for a subject who had no preference for either visual stimulus (*rv*), whereas Fig. 4.29 shows the data for a subject (*jj*) who still had a very strong preference for the visual stimulus at 8°, although it was less intensive than the visual stimulus at 24°.

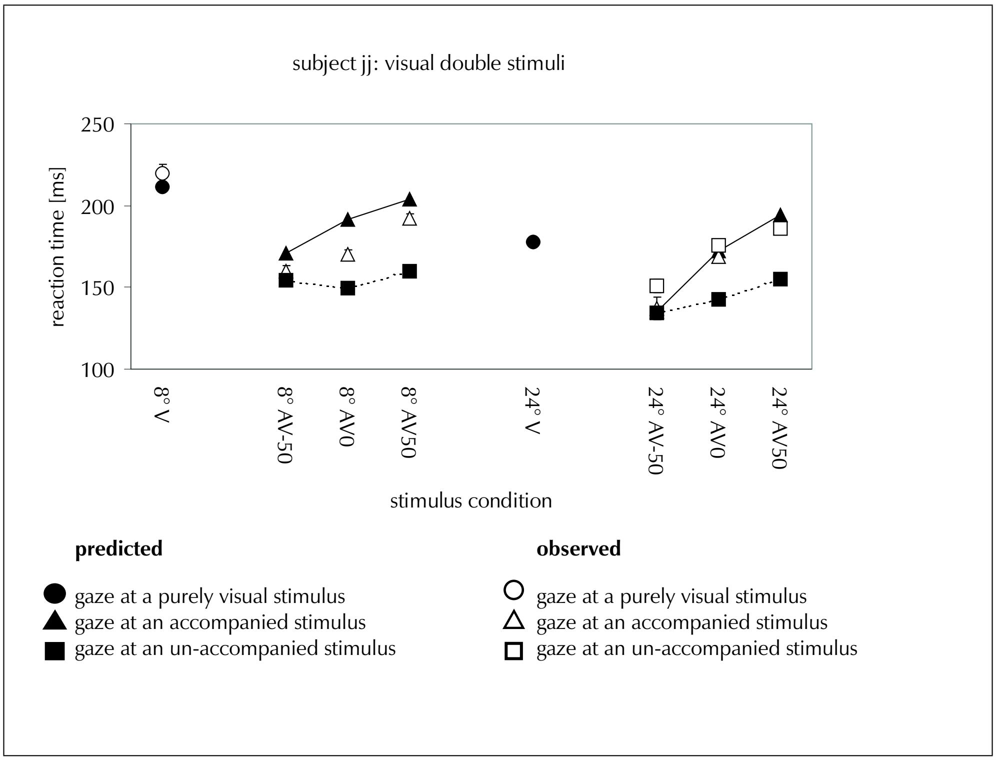

Figure 4.27: Subject *jj*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

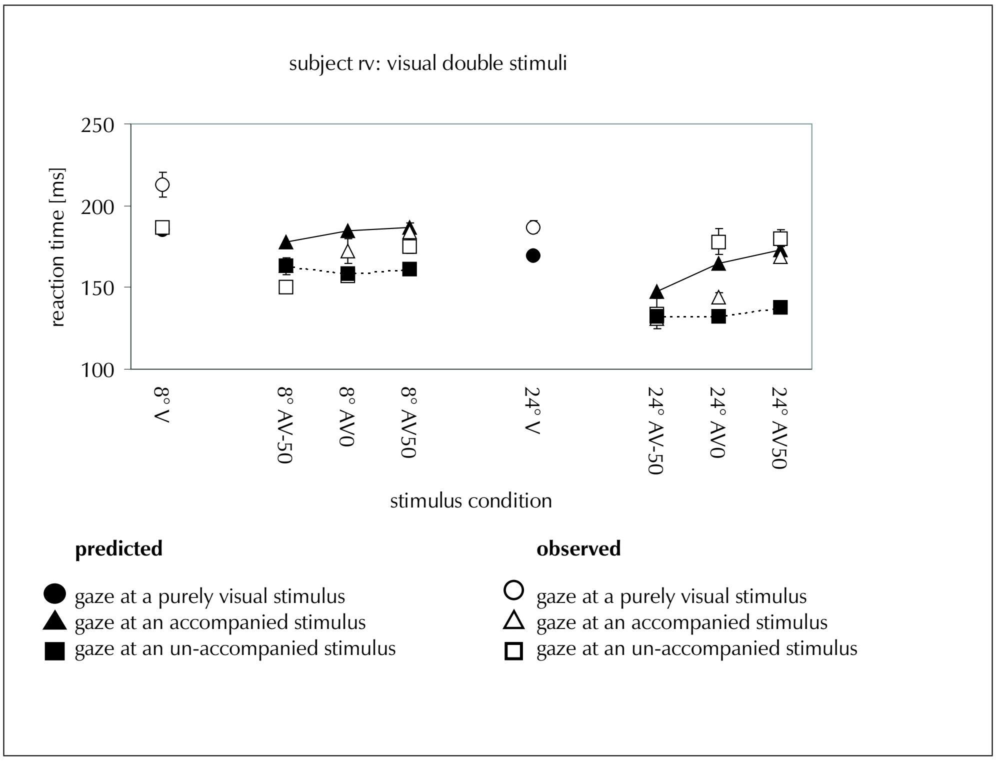

Figure 4.28: Subject *rv*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

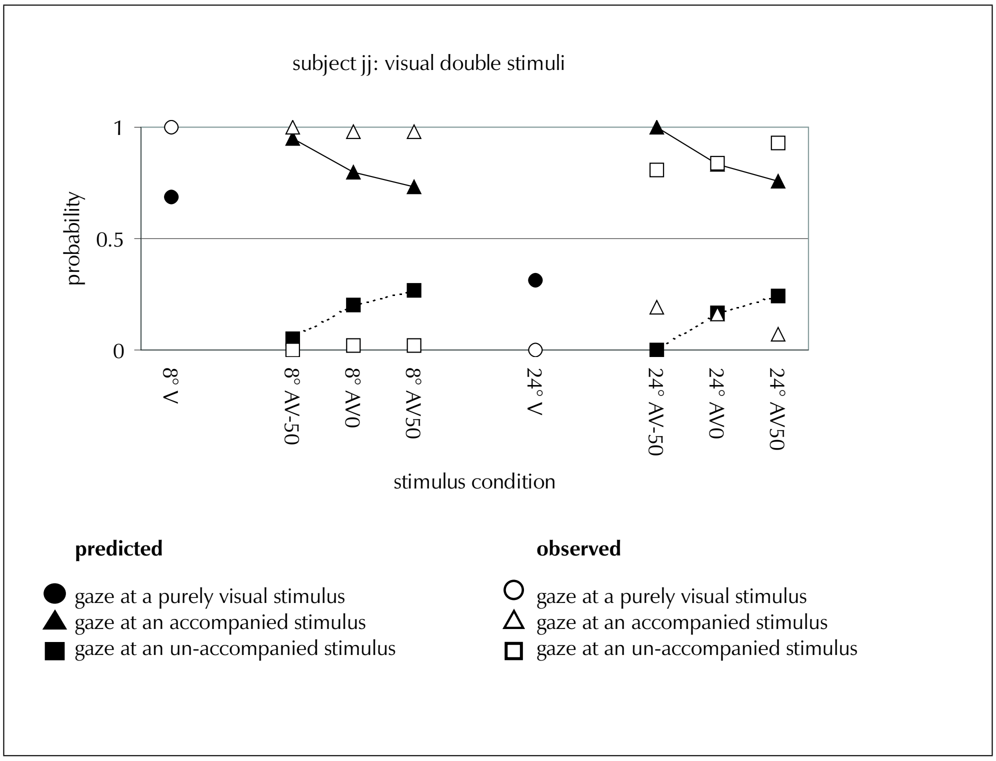

Figure 4.29: Subject *jj*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed probabilities for three SOAs.

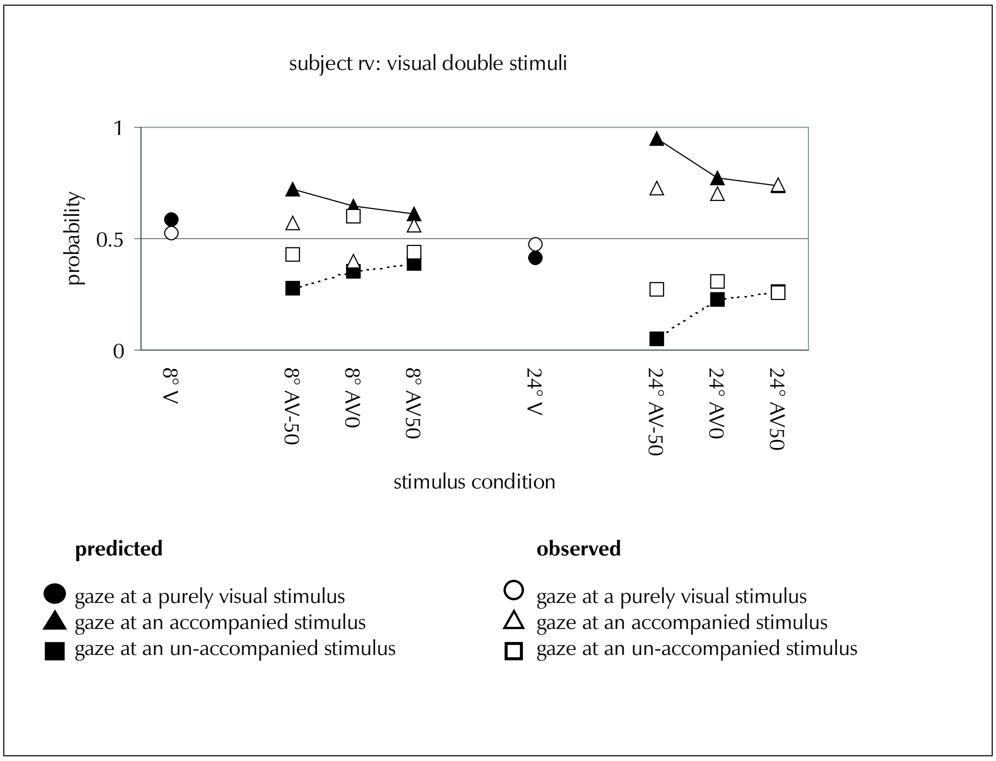

Figure 4.30: Subject *rv*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed probabilities for three SOAs.

Chapter 5

General discussion

The present study is concerned with the influence of an auditory accessory stimulus on the choice frequency and reaction times in a visual double target task. Subjects had to gaze at one out of two visual stimuli, ignoring an additional auditory stimulus presented in some trials at the same location as the visual stimulus with one of three SOAs (−50 ms, 0 ms, 50 ms).

The results confirm previous findings on the double target paradigm using purely visual stimuli (Findlay, 1982; Lévy-Schoen, 1969) and extend them to a bimodal paradigm (Experiments 1 and 4). For both purely visual and audio-visual stimuli saccadic reaction times were prolonged (compared to single control stimuli), if two visual stimuli were presented in opposite hemispheres. In contrast, no slowing was observed when the targets were presented within the same hemisphere. It should be added that in the latter condition, subjects not always reached a clear decision in my experiments: For a small proportion of trials, I observed saccades whose amplitudes lay between the two targets. This might partly be attributed to general inaccuracies; but, on the other hand, a separation of 16° might be not wide enough to preclude averaging processes for sure as they are reported in literature for smaller distances (e.g., see Findlay, 1982). Furthermore, it must be considered that due to my strict criterion for accepting a saccade as correct, a large portion of saccades was discarded (see Section 2.1.3). Therefore, it might be interesting to analyze this portion of saccades in more detail in further studies. It was reported in many experiments that reaction times are shorter to bimodal (e.g. audio-visual) stimuli than to unimodal (e.g. visual) stimuli (Hughes et al., 1998; Frens et al., 1995; Colonius & Arndt, 2001). The present study is in line with these results. But while in all of these studies only a single visual target stimulus had been presented, I extended the finding to a double target paradigm. Reaction times to unimodal single stimuli decreased, when an auditory accessory stimulus was presented. The observed facilitation was strongest for SOA = −50 ms and the weakest for SOA = 50 ms. It is an interesting fact that presenting an auditory co-stimulus reduced the reaction times generally. Facilitation (compared to saccades to purely visual stimuli) was observed even when the subject gazed at the un-accompanied stimulus. Therefore, this latency decrease might be attributed partly to some kind of 'global warning' effect. However, latency for saccades to auditorily accompanied stimuli was under most conditions (see below) even more reduced than for un-accompanied ones. Thus the auditory stimulus might have a second component: That is a facilitation effect specific to its position in space. However, the results differed with respect to ipsi- or contralateral presentations for both Experiment 1 and Experiment 4. Only if the stimuli were presented to both hemispheres, saccades to the auditorily accompanied stimulus were faster than those to the un-accompanied one. If the stimuli were presented within one hemisphere and the subject gazed at the 8°-stimulus, no such facilitation besides the general warning effect was observed. That this was not true for saccades to 24°-stimuli is in fact puzzling.

Concerning gaze frequencies, the auditorily accompanied stimulus was selected more often than its un-accompanied counterpart. This was true for both saccades to 8° and 24°, although greater shifts in frequency were observed, when the 24°-stimulus was accompanied. But since the baseline for saccades to 24° was much lower than for saccades to 8°, this might be explained by some kind of 'ceiling effect' for saccades to 8°. In fact, subjects continued to prefer the 8° stimulus over the one at 24°, even though it was delayed by 26.6 ms. Therefore, it might be useful to choose a greater time interval in further experiments.

Interestingly, in the ipsilateral condition, I did not find a clear effect on choice frequency induced by the auditory stimulus in Experiment 1. This might be caused, at least partly, by a poor ability to localize the auditory stimuli in this experiment. To evaluate this thesis, subjects' ability to localize the auditory stimuli was investigated. Indeed, Experiment 2 underlined that the localization was very poor within one hemisphere. Therefore, the task was facilitated by presenting the auditory stimuli at one of only *two* possible locations within one experimental session (Experiment 3, Experiment 4). As shown in Experiment 3, under this restriction almost each subject was able to localize the auditory stimulus correctly, even within one hemisphere. Therefore, a blocked design was used in Experiment 4 to improve the localization of the auditory stimuli. Furthermore, to provide a better balance in selection frequency between the stimuli at 8° and 24°, the intensity of the 8° stimulus was lessened. Under these restrictions, auditorily accompanied stimuli were in fact selected more frequently even if presented within one hemisphere.

What can we learn from these experimental findings? Some important implications for models of saccade generation might be concluded.

The results might be explained by a model proposed by Becker & Jürgens (1979) assuming two different stages in saccade programming: The first stage is to decide whether the eye movement is going to the left or to the right. In a second stage, its amplitude is calculated by integrating the information over a specific time period. Such an assumption might, for instance, explain why no latency increase was observed when presenting two visual stimuli within one hemisphere. In contrast, presentation to both hemispheres requires a apparently time-consuming decision process for direction.

Such a decision process may be mediated by competitive inhibition as suggested by several researchers (Van Opstal & Van Ginsbergen, 1989; Koch & Ullman, 1985). Most models assume that targets on opposite sides inhibit each other until one of them wins the competition and a saccade to its direction is elicited (*Winner-Take-All*). This hypothesis is as well supported by physiological studies investigating the superior colliculus, a structure which is assumed to be strongly involved in saccade generation. Schiller, H. & Maunsell (1987) found that SC lesions in monkeys decreased saccade latency in the ipsilesional hemisphere. This is widely accepted as an account for permanent mutual inhibition among the two halves of the superior colliculus.

An interesting extension of the work of Becker & Jürgens (1979) was recently proposed by Findlay & Walker (1999). Their model assumes two different pathways of saccade generation. While the WHEN-System is concerned with the triggering of a saccade, the WHERE-System addresses to the computation of its amplitude. Due to their model, a saccade is elicited as soon as the activity in the fixation centre falls below a certain threshold level. Their assumption that this 'disengagement' is promoted by an increased activity in the 'move centre' envisages again reciprocal inhibitory connections between these two centres.

Such an approach is useful to explain the striking result found in Experiment 4 that—when presenting stimuli within one hemisphere—saccades were shifted in frequency to the auditorily accompanied stimulus, but not facilitated. In terms of their framework, presenting two visual targets to one hemisphere may reduce the activity in the 'fixate centre'. As a result, in neurophysiological terms, the omnipause neurons in the brainstem may become silent and a saccade is triggered. The amplitude of this saccade may be defined by the current location of the maximum of the activation in the 'salience map' of the WHERE-Pathway. Since the auditory stimulus might provide additional information on the location, the accompanied stimulus might be chosen more often.

So far these models only provide a rather descriptive framework for understanding the processes involved in saccade generation. Since my intention was to gain explicit predictions in quantitative terms, I followed a somewhat different approach. In detail, I engaged the *Multi-Channel Diffusion Model* (Diederich, 1992, 1995, 1997) to model my experimental findings. It employs a more abstract representation of neural events than, for instance, competitive inhibition models. Rather, the decision process is resembled by a symmetrical pair of threshold values for the stochastic process, each having the same distance to the 'neutral' starting (or zero) position. This results in a significantly longer decision time than with single visual stimuli, since in most cases the stochastic process crosses the 'zero' line several times before it finally reaches one of the threshold boundaries.

Accordingly, I was able to provide reasonably good data fits for most of the experimental conditions (with the notable exception of choice frequencies with ipsilateral visual double stimuli, see below). By introducing a 'bias-parameter', the model could as well account for subjective preferences for one hemisphere.

In detail, choice probabilities and reaction times in double target trials were predicted from the reaction times observed in the single (visual and visual-auditory) trials. The predictions were much better for accompanied stimuli than for un-accompanied ones. In fact, the reaction times to un-accompanied stimuli were constantly underestimated by the model. But since there were only very few reactions to un-accompanied stimuli, the data base is very poor. Nonetheless, such an underestimation might result from assumptions inherent to the model, i.e. the reactions to un-accompanied stimuli are interpreted as 'fast errors' in terms of the model. That means, if the 'un-expected' (auditorily un-accompanied) stimulus is selected, this should be done very early in the diffusion process, since such a decision becomes more and more unlikely as the decision process goes on.

Another limitation inherent to the nature of the Multi-Channel Diffusion Model is to predict higher choice probabilities without shorter reaction times as observed in Experiment 4. Since only *one* stochastic process is responsible for both mean reaction time and choice probability it is impossible for the model to account for this.

To overcome this limitation, I would suggest to employ some additional assumptions:

First, one should split up the process into two processing stages, with the first essentially keeping the model structure and modeling the time-consuming decision for a saccade to the left or right. In a second stage the amplitude of a saccade is computed. In this stage, the sensory information about the different target locations is still accumulated independently, but the conclusive decision for the amplitude of the eye movement is based on the amount of information collected after a fixed *time period* rather than on a fixed threshold. This might explain the observed findings: The accompanied stimulus is selected more frequently since there is more information about it; but the reaction times are not shorter, because the selection mechanism always has to wait until a preset decision time has passed. However, the observed variability in reaction times might be caused by the stochastic nature of the process in the first stage or by some stochastic variability of the time delay in the second stage.

Another point critical to the model might be its strong assumption of context independence. Remember that only due to this assumption, it was possible to use the drift rates gained from the single target conditions to make predictions for the double target condition. This assumption is in fact rather difficult since it is known that visual targets in close proximity do in fact interact with each other (Findlay, 1982; Deubel et al., 1984; Ottes F.P. & Eggermont, 1984). This may be another reason why predictions for the ipsilateral condition, were not as good as with bilateral stimulus conditions.

One might object that the Multi-Channel Diffusion Model was developed for an experimental setting in which the subject was asked to react to *any* stimulus recognized first, i.e. a so-called *redundant target paradigm*). But in my experiments, subjects were instructed to gaze only at *visual* stimuli and to ignore the auditory one (*focused attention paradigm*). Can the engagement of the model for the provided experiments be considered as legitimate at all? I suppose, it can, for the following reasons. First, it was shown by Hughes et al. (1995) that intersensory facilitation might occur in both tasks. Besides this, it seems that the auditory stimulus automatically evokes some kind of activation, even if the subjects are told to ignore the auditory stimulus. This was shown in Experiment 5. When presenting spatially disparate bimodal stimuli, some subjects made a considerably high proportion of saccades to the auditory non-target, especially if it was presented before the visual target.

Recently, (Leach & Carpenter, 2001) have proposed a stochastic model that seems rather similar to the Multi-Channel Diffusion Model. The LATER (Linear Approach to Threshold with Ergodic Rate) model assumes that—when a stimulus is presented—a decision signal S rises linearly with a rate r from an initial level S_0 to a threshold level S_T. A response is elicited as soon as S reaches this threshold. In contrast to the model presented here, variation in reaction times comes from variation of the rate of rise and not from a stochastic diffusion process. Such an assumption is quite parsimonious since—according to the authors—only two parameters are needed to describe reaction time distributions. By assuming that the rate of rise varies independently at different sites, they can explain the variation of choice frequency when presenting two visual targets asynchronously. However, LATER can not easily explain why reaction times are prolonged with two targets compared to those to one. According to its inherent assumption that the faster of the two processes defines the response, it would—as all *Race Models* predict even *faster* reactions with double stimuli than with single stimuli. Therefore, it must assume an additional parameter for lateral inhibition, i.e. an attenuating factor p that is to be subtracted from each rate of rise. Such a simplifying assumption seems to have limitations in experimental settings where the inhibition is not equal to each stimulus. For example, if one target provides stronger inhibition on the other target than vice versa as it was reported by Walker et al. (1997). They observed that the latency increase was the greatest when the second target was presented at the fixation point. Besides this the model fails as well to explain findings like the one stated above that the 'faster target' is not as well the more frequently selected target'. Furthermore, although LATER can make quantitative predictions on reaction times and choice frequencies by running Monte-Carlo-simulations, it provides no analytical derivations so far.

Finally, it should be noted that at present, quantitative models like the Multi-Channel Diffusion Model or LATER only explain quite specific aspects of saccade generation, e.g., the decision process or audio-visual facilitation. On the other hand, descriptive models such as the one proposed by Findlay & Walker (1999) do provide a comprehensive framework for understanding of a huge variability of findings in current eye movement research. However, those models fail in making quantitatively testable predictions. Therefore, future research should be aimed at integrating both approaches.

Bibliography

Ashby, F. (1983). A biased random walk model for two choice reaction times. *Journal of Mathematical Psychology*, 27:277–297. 3.1

Becker, W. & Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research*, 19:967–983. 1, 5

Bernstein, I., Rose, R. & Ashe, V. (1970). Energy integration in intersensory facilitation. *Journal of Experimental Psychology*, 86:196–203. 1

Bernstein, Chu, P., Briggs, P. & Schurman, D. (1973). Stimulus intensity and foreperiod effects in intersensory facilitation. *Quartely Journal of Experimental Psychology*, 25:171–181. 1

Bhat, U. (1984). *Elements of applied stochastic processes.* Wiley Series in probability and mathematical statistics, United States of America. A

Busemeyer, J. & Townsend, J. (1993). Decision field theory: A dynamic-cognitive approach to decision making. *Psychological Review*, 100:432–459. 3.1

Colonius, H. & Arndt, P. (2001). A two-stage model for visual-auditory interaction in saccadic latencies. *Perception and Psychophysics*, 63(1):126–147. 1, 1.1, 1, 19, 5

Deubel, H., Wolf, W. & Hauske, G. (1984). Gale A. G. and Johnson F., North-Holland, Amsterdam. 1, 5

Diederich, A. (1992). *Intersensory facilitation: Race, superposition, and diffusion models for reaction time to multiple stimuli (Dissertation).* Verlag Peter Lang, Frankfurt am Main. 1, 1, 3.1, 1, 4, 5, A

Diederich, A. (1995). Intersensory facilitation of reaction time: Evaluation of counter and diffusion coactivation models. *Journal of Mathematical Psychology*, 39:197–215. (document), 1, 3.1, 5

Diederich, A. (1997). Dynamic stochastic models for decision making under time constraints. *Journal of Mathematical Psychology*, 41:260–274. (document), 1, 3.1, 5

Edwards, W. (1965). Optimal strategies for seeking information: Models for statistics, choice reaction times, and human information processing. *Journal of Mathematical Psychology*, 2:312–329. 3.1

Engelken, E. & Stevens, K. (1989). Saccadic eye movements in response to visual, auditory, and bisensory stimuli. *Aviation, Space, and Evironmental Medicine*, 60:762–768. 1

Findlay, J. (1980). The visual stimulus for saccadic eye movements in human observers. *Perception*, 9:7–21. 1

Findlay, J. (1982). Global visual processing for saccadic eye-movements. *Vision Research*, 22:1033–1045. 1, 2.5.3, 5

Findlay, J. & Walker, R. (1999). A model of saccade generation based on parallel processing and competive inhibition. *Behavioral and Brain Sciences*, 22:661–721. 1, 15, 5

Frens, M. & Van Opstal, A. (1995). A quantitative study of auditory-evoked saccadic eye movement in two dimensions. *Experimental Brain Research*, 107:103–117. 1

Frens, M., Van Opstal, A. & Van d. Willungen, R. (1995). Spatial and temporal factors determine auditory-visual interactions in human saccadic eye movements. *Perception and Psychophysics*, 57:802–816. 1, 5

Gordon, B. (1973). Receptive fields in the deep layers of the cat superior colliculus. *J. Neurophysiol.*, 36:157–178. 1

Harris, L.-R., Blakemore, C. & Donaghy, M. (1980). Integration of visual and auditory space in the mammalian superior colliculus. *Nature*, 288:56–59. 1

Heath, R. (1981). A tandem random walk model for psychological discrimination. *British Journal of Mathematical and Statistical Psychology*, 34:76–92. 3.1

Heuermann, H. & Colonius, H. (1999). Localization experiments with saccadic responses in virtual auditory environments. In T. Dau, V. Hohmann & B. Kollmeier (eds.), *Psychophysics, Physiology and Models of Hearing*, pp. 89–96. Word Scientific Publishing, Singapore. 1, 2.3

Hughes, H., Nelson, M. & Aronchick, D. (1998). Spatial characteristics of visual-auditory summation in human saccades. *Vision Research*, 38:3955–3963. 1, 5

Hughes, H., Reuter-Lorentz, P., Nozawa, G. & Fendrich, R. (1995). Visual-auditory interactions in sensorimotor processing: Saccades versus manual responses. *Journal of Experimental Psychology*, 20:131–153. 1, 5

Jay, M. & Sparks, D. (1987). Sensorimotor integration in the primate superior coliculus. II. Coordinates of auditory signals. *J.Neurophysiol*, 57:35–55. 1

Kingstone, A. & Klein, R. M. (1993). Visual offset facilitates saccade lateny: Does pre-disengagement of attention mediate this gap effect? *Journal of Experimental Psychology: Human Perception and Performance*, 19:251–265. 1

Koch, C. & Ullman, S. (1985). Shifts in visual attention: Towards the underlying circuitry. *Human Neurobiology*, 4:219–227. 5

Kurylo, D., Vimal, R. & Hartline, P. (1992). Effects of multiple stimuli on ocular orientation by cats. *Journal of Cognitive Neuroscience*, 4(2):165–174. 1

Laming, D. (1968). *Information Theory of Choice-Reaction Times.* Academic Press, London. 3.1

Leach, J. & Carpenter, R. (2001). Saccadic choice with asynchronous targets: evidence for independent randomisation. *Vision Research*, 41:In Press. 5

Levitt, H. (1971). Transformed up-down procedures in psychoacoustics. *J. Acoust. Soc. Am.*, 49:467–477. 2.5

Lévy-Schoen (1969). Détermination et latence de la réponse oculo-motrice à deux stimulus simultanés ou successifs selon leur excentricité relative. *L'Année Psychologique*, 69:373–392. 1, 5

Lévy-Schoen, A. & Blanc-Garin, J. (1974). On oculomotor programming and perception. *Brain Research*, 71:443–450. 1

Link, S. & Heath, R. (1975). A sequential theory of psychological discrimination. *Psychometrika*, 40:77–105. 3.1

Luce, R. (1986). *Response times.* Oxford University Press, New York. 3.1

Meredith, M., Nemitz, J. & Stein, B. (1987). Determinants of multisensory integration in superior colliculus neurons. I. Temporal factors. *Journal of Neuroscience*, 7(10):3215–3229. 1

Meredith, M. A. & Stein, B. E. (1986). Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. *J. Neurophysiol.*, 56:640–662. 1

Miller, J. (1982). Divided attention: Evidence for coactivation signals with redundant signals. *Cognitive Psychology*, 14:247–279. 1

Munoz, D. & Wurtz, R. (1993a). Fixation cells in monkey superior colliculus. I. Characteristics of cell discharge. *Journal of Neurophysiology*, 70:559–575. 1, 1

Munoz, D. & Wurtz, R. (1993b). Fixation cells in monkey superior colliculus. II. Reversible activation and deactivation. *Journal of Neurophysiology*, 70:576–589. 1

Nickerson, R. (1973). Intersensory facilitation of reaction time: Energy summation or preparation enhancement? *Psychological Review*, 80:489–509. 1

Nosofsky, R. & Palmeri, T. (1997). An exemplar based random walk model of speeded classification. *Psychological Review*, 104:266–300. 3.1

Ottes F.P., van Ginsbergen, J. v. & Eggermont, J. J. (1984). Metrics of saccade responses to visual double stimuli: Two different modes. *Vision Research*, 24:1169–1179. 1, 5

Pacut, A. (1980). Mathematical modelling of reaction latency: The structure of the models and its motivation. *Acta Neurobiologicae Experimentalis*, 40:199–215. 3.1

Pacut, A. (1982). Mathematical modelling of reaction latency Part II. *Acta Neurobiologicae Experimentalis*, 42:379–395. 3.1

Perrott, D. & Cisneros, J. (1996). Aurally aided visual search under virtual and free-field listening conditions. *Human Factors*, 38(4):702–715. 1

Raab, D. (1962). Statistical facilitation of simple reaction times. *Transactions of the NY academy of science*, 14:71–83. 1

Ratcliff, R. (1978). A theory of memory retrival. *Psychological Review*, 85:59–108. 3.1

Riggs, L. (1971). Vision. In J. Kling & L. A. Riggs (eds.), *Woodworth and Schlosberg's experimental psychology*. Holt, Rinehart and Winston, New York, 3rd edition. 1

Ross, L. E. & Ross, S. (1980). Saccade latency and warning signals: Stimulus onset, offset and change as warning events. *Perception and Psychophysics*, 27(3):251–257. 1

Saslow, M. G. (1967). Effects of components of displacement-step stimuli upon latency for saccadic exe movement. *Journal of the Optical Society of America*, 57:1024–1029. 1

Schiller, P. H., H., S. J. & Maunsell, J. H. (1987). The effect of frontal eye field and superior colliculus lesions on saccadic latencies in the rhesus monkey. *Journal of Neurophysiology*, 57:1033–1049. 5

Smith, P. (1990). Attention, redundancy, and perceptual integration. Paper presented at the 23 rd Annual Mathematical Psychology Meetings. Univerity of Toronto, Canada. 3.1

Smith, P. (1995). Psychophysical principled models of visual simple reaction time. *Psychological Review*, 102:567–591. 3.1

Smith, P. (2000). Stochastic dynamic models of response time and accuracy: A foundational primer. *Journal of Mathematical Psychology*, 44(3):408–463. 3.1

Sparks, D. L. (1978). Functional properties of neurons in the monkey superior colliculus: Coupling of neuronal activity and saccade onset. *Brain Res*, 156:1–16. 1

Sparks, D. L., Holland, R. & Guthrie, B. L. (1976). Size and distribution of movement field in the monkey superior colliculus. *Brain Res*, 113:21–43. 1

Sparks, D. l. & Nelson, J. S. (1987). Sensory and motor maps in the mammalian superior colliculus. *TINS*, 10:312–317. 1

Stein, B., Huneycutt, W. & Meredith, M. (1988). Neurons and behavior: the same rules of multisensory integration apply. *Brain Research*, 448:355–358. 1

Stein, B. & Meredith, M. (1993). Massachusetts Institue of Technology, Cambridge. 1, 1, 1.2

Stein, B. E., Magalhaes-Castro, B. & Kruger, L. (1976). *J.Neurophysiol*, 39:401–419. 1

Stone, M. (1960). Models for choice-reaction time. *Psychometrika*, 25:251–260. 3.1

Townsend, J. & Ashby, F. (1983). *Stochastic Modeling of Elementary Psychological Processes*. Cambridge University Press, Cambridge. 3.1

Van Opstal, A. & Van Ginsbergen, J. (1989). A nonlinear model for collicular spatial interactions underlying the metrical properties of electrically elicited saccades. *Biol. Cybern.*, 60:171–183. 5

Walker, R., Deubel, H. & Findlay, J. (1997). The effect of remote distractors on saccade programming: Evidence for an extended fixation zone. *Journal of Neurophysiology*, 78:1108–1119. 1, 5

Walker, R., Kentridge, R. & Findlay, J. (1995). Independent contributions of the orienting of attention, fixation offset and bilateral stimulation on human saccadic latencies. *Experimental Brain Research*, 103:294–310. 1

Welch, R. & Warren, D. (1986). Intersensory interaction. In K. Boff, L. Kaufmann & J. Thomas (eds.), *Handbook of Perception and Human Performance*, volume I, pp. 25–1–25–35. 1

Wurtz, R. H. & Optican, L. M. (1994). Superior colliculus cell types and models of saccade generation. *Curr Opin Neurobiol*, 4:857–861. 1

Yao, L. & Peck, C. (1997). Saccadic eye movements to visual and auditory targets. *Experimental Brain Research*, 115:25–34. 1, 4.2.2.1

Zahn, J., Abel, L., Dell'Osso, L. & Daroff, R. (1995). The audioocular response: intersensory delay. *Sens Proc*, 3:60–65. 1

Appendix A

Mathematical background for estimating reaction time and choice probability

To model the *first passage time* and the *first passage probability* a Wiener process with drift was used. Since I had three different SOAs τ_1 for $SOA = -50$, τ_2 for $SOA = 0$ and τ_3 for $SOA = 50$, the process can be divided into three different time intervals $\iota_1 = 0 < x(t) < \tau_1$, $\iota_2 = \tau_1 < x(t) < \tau_2$ and $\iota_3 = \tau_2 < x(t) < \infty$. Each time interval is characterized by its drift coefficient $\mu(x)$, with $\mu(x_V) = \delta_v$ for pure visual stimuli and $\mu(x_V A) = (\delta_V + \delta_A)$ for audio-visual stimuli, and a diffusion coefficient σ^2. However, in this implementation of the model σ^2 is set to 1. Note, that in the case of two visual stimuli, the drift coefficient $\mu(x)$ represents some kind of 'relative preference' for one visual stimulus with regard to the other visual stimulus. If $\mu(x) > 0$, the process is driven to the upper criterion, or to the so called *absorbing boundary*, if $\mu(x) < 0$, it is driven to the lower criterion.

The calculations for the *mean response time* and the *choice probability* were achieved by approximating the diffusion process by a birth-death chain (for details see Diederich, 1992; Bhat, 1984, for basics of Markov chain theory). With this method the transition probabilities $p(x)$ and $q(x)$ can be determined as

$$p(x) = \frac{1}{2}[1 - \frac{\sqrt{h}}{\sigma}\mu(x)] \tag{A.1}$$

$$q(x) = \frac{1}{2}[1 + \frac{\sqrt{h}}{\sigma}\mu(x)], \tag{A.2}$$

with $p(x) = 1 - q(x)$ and h denoting a constant.

In the next step, the transition probability matrix for the Markov chain is to be drawn up. The state space S of the diffusion process for one visual target (that means a process with one absorbing and one reflecting boundary) was defined as

$$S = \{0, \Delta, 2\Delta, ..., k\Delta\} \tag{A.3}$$

with Δ denoting a single step.

In the case of two visual stimuli, that means two absorbing boundaries, S equals

$$S = \{0, \pm\Delta, \pm2\Delta, ..., \pm(l-1)\Delta, \pm l\Delta\} \tag{A.4}$$

with Δ denoting a single step.

In the case of one visual stimulus, the criterion c is reached after $k * \Delta$ steps in time. The matrix size m can be defined as the cardinality of S and is $k+1$ in the case of one visual stimulus. In the case of two visual stimuli, the cardinality of S is $2 \times l + 1 \equiv m$ and the process is bounded by $l \times \Delta$ and $-l \times \Delta$.

Proposing that the process must run through every state, the transition probabilities $p_{i,j}$ can be determined:

$$p_{i,j} = \begin{cases} p((i-1)\Delta) & : \; j = i-1 \\ q((i-1)\Delta) & : \; j = 0 \\ 1 - p_{i,i-1} - p_{i,i+1} & : \; j = 1 \\ 0 & : \; otherwise \end{cases}$$

$$P = \|p_{ij}\| \tag{A.5}$$

One can build the transition matrix as

$$T = \begin{bmatrix} 0 & P \\ Q & R \end{bmatrix} \tag{A.6}$$

P contains the transition probabilities for the absorbing states. In case of one visual stimulus P is an 1×1 matrix, in case of two visual stimuli it is a 2×2 matrix. The matrix Q denotes the transition probabilities $p_{i,j}$ and is for one visual stimulus a $(m-1) \times (m-1)$ matrix, for two visual stimuli a 2×2 matrix. In R you can find the transition probabilities from the transient to the recurrent states, which is a $(m-1) \times 1$ matrix for single target stimulation and a $(m-2) \times 2$ matrix for double target stimulation.The next requirement is to define the starting conditions of the diffusion process. This is done by a definition of the initial distribution Z, which contains the initial probability distribution over the transient states. Z is a vector containing $(m-1) \times 1$ zeros in the single target condition resp. $(m-2) \times 1$ zeros for double target condition except for one position: If a subject has not got a bias for one hemisphere, the vector Z contains 1 in the middle position, e.g., at $j = (m-1)/2$, if the subject is biased, 1 is denoted on a position somewhat below or above. It is now possible to define the first passage transition T_{ij} from the transient state i to the recurrent state j in n steps:

$$F^{(n)} = Q^{n-1}R \tag{A.7}$$

Taking into account that the process starts with a special initial distribution, one may write:

$$F^{(n)} = Z'Q^{n-1}R \tag{A.8}$$

For the double target condition, I define looking at one visual stimulus as *response* A, and looking at the other one as *response* B. Now one can denote the choice probability and the expectation values for the reaction times in the case of one attribute as

$$Prob[A] = Z' \sum_{n=1}^{\infty} Q^{n-1} R_A = Z'(I-Q)^{-2} R_A(-\tau) \tag{A.9}$$

and

$$E[T|A] = \frac{\tau Z'(I-Q)^{-1} R_A}{Z'(I-Q)^{-1} R_A} \tag{A.10}$$

where I is the identity matrix.

One can extend this to the case of three time intervals (for details see Diederich, 1995) and get:

$$\begin{aligned} &Prob[A] = \\ &\quad Z' \sum_{i=1}^{n_1} Q_1^{i-1} R_{A_1} + \\ &\quad Z' Q_1^{n_1} \sum_{i=n_1+1}^{n_2} Q_2^{i-(n_1+1)} R_{A_2} + \\ &\quad Z' Q_1^{n_1} Q_2^{n_2-n_1} \sum_{i=n_2+1}^{\infty} Q_3^{i-(n_2+1)} R_{A_3} \end{aligned} \tag{A.11}$$

with the first interval being denoted as $Z' \sum_{i=1}^{n_1} Q_1^{i-1} R_{A_1}$, the second interval being denoted as $Z' Q_1^{n_1} \sum_{i=n_1+1}^{n_2} Q_2^{i-(n_1+1)} R_{A_2}$ and the third interval being denoted as $Z' Q_1^{n_1} Q_2^{n_2-n_1} \sum_{i=n_2+1}^{\infty} Q_3^{i-(n_2+1)} R_{A_3}$.

For the expectancy values it holds that:

$$\begin{aligned} &E[T|A] = \\ &\quad \tau[Z' \sum_{i=1}^{n_1} Q_1^{i-1} R_{A_1} + \\ &\quad Z' Q_1^{n_1} \sum_{i=n_1+1}^{n_2} Q_2^{i-(n_1+1)} R_{A_2} + \\ &\quad Z' Q_1^{n_1} Q_2^{n_2-n_1} \sum_{i=n_2+1}^{\infty} Q_3^{i-(n_2+1)} R_{A_3}]/Prob[A] \end{aligned} \tag{A.12}$$

Appendix B

Experiment 1: Parameter estimations for all single and all double target conditions for all subjects not shown in text

B.1 Parameter estimations for the single target condition

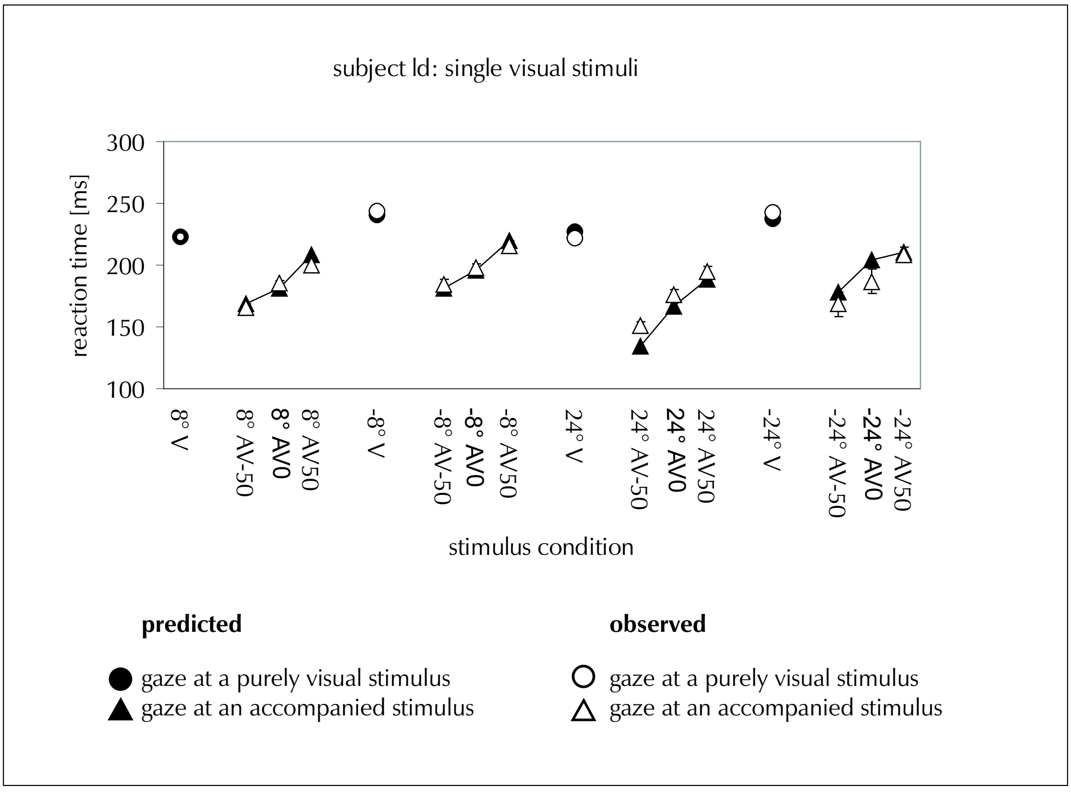

Figure B.1: Subject *ld*: Single target condition. Given are the predicted and observed mean reaction times and standard errors.

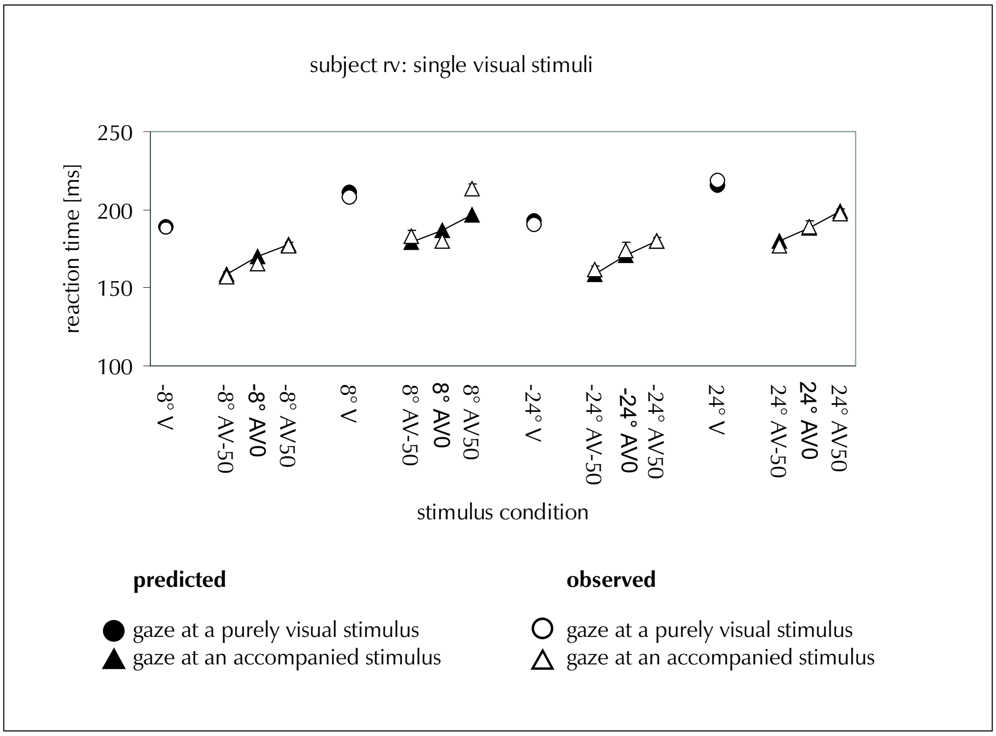

Figure B.2: Subject *rv*: Single target condition. Given are the predicted and observed mean reaction times and standard errors.

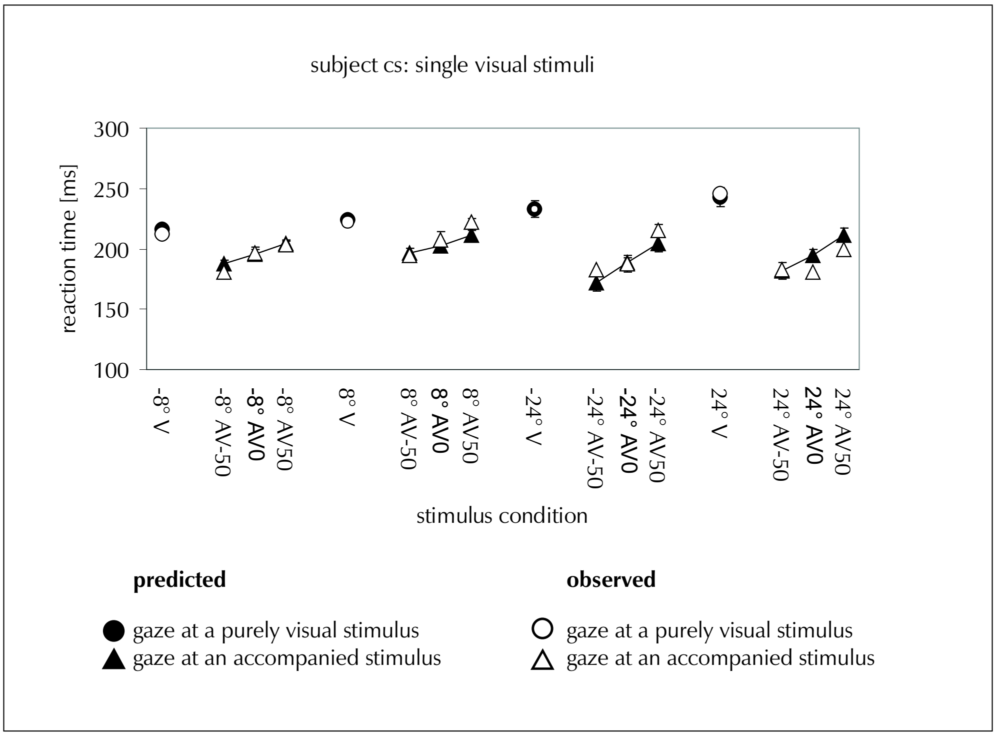

Figure B.3: Subject *cs*: Single target condition. Given are the predicted and observed mean reaction times and standard errors.

B.2 Parameter estimations for the double target condition

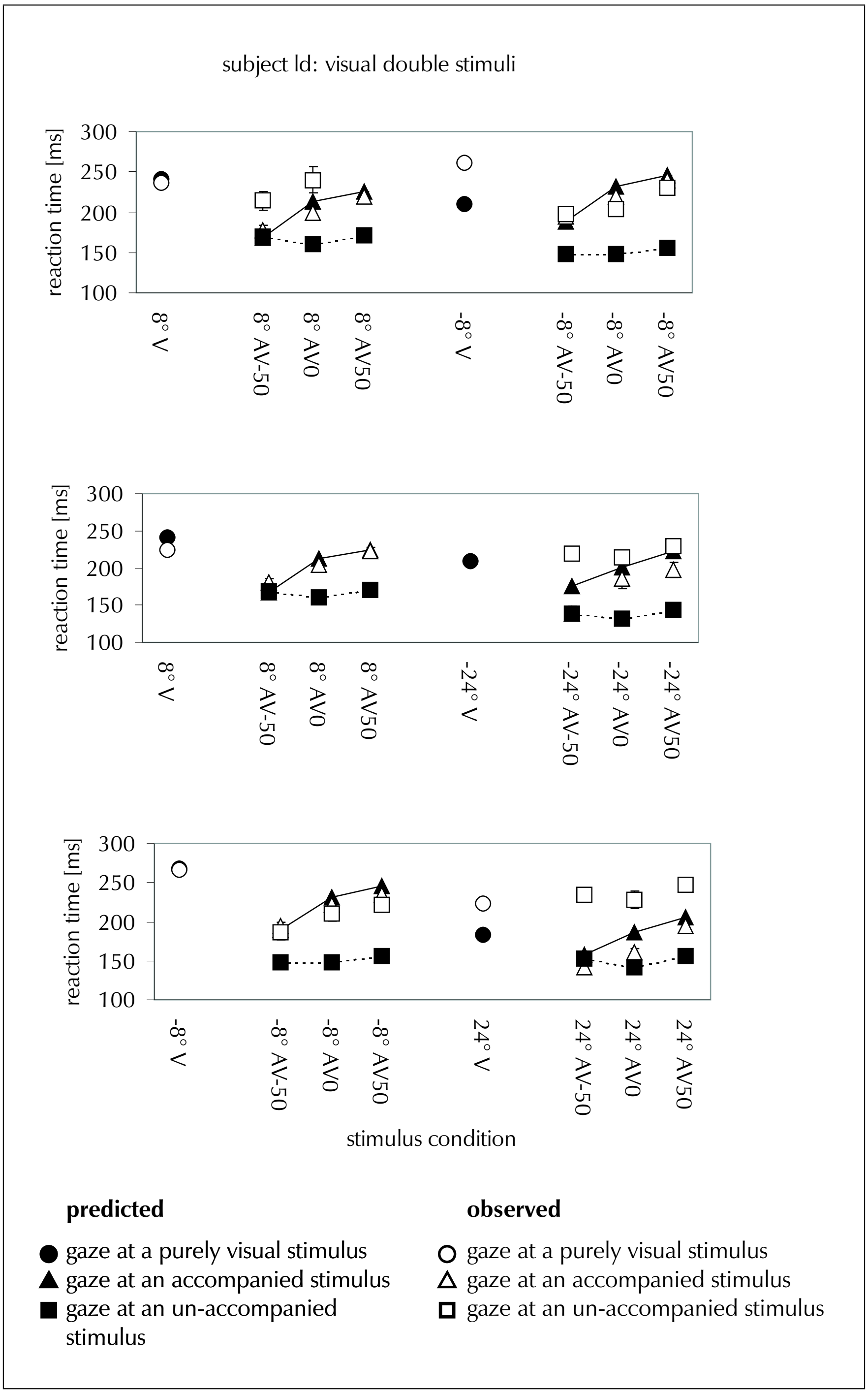

Figure B.4: Subject *ld*: Three double target conditions. Given are the predicted and observed mean reaction times and standard errors.

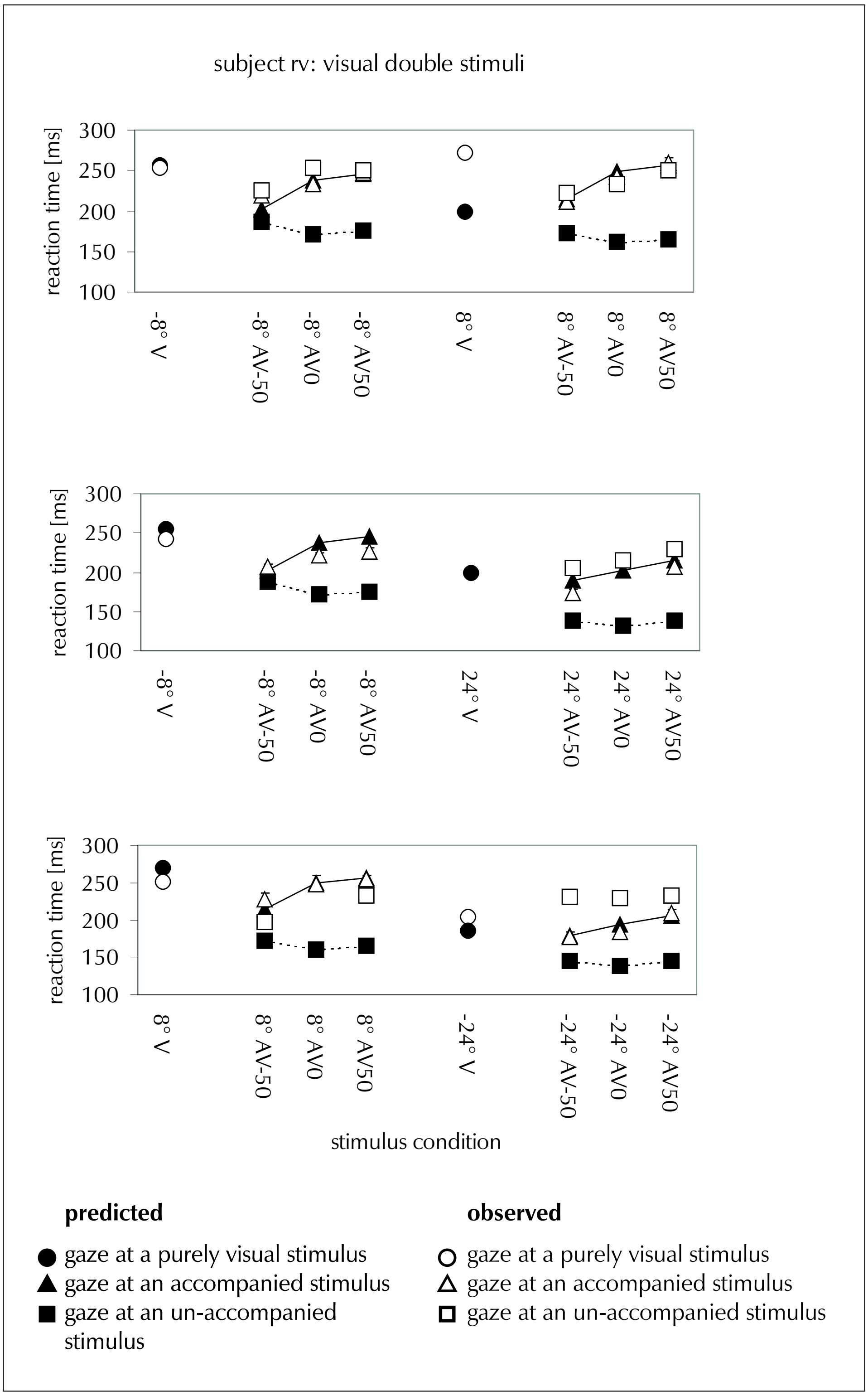

Figure B.5: Subject *rv*: Three double target conditions. Given are the predicted and observed mean reaction times and standard errors.

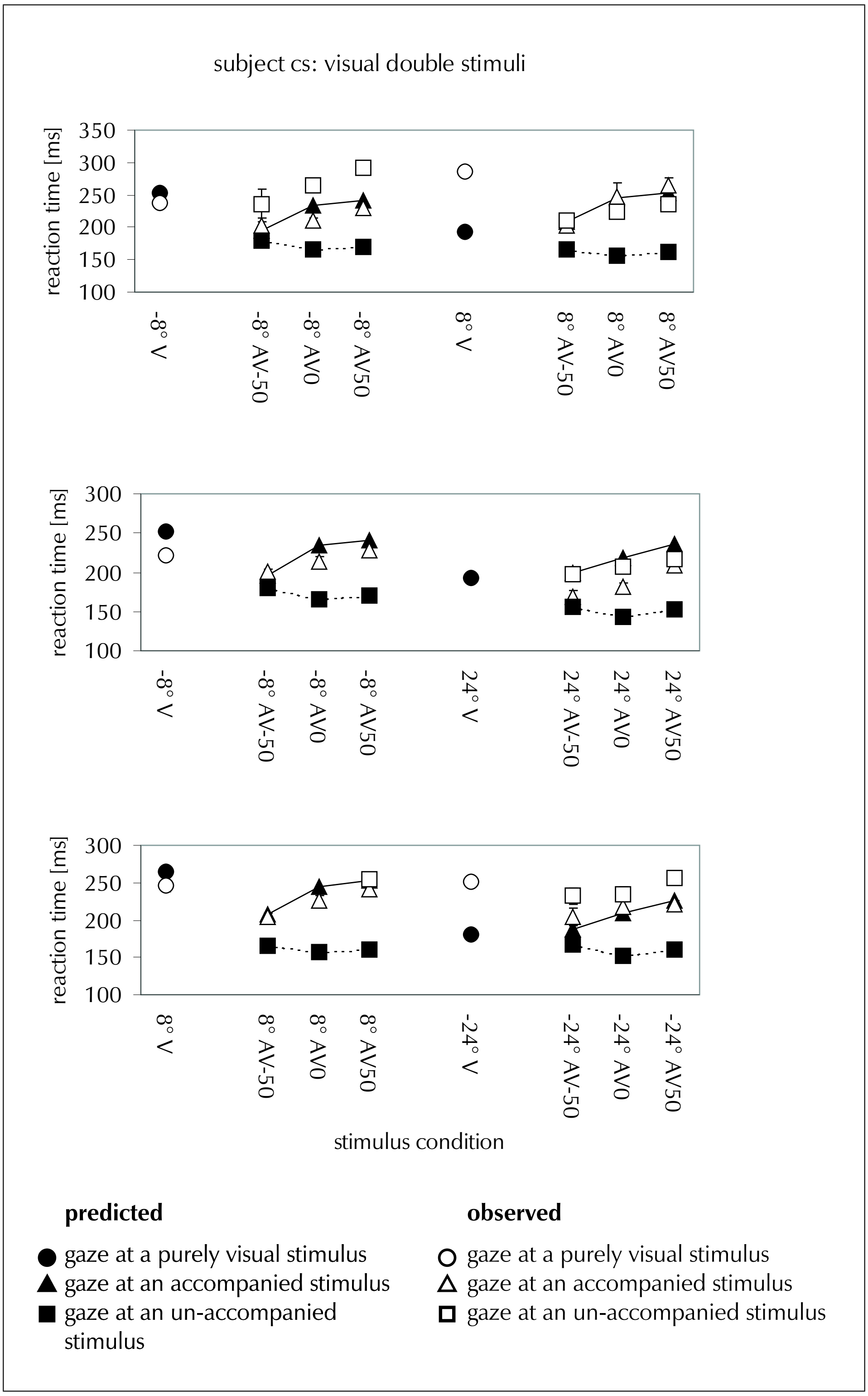

Figure B.6: Subject *cs*: Three double target conditions. Given are the predicted and observed mean reaction times and standard errors.

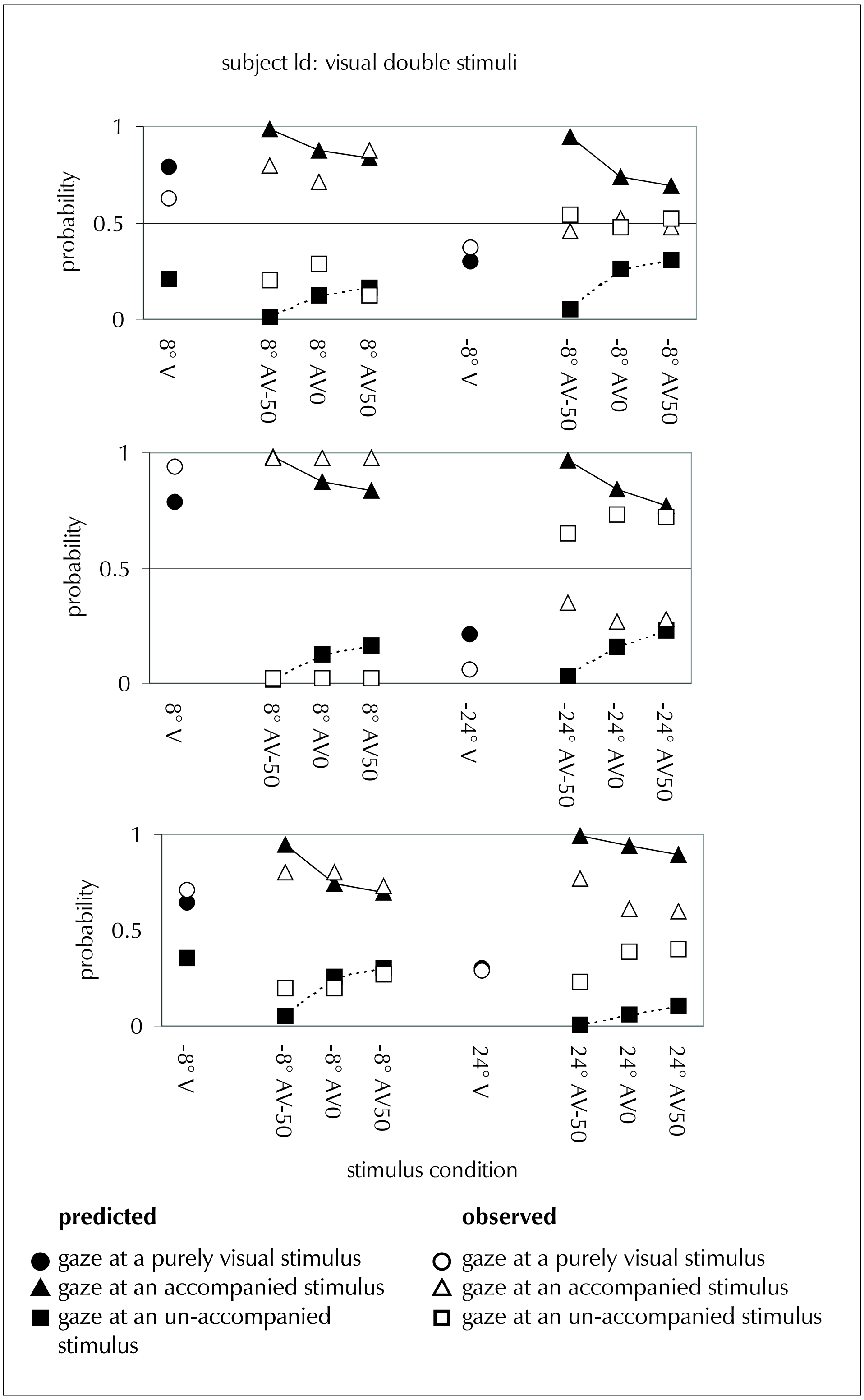

Figure B.7: Subject *ld*: Three double target conditions. Given are the predicted and observed probabilities.

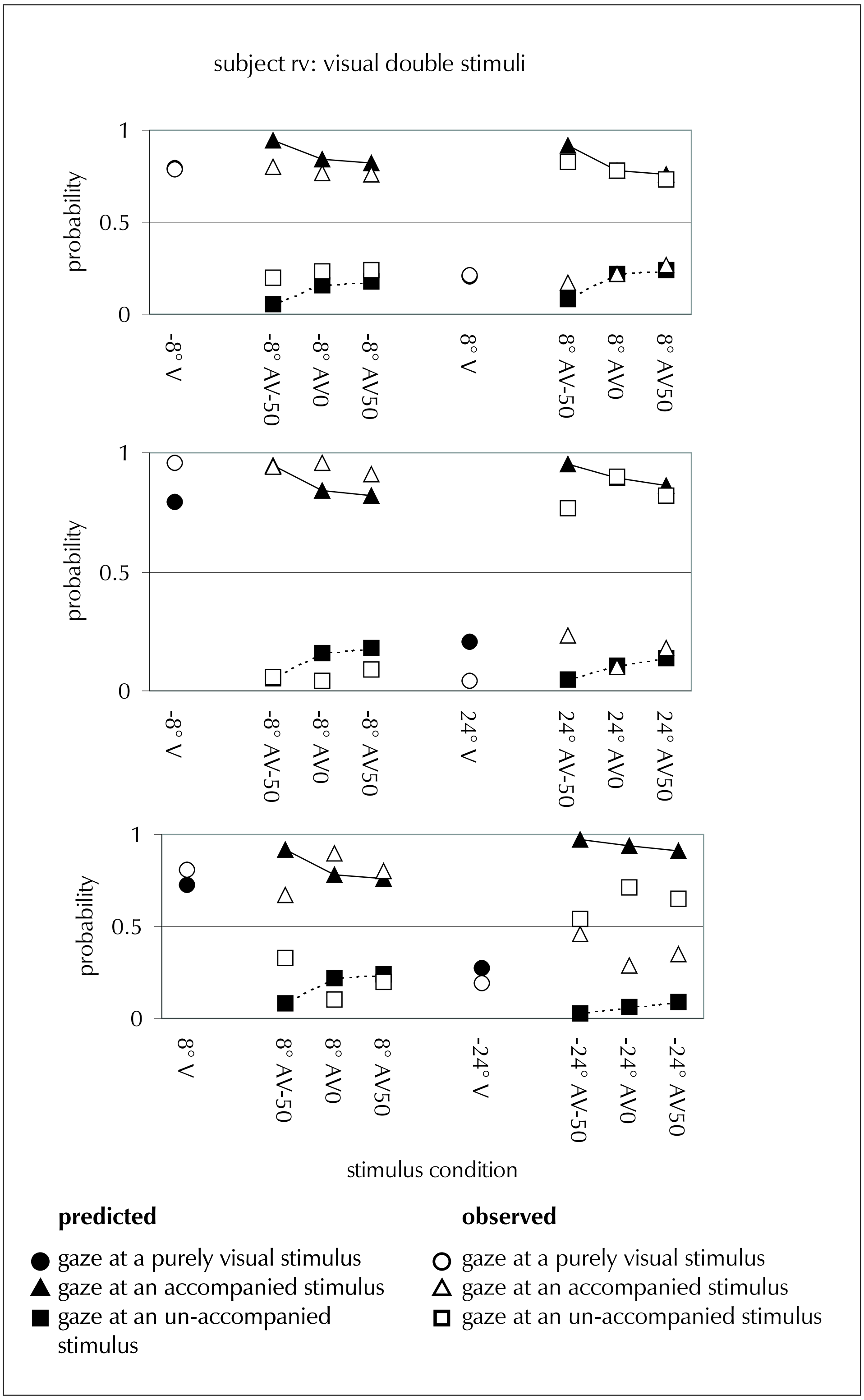

Figure B.8: Subject *rv*: Three double target conditions. Given are the predicted and observed probabilities.

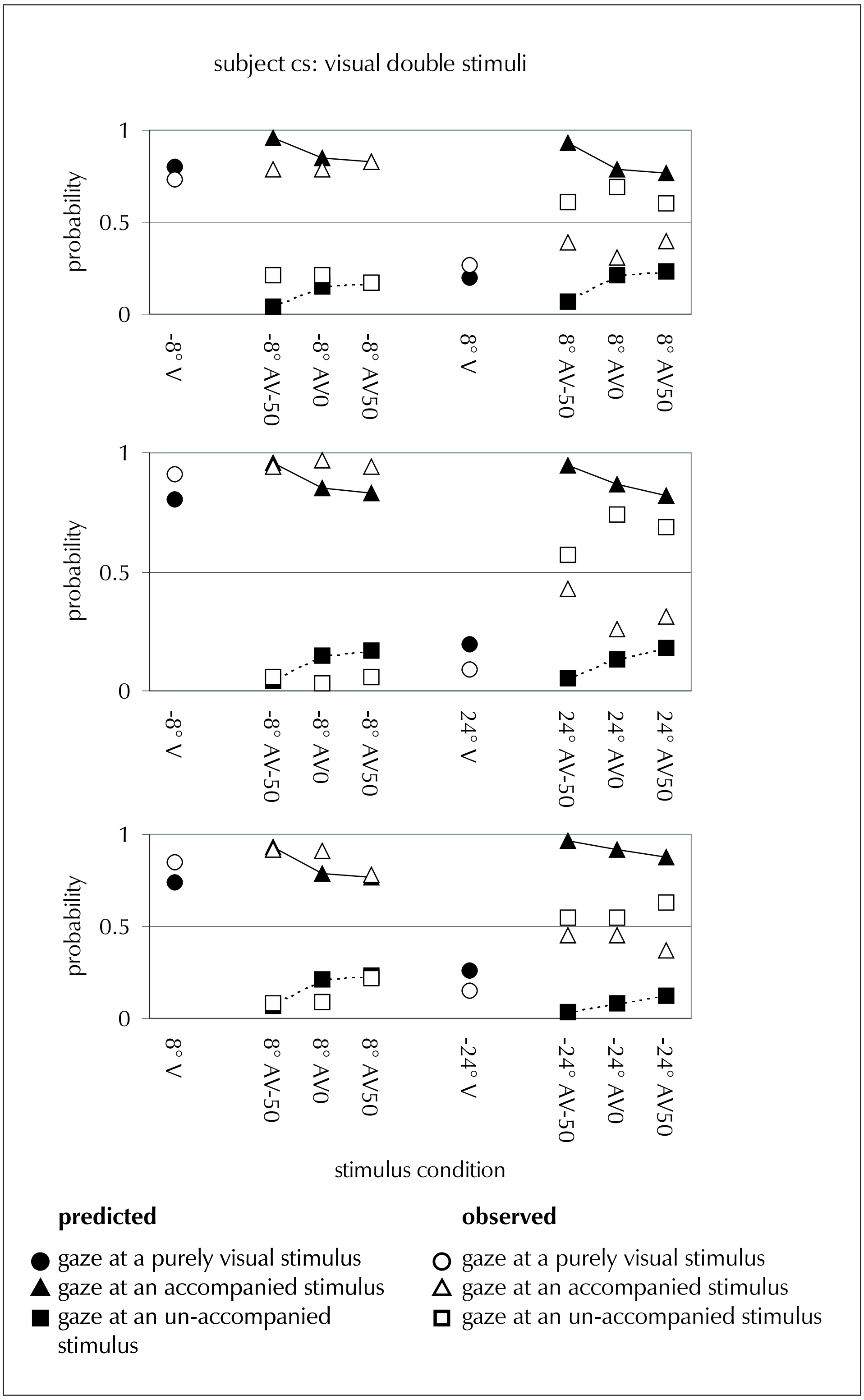

Figure B.9: Subject *cs*: Three double target conditions. Given are the predicted and observed probabilities.

Appendix C

Experiment 4: Parameter estimations for all single and all double target conditions for all subjects not shown in text

C.1 Parameter estimations for the single target conditions

C.1.1 Parameter estimations for the single target condition for the visual stimulus pair 8° right/8° left

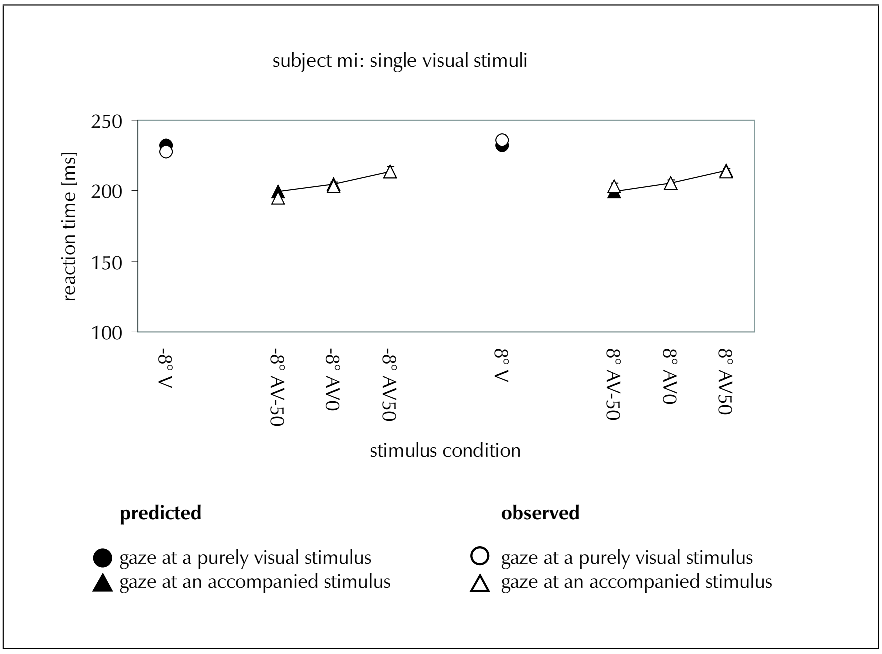

Figure C.1: Subject *mi*: Single target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

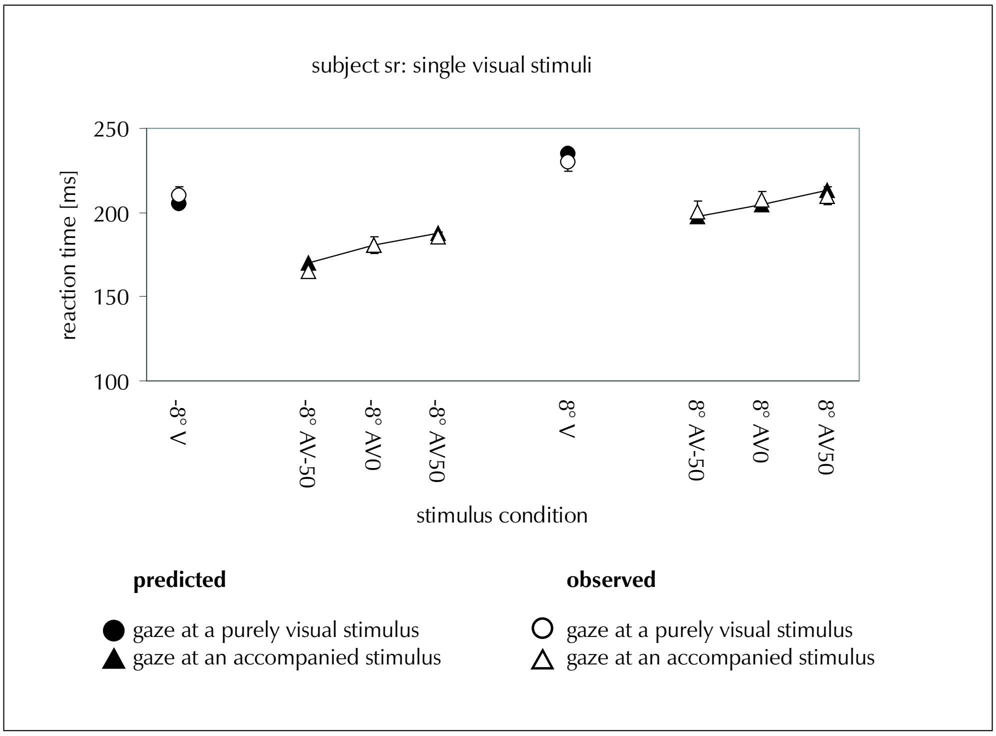

Figure C.2: Subject *sr*: Single target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

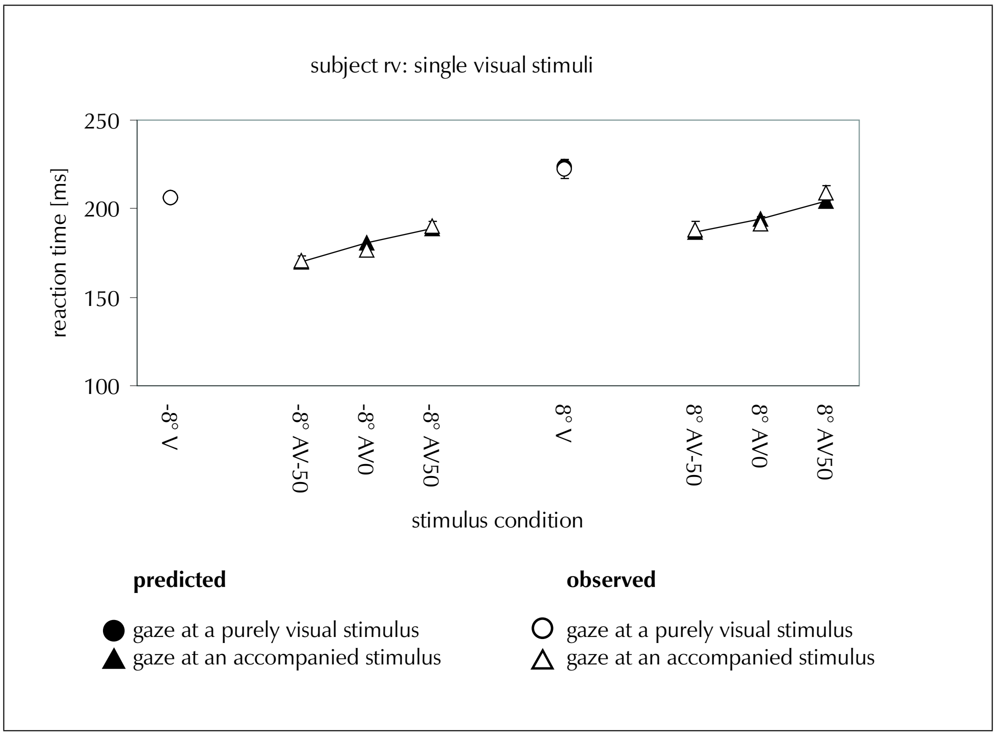

Figure C.3: Subject *rv*: Single target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

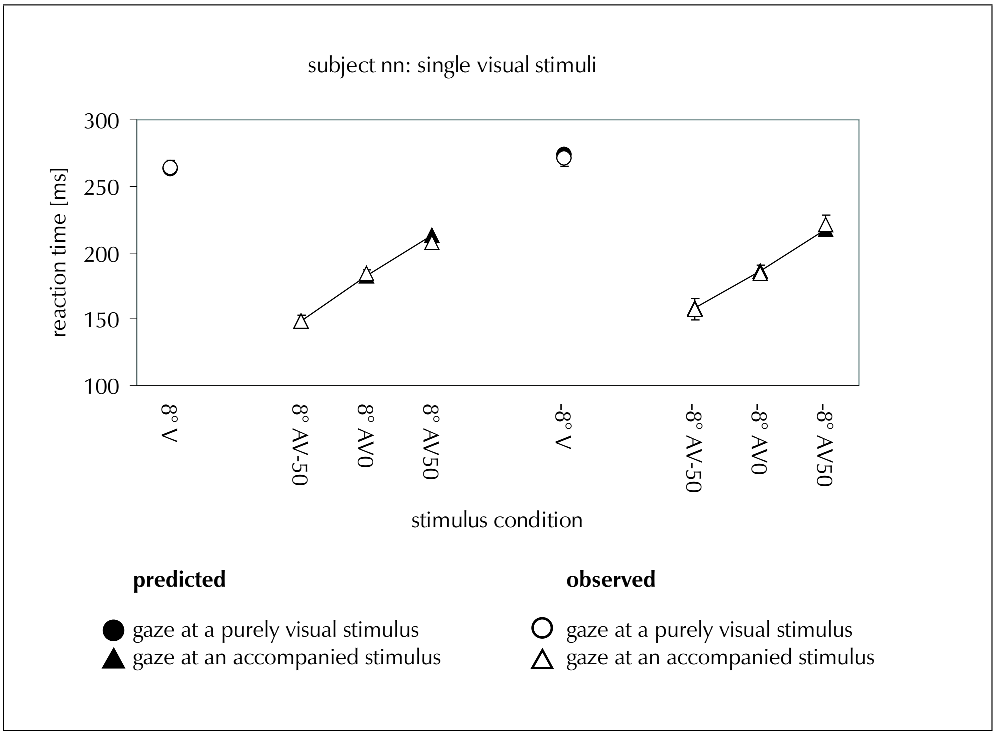

Figure C.4: Subject *nn*: Single target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

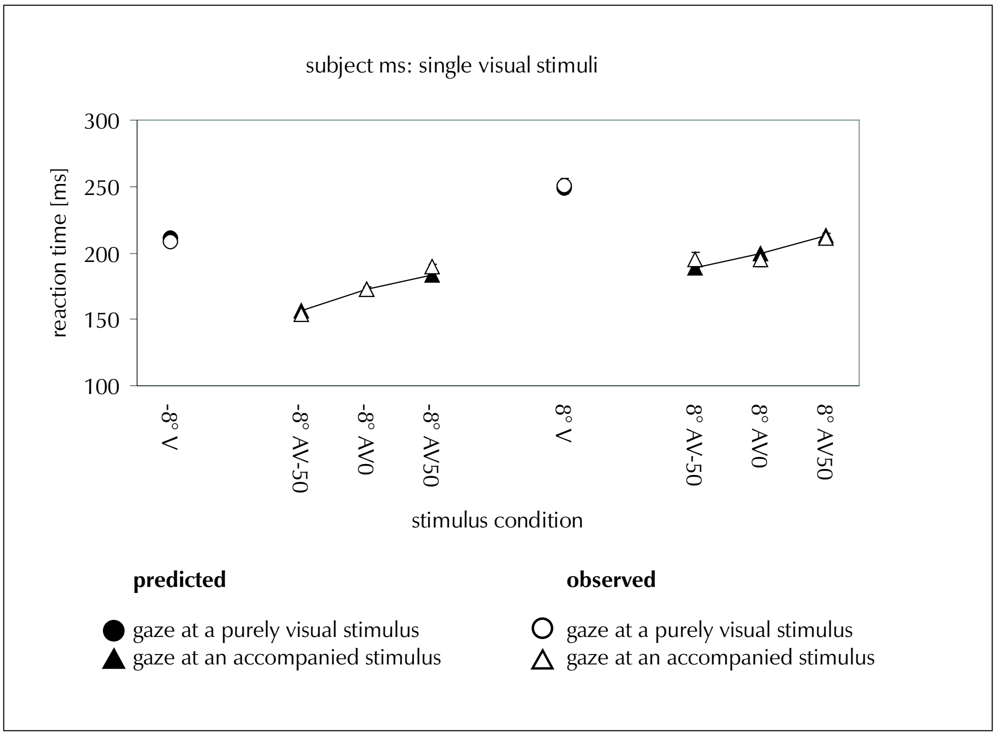

Figure C.5: Subject *ms*: Single target condition, visual stimulus pair 8° right/8° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

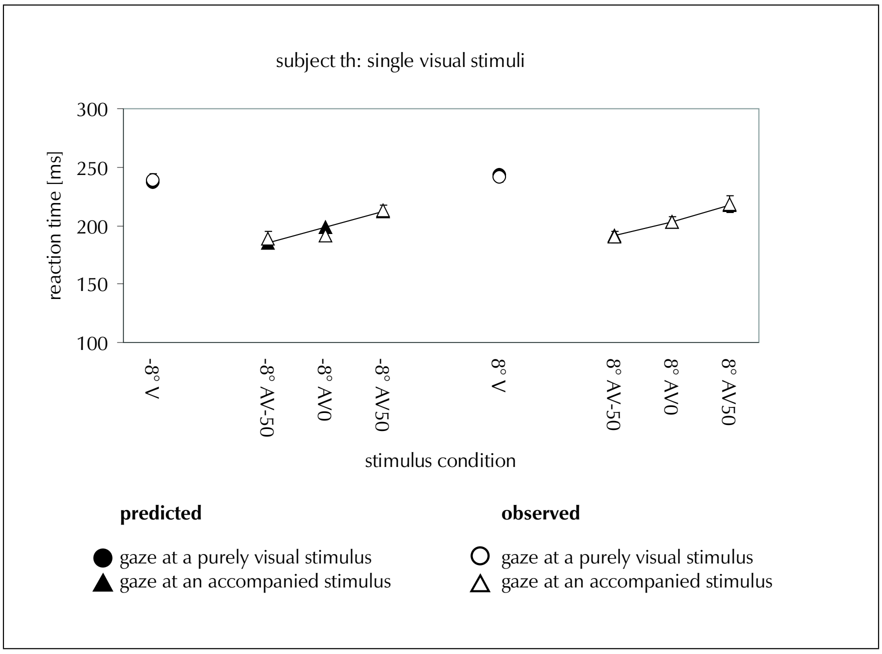

Figure C.6: Subject *th*: Single target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

C.1.2 Parameter estimations for the single target condition for visual stimulus pair 24° right/24° left

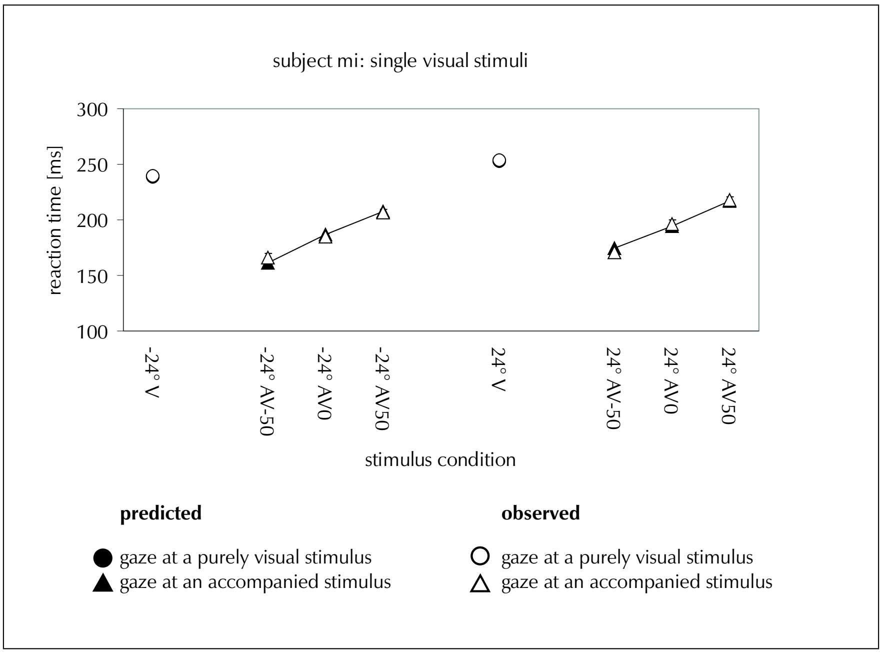

Figure C.7: Subject *mi*: Single target condition, visual stimulus pair 24° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

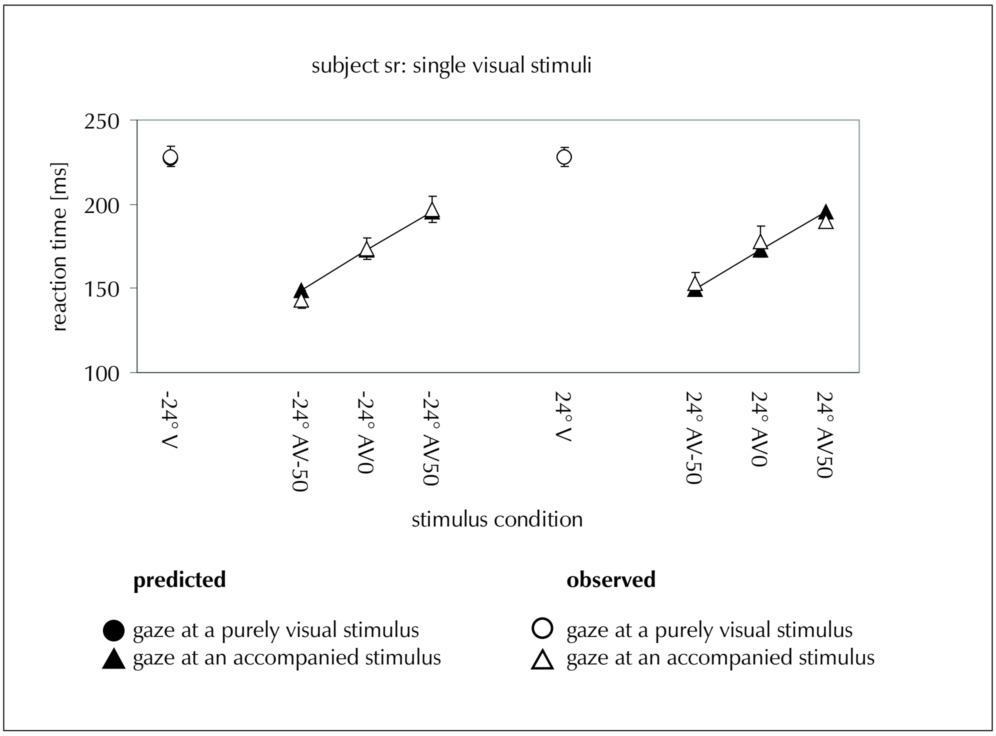

Figure C.8: Subject *sr*: Single target condition, visual stimulus pair 24° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

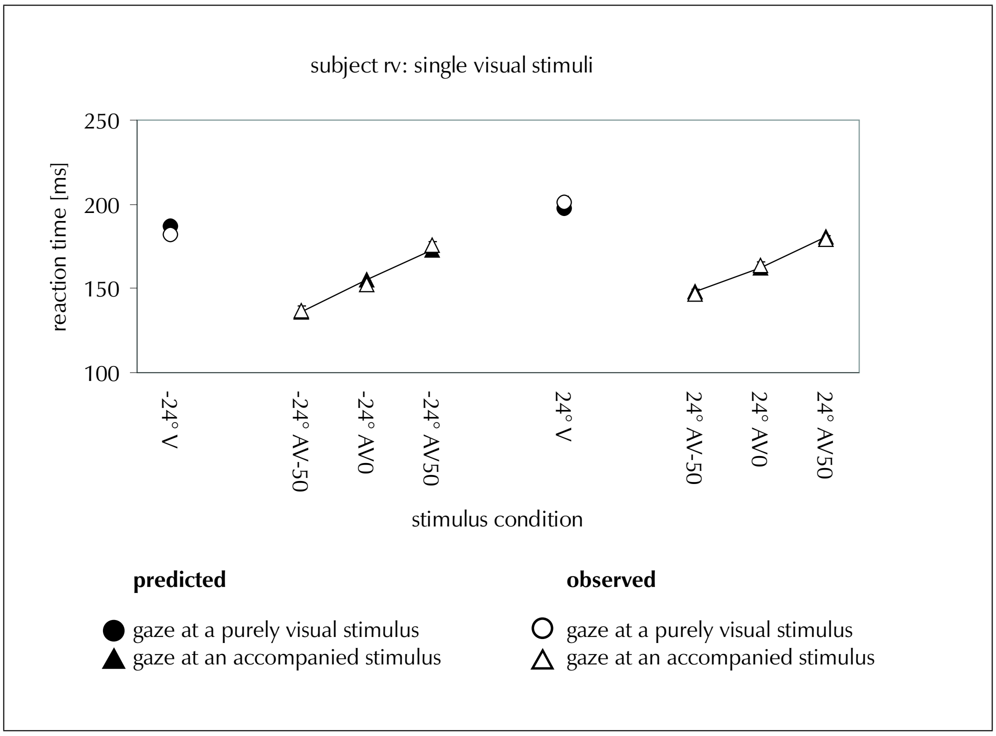

Figure C.9: Subject *rv*: Single target condition, visual stimulus pair 24° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

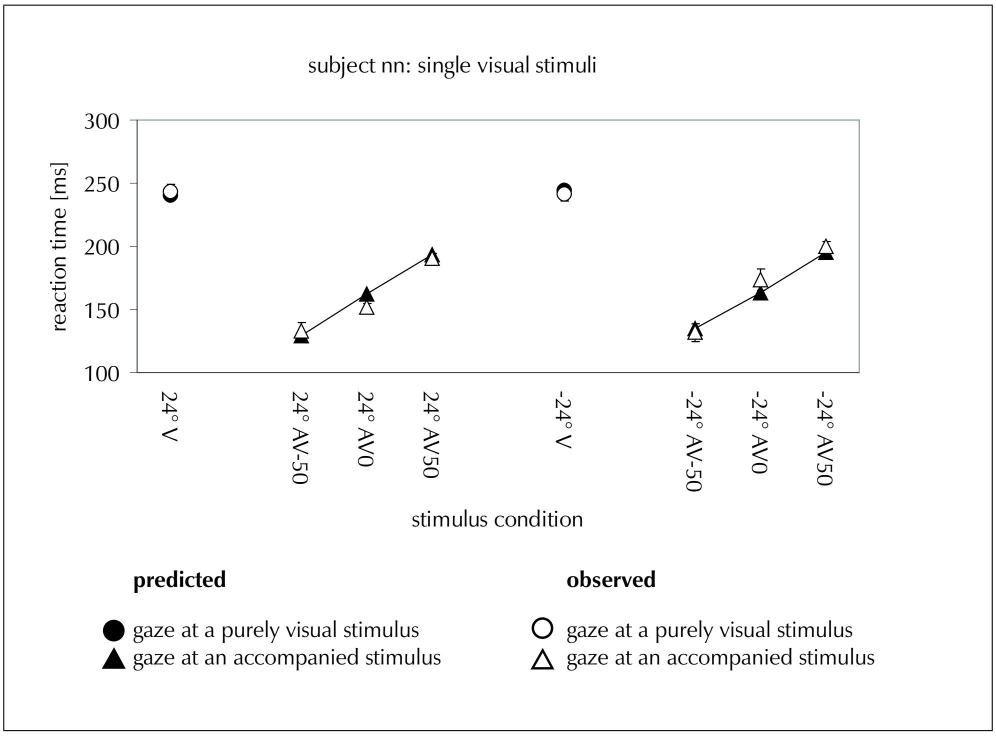

Figure C.10: Subject *nn*: Single target condition, visual stimulus pair 24° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

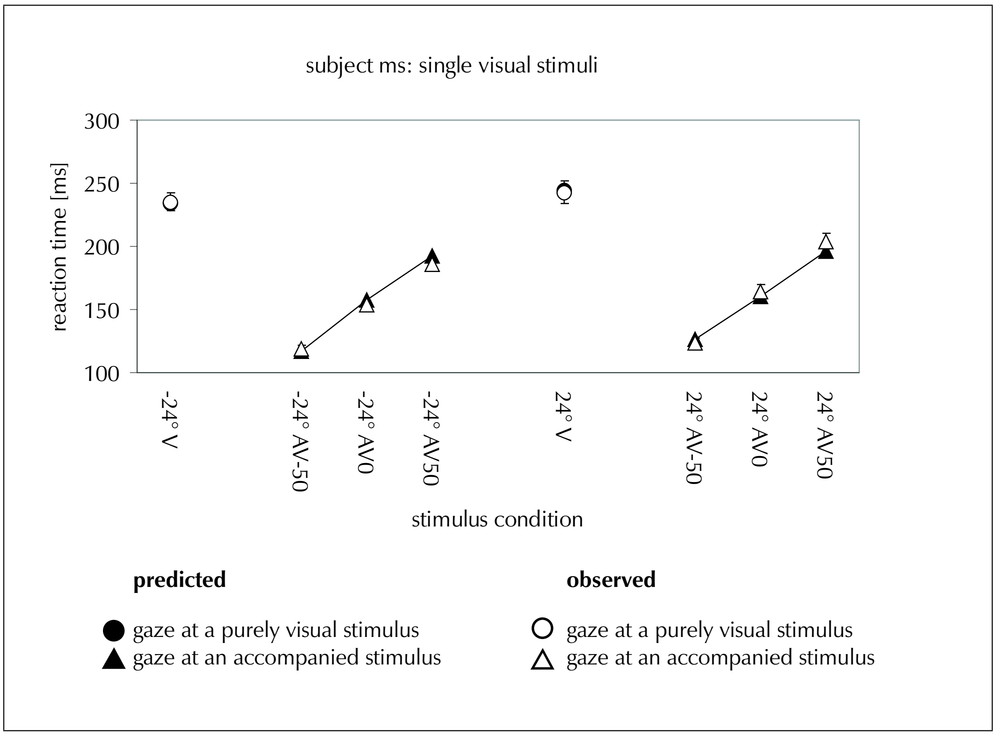

Figure C.11: Subject *ms*: Single target condition, visual stimulus pair 24° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

C.1.3 Parameter estimations for the single target condition for the visual stimulus pairs 8° right/24° left or 8° left/24° right

C.1.3.1 3-Parameter-Version

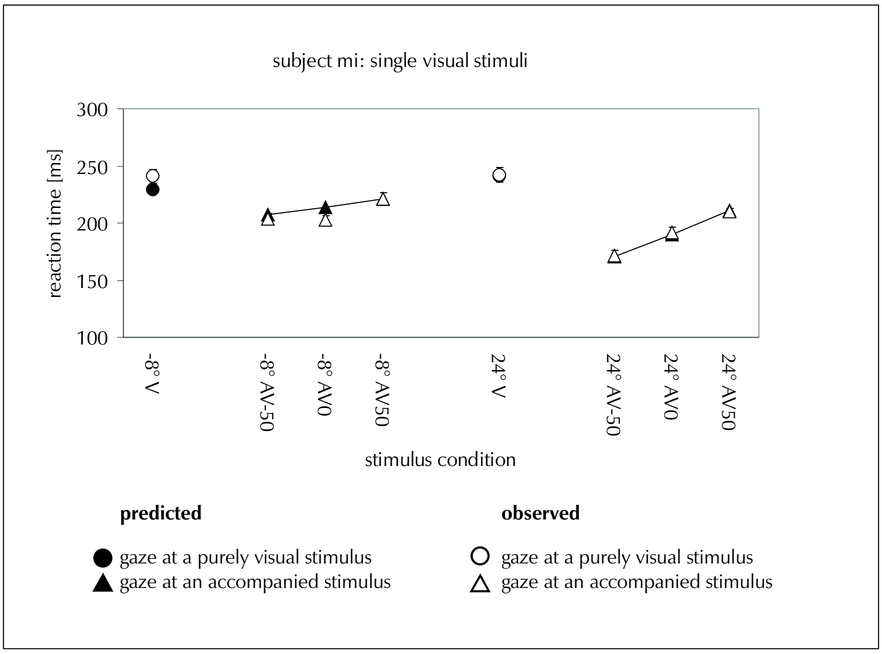

Figure C.12: Subject *mi*: Single target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

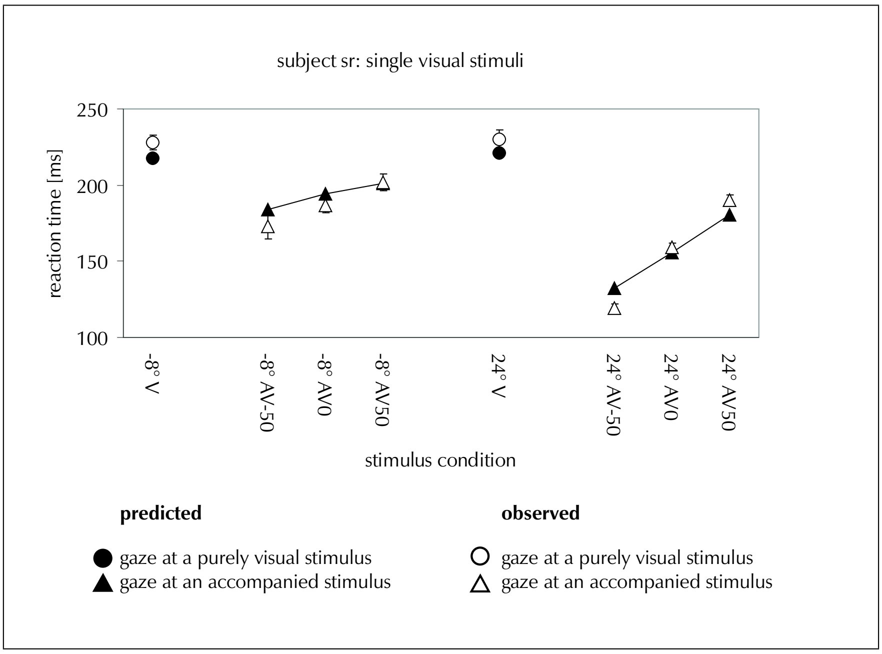

Figure C.13: Subject *sr*: Single target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

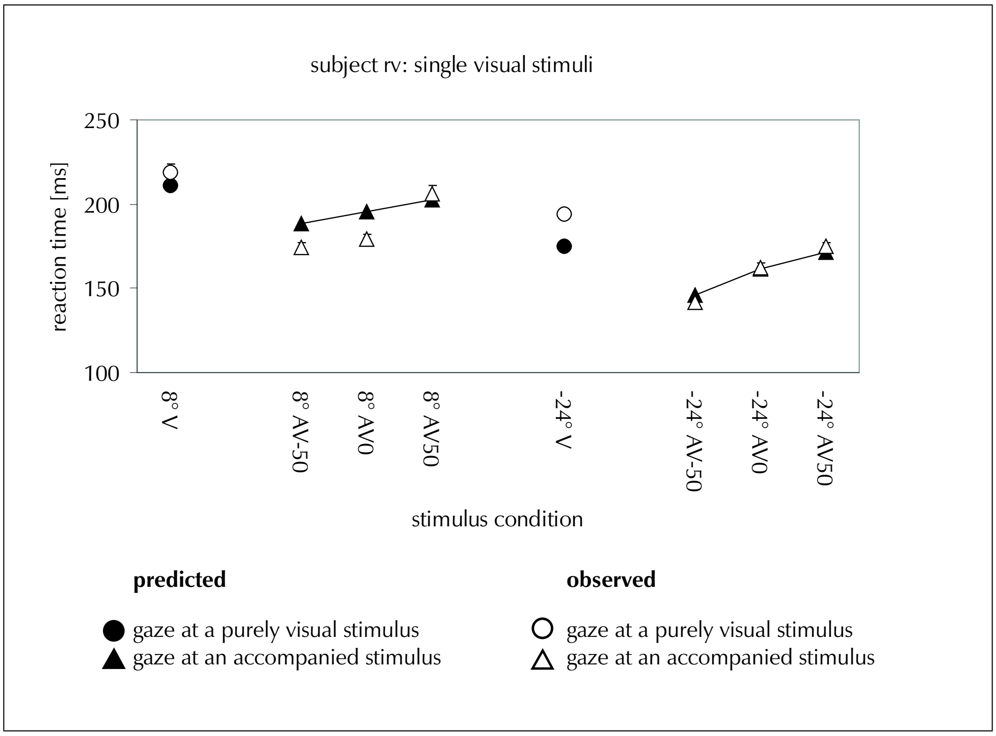

Figure C.14: Subject *rv*: Single target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

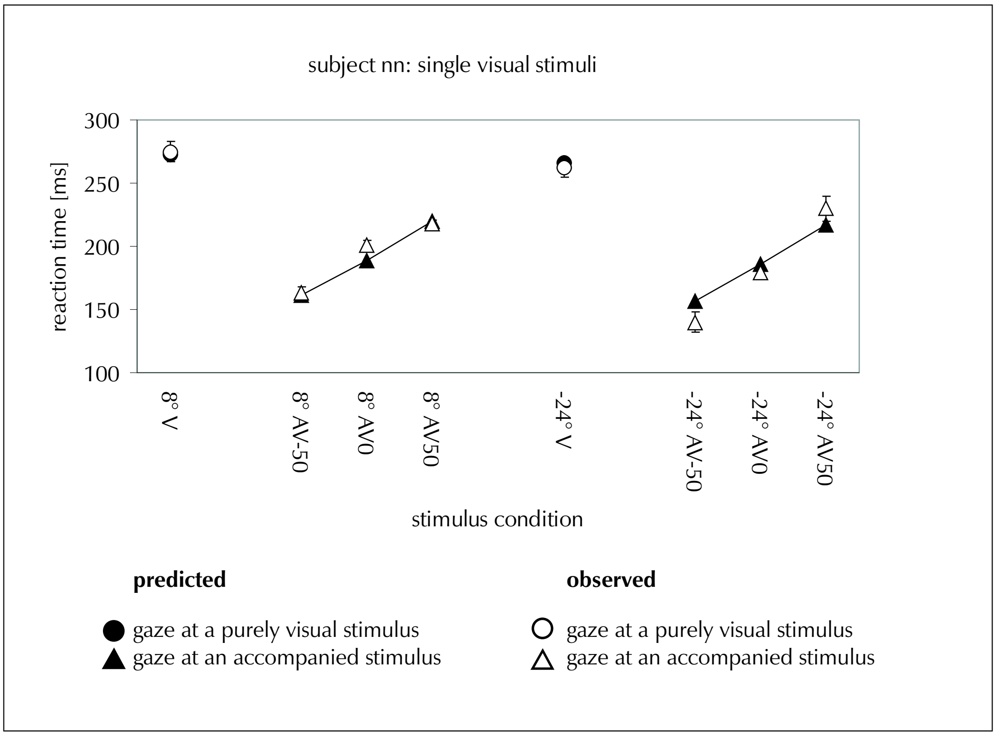

Figure C.15: Subject *nn*: Single target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

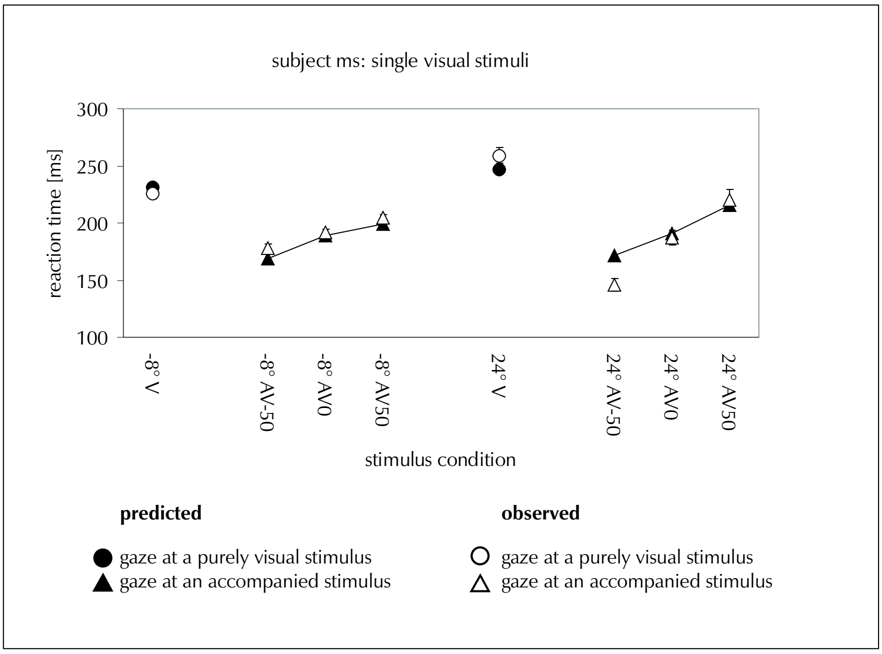

Figure C.16: Subject *ms*: Single target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

C.1.3.2 7-Parameter-Version

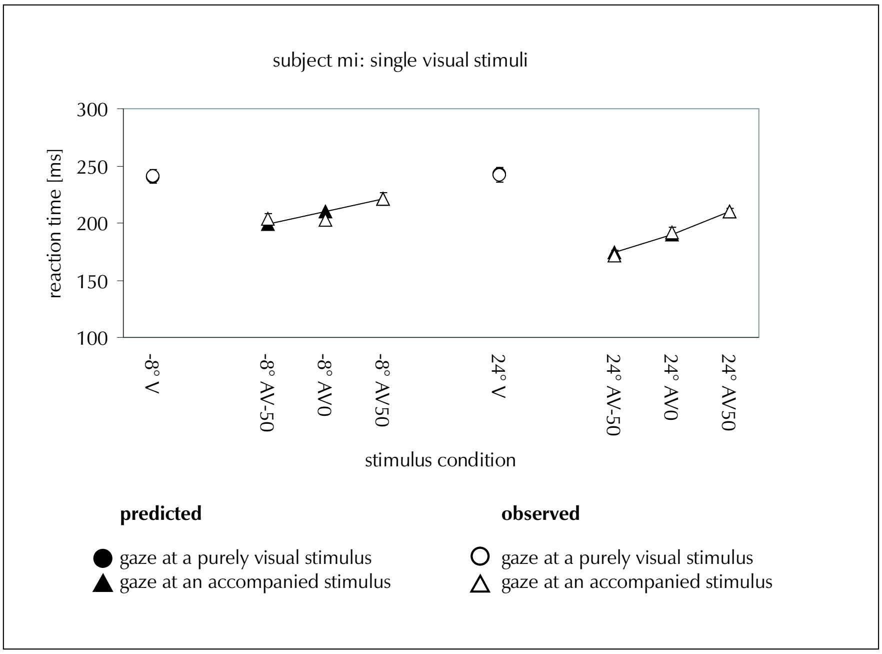

Figure C.17: Subject *mi*: Single target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

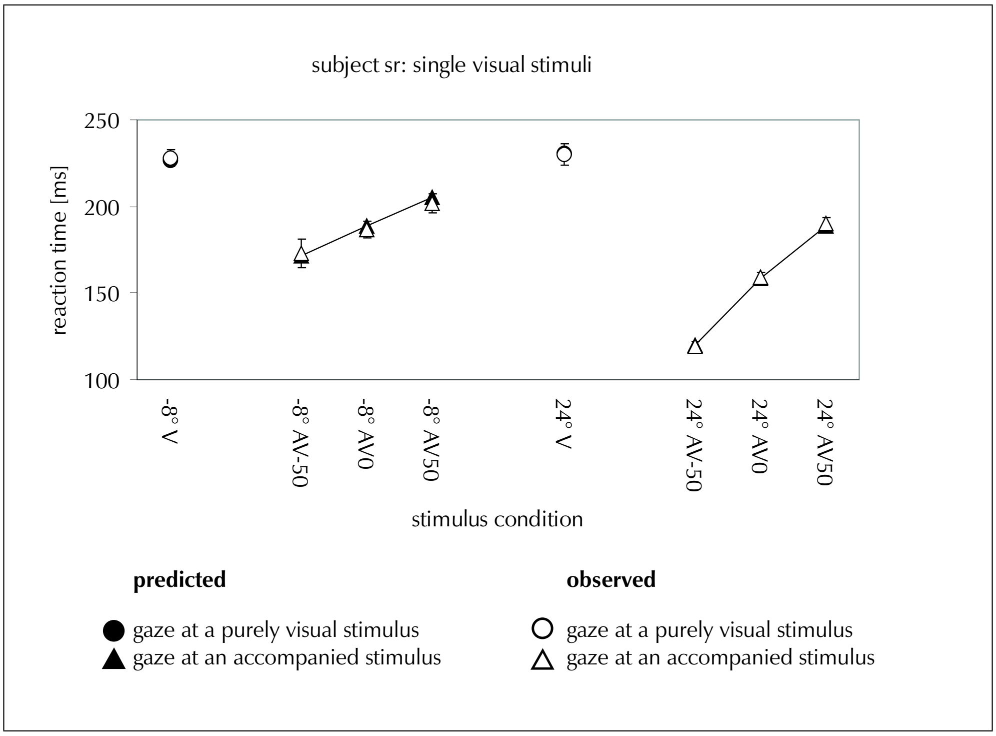

Figure C.18: Subject *sr*: Single target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

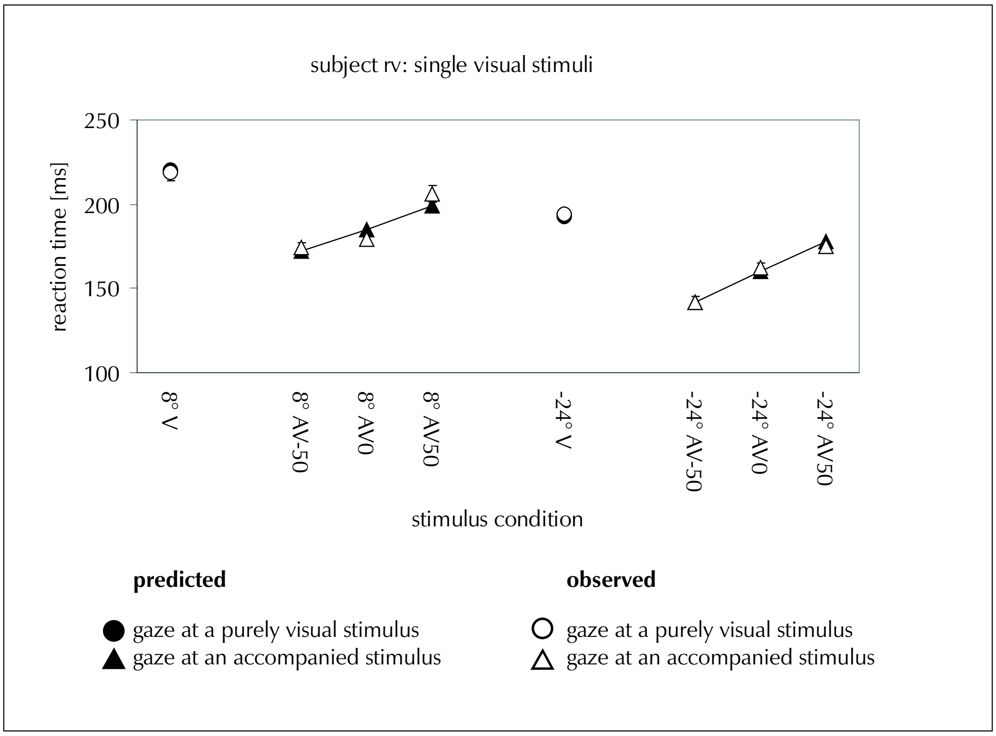

Figure C.19: Subject *rv*: Single target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

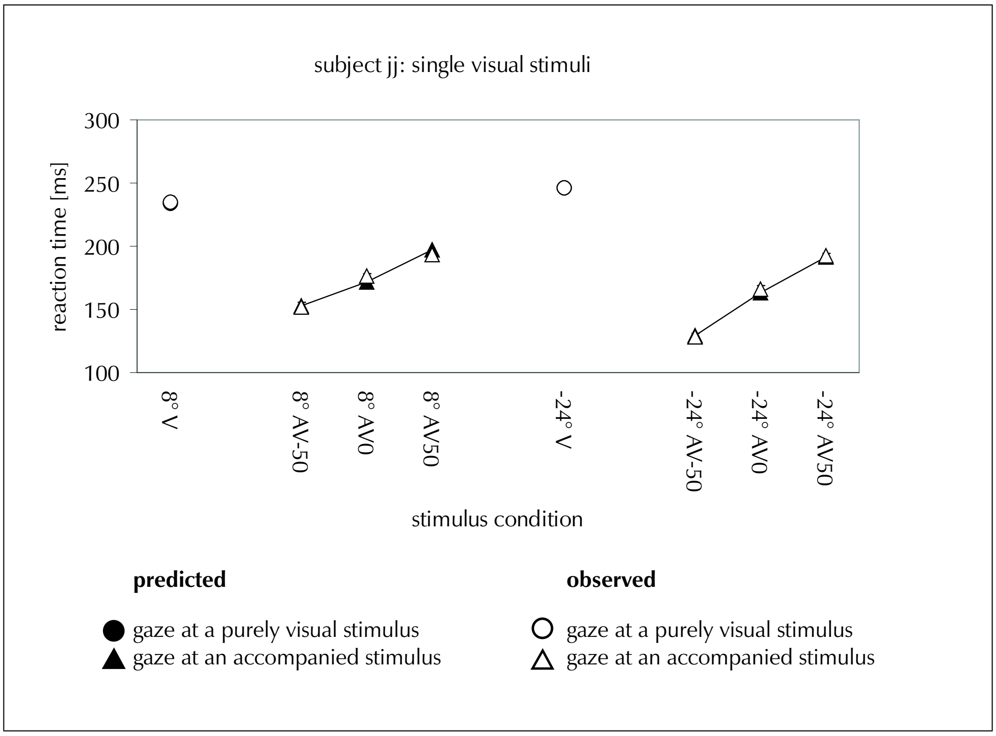

Figure C.20: Subject *jj*: Single target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

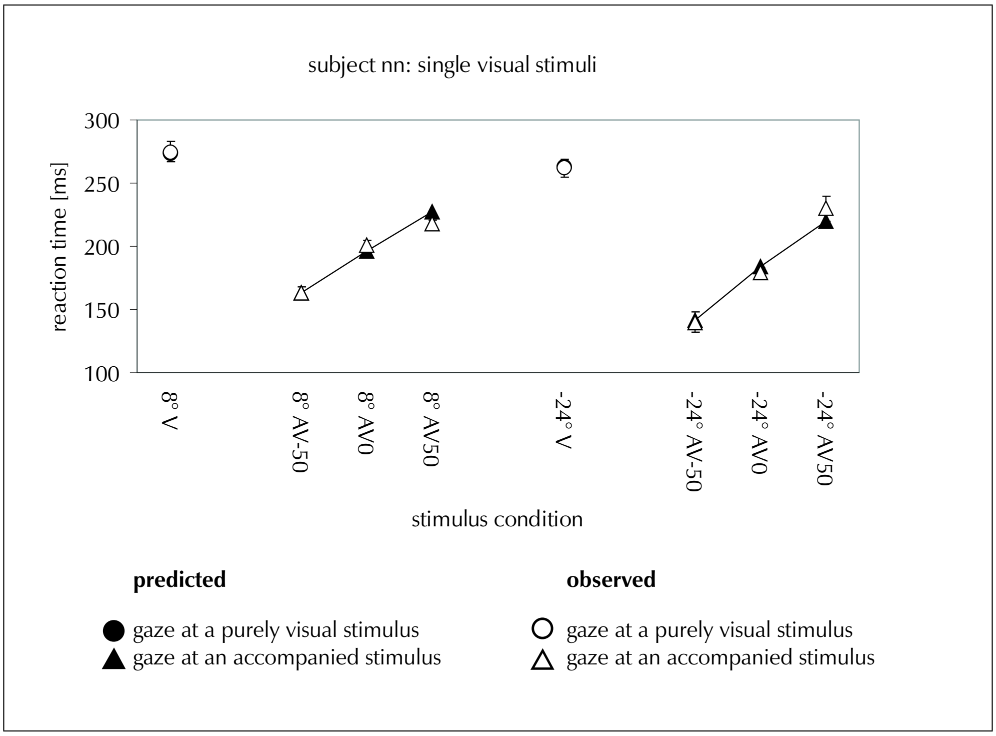

Figure C.21: Subject *nn*: Single target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

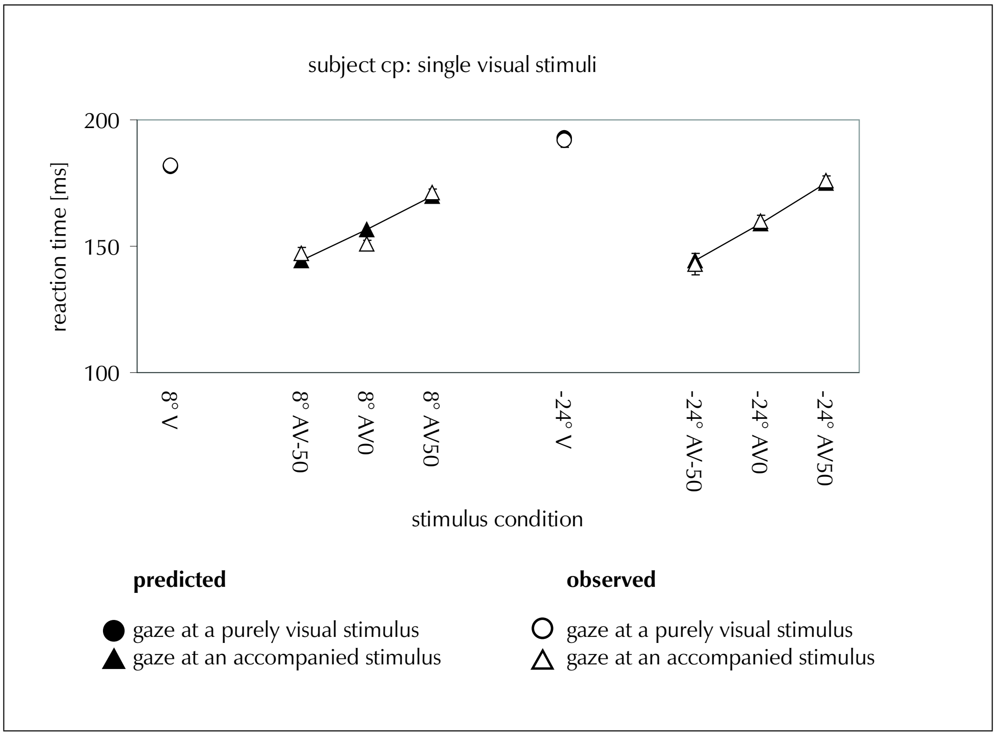

Figure C.22: Subject *cp*: Single target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

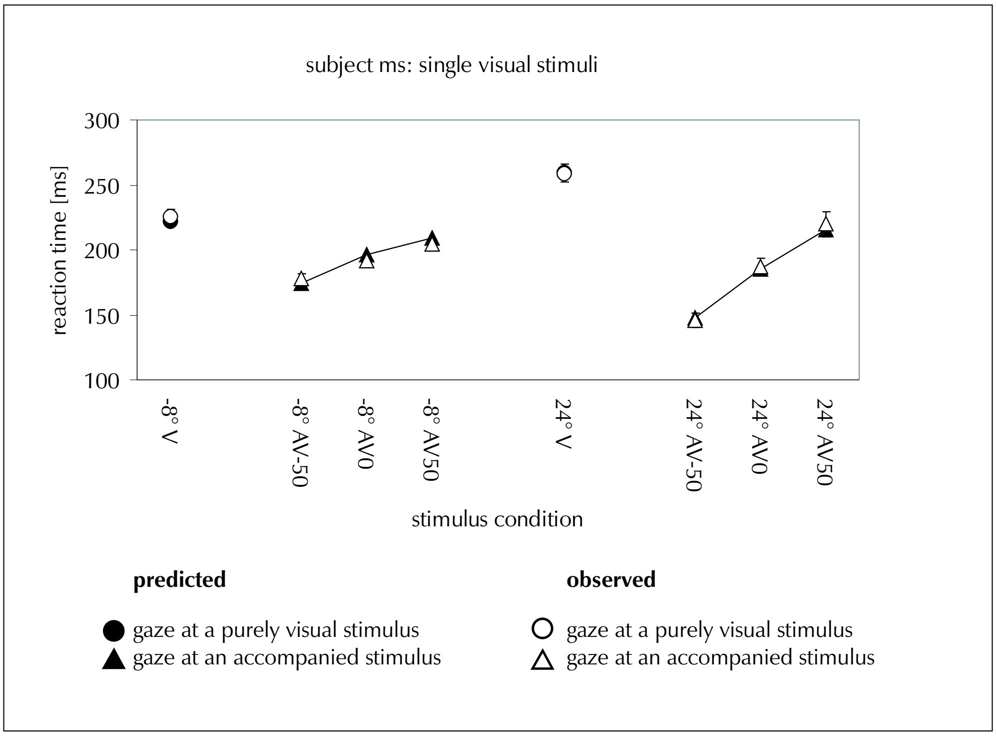

Figure C.23: Subject *ms*: Single target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

C.1.4 Parameter estimations for the single target condition for the visual stimulus pair 8° right/24° right or 8° left/24° left

C.1.4.1 2-Parameter-Version

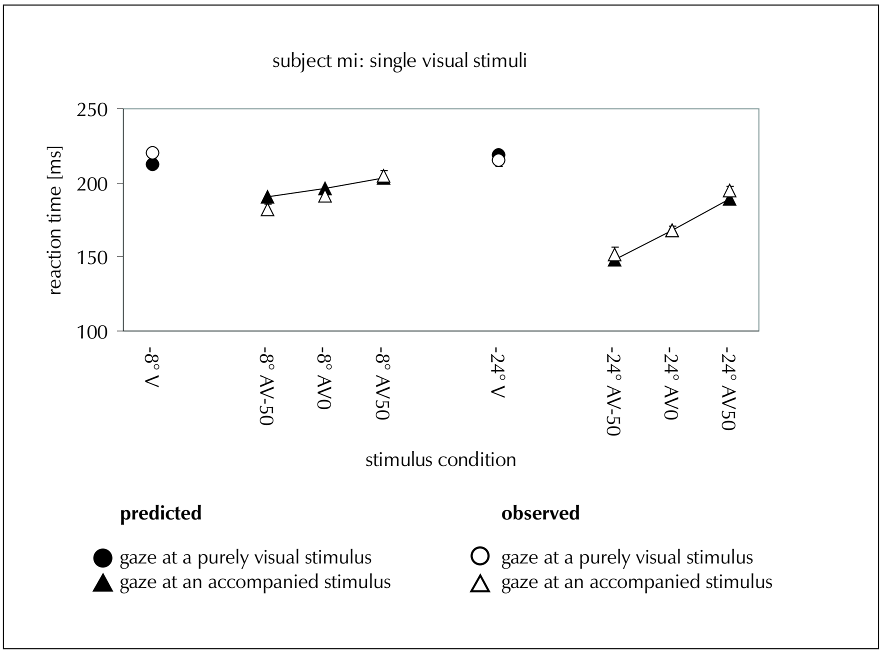

Figure C.24: Subject *mi*: Single target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

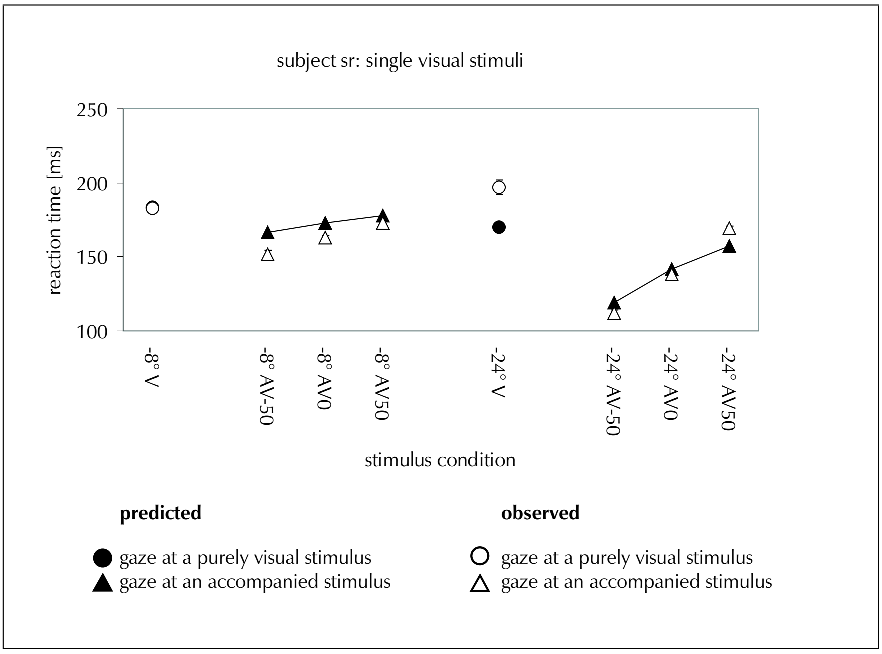

Figure C.25: Subject *sr*: Single target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

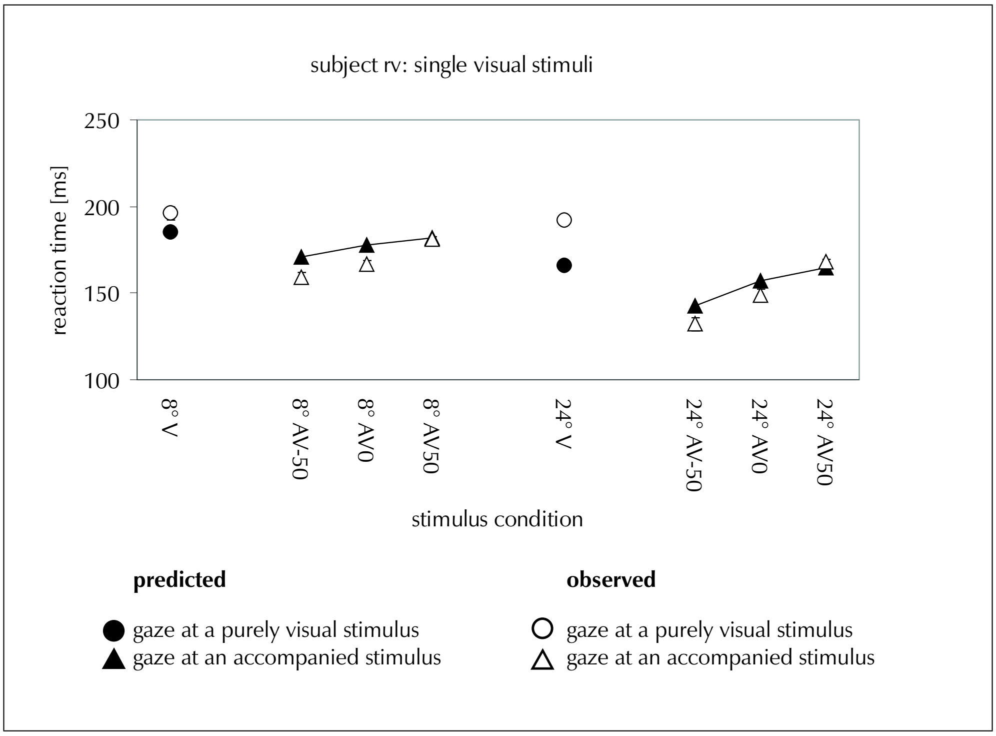

Figure C.26: Subject *rv*: Single target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

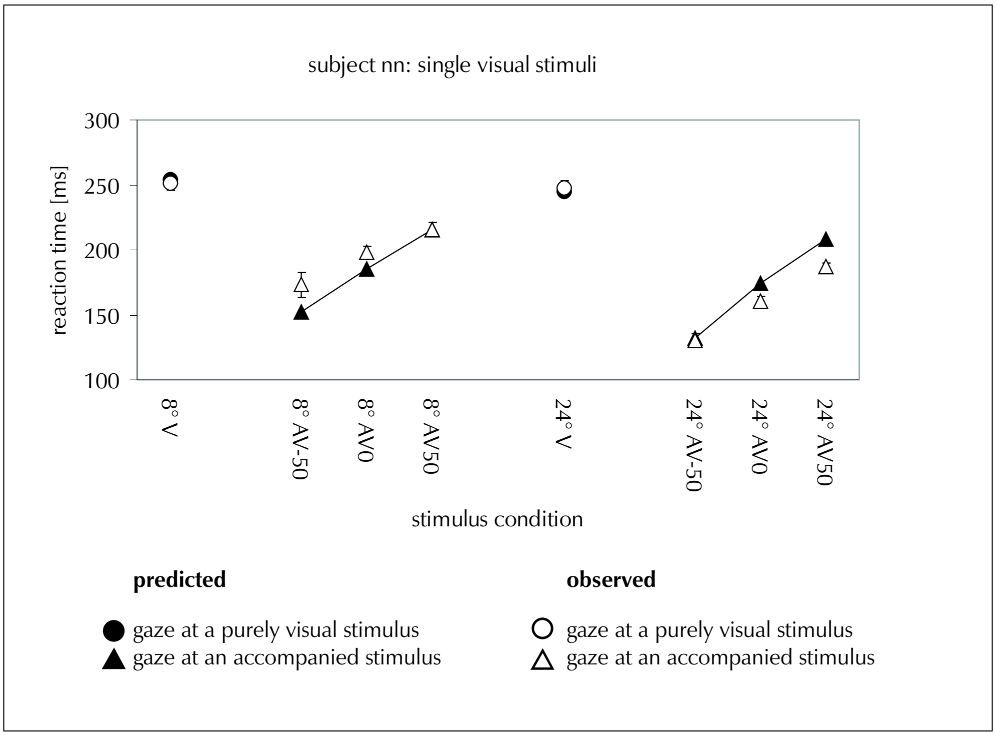

Figure C.27: Subject *nn*: Single target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

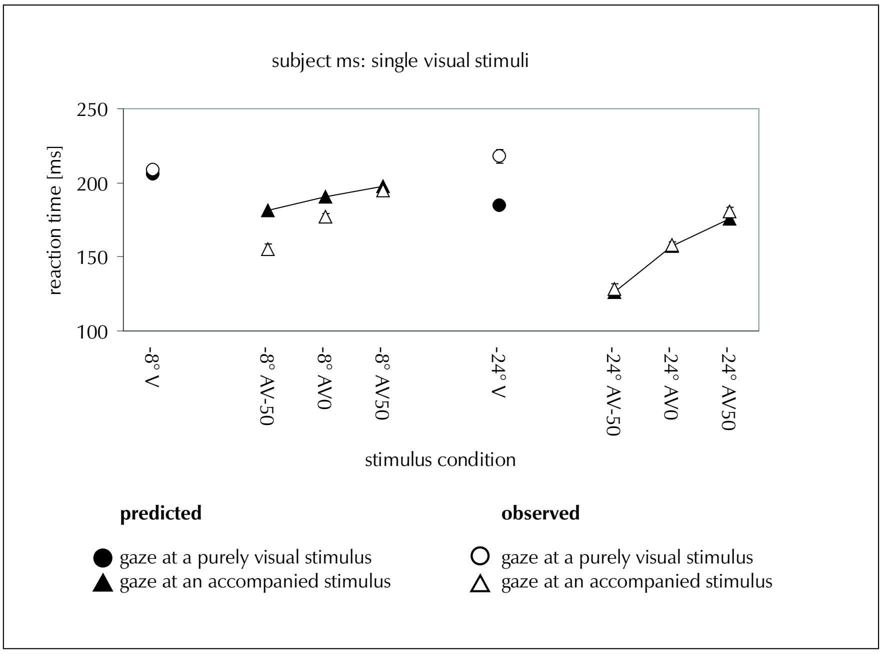

Figure C.28: Subject *ms*: Single target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

C.1.4.2 6-Parameter-Version

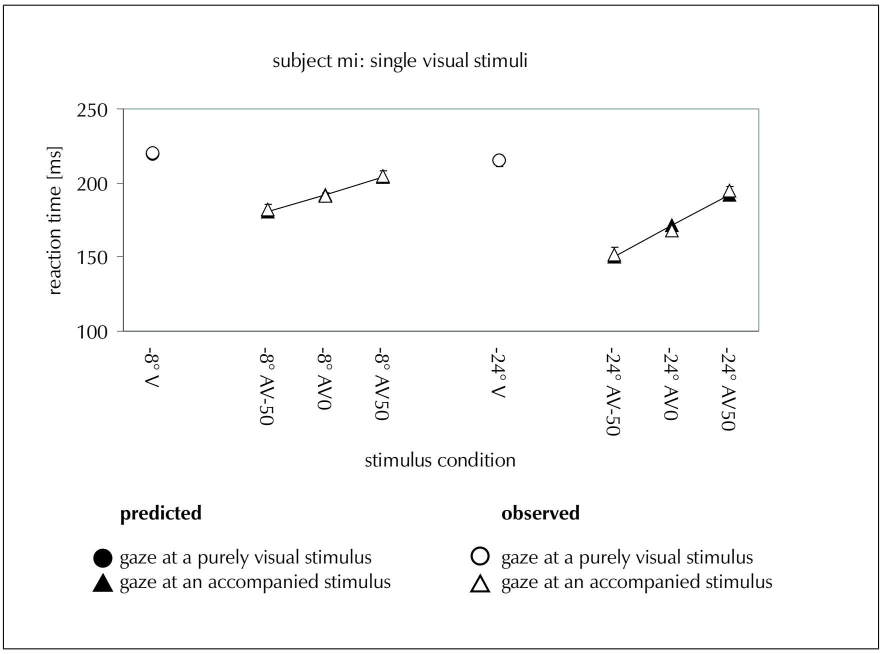

Figure C.29: Subject *mi*: Single target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

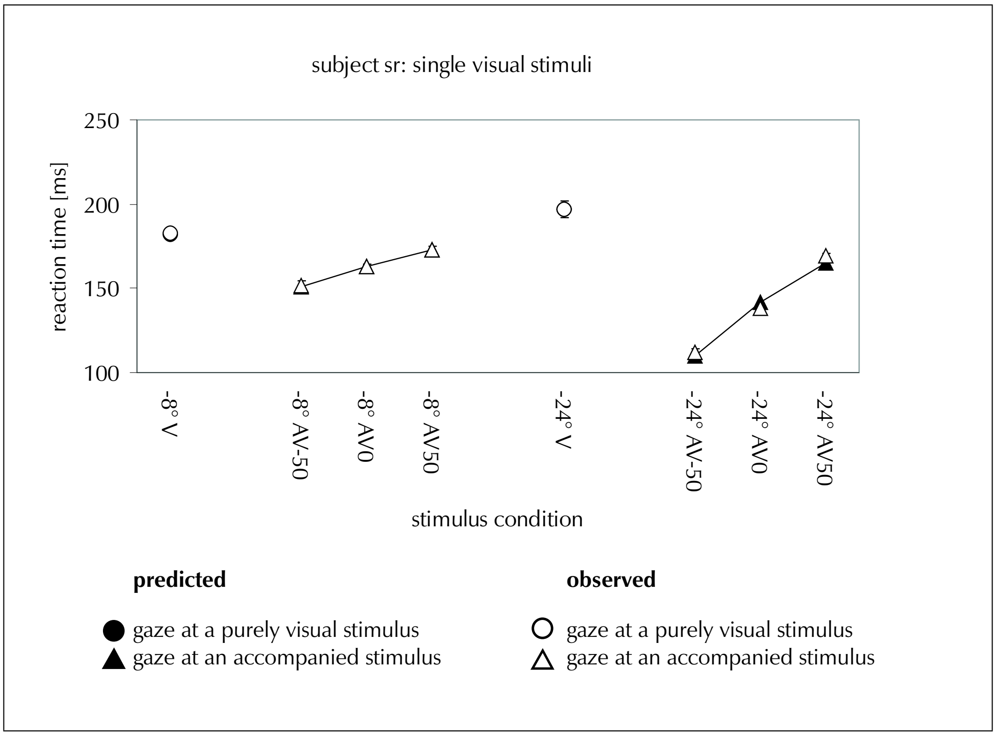

Figure C.30: Subject *sr*: Single target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

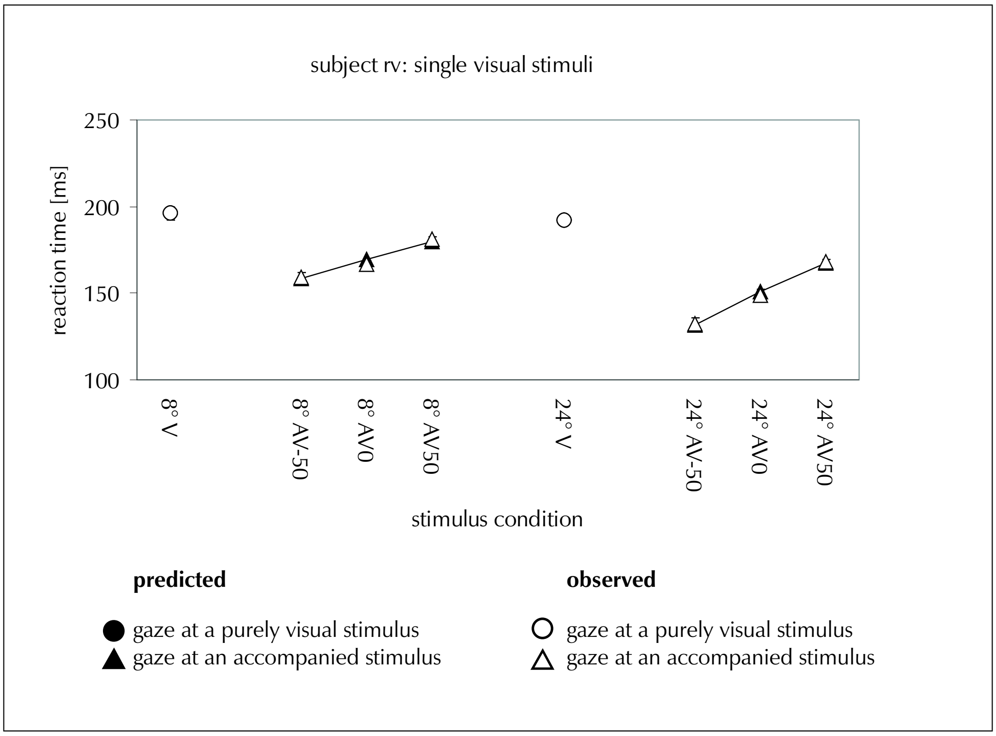

Figure C.31: Subject *rv*: Single target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

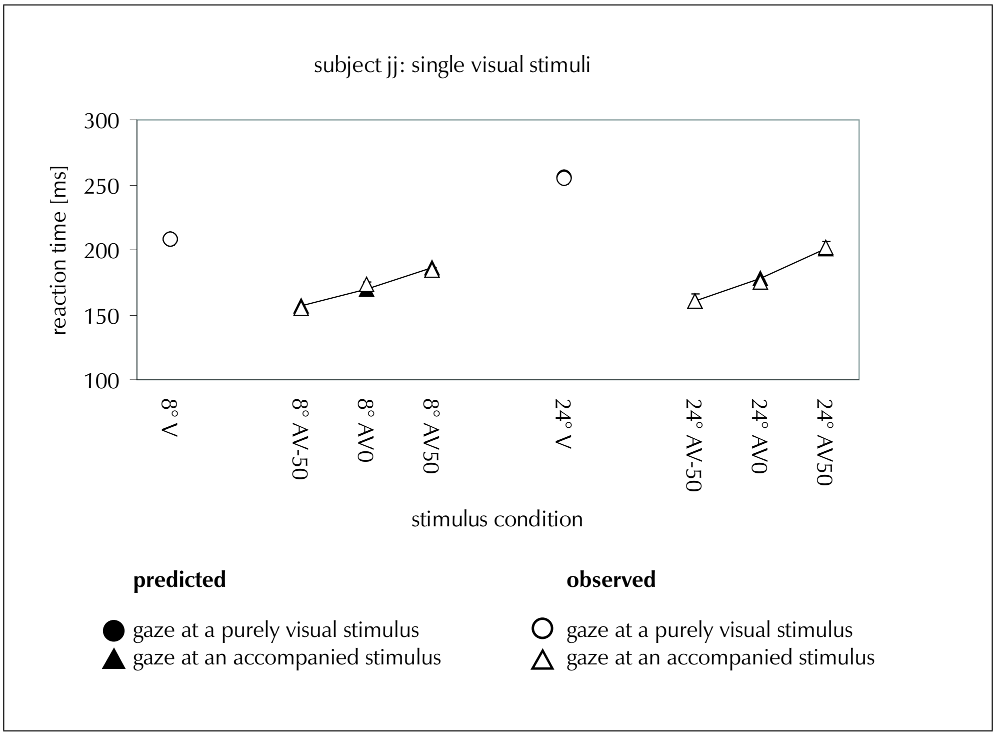

Figure C.32: Subject *jj*: Single target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

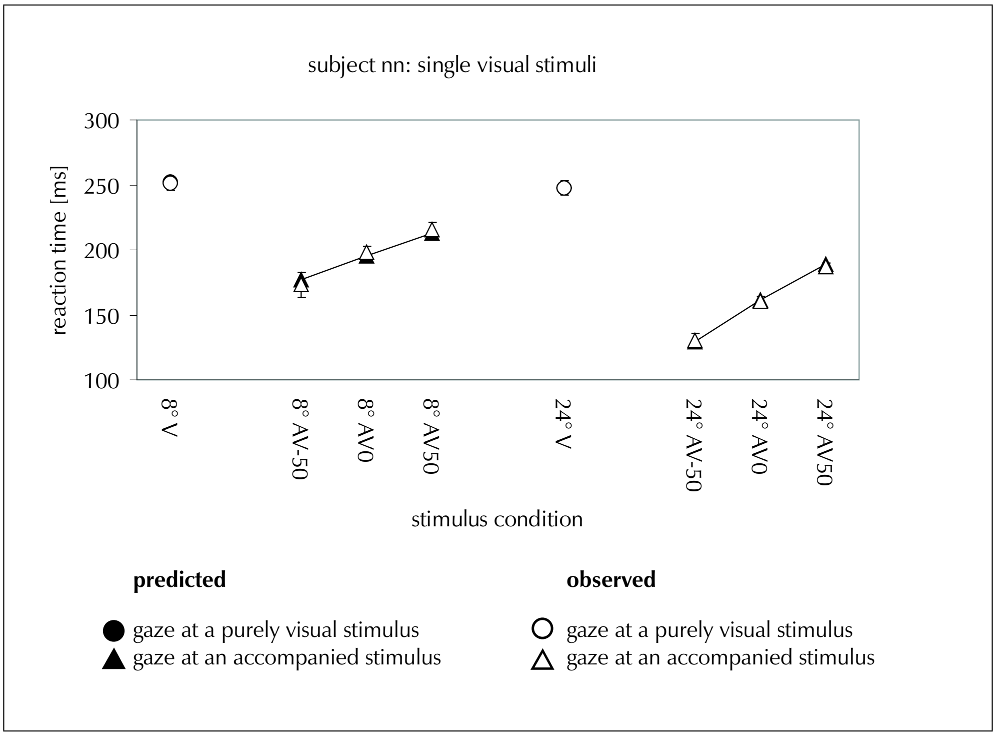

Figure C.33: Subject *nn*: Single target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

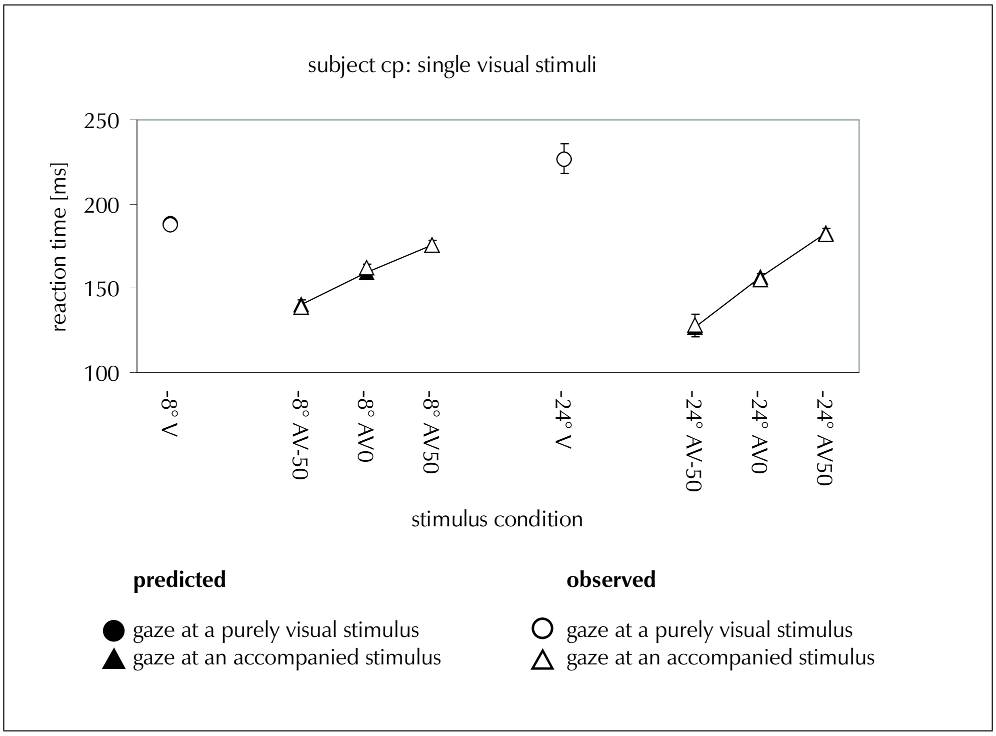

Figure C.34: Subject *cp*: Single target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

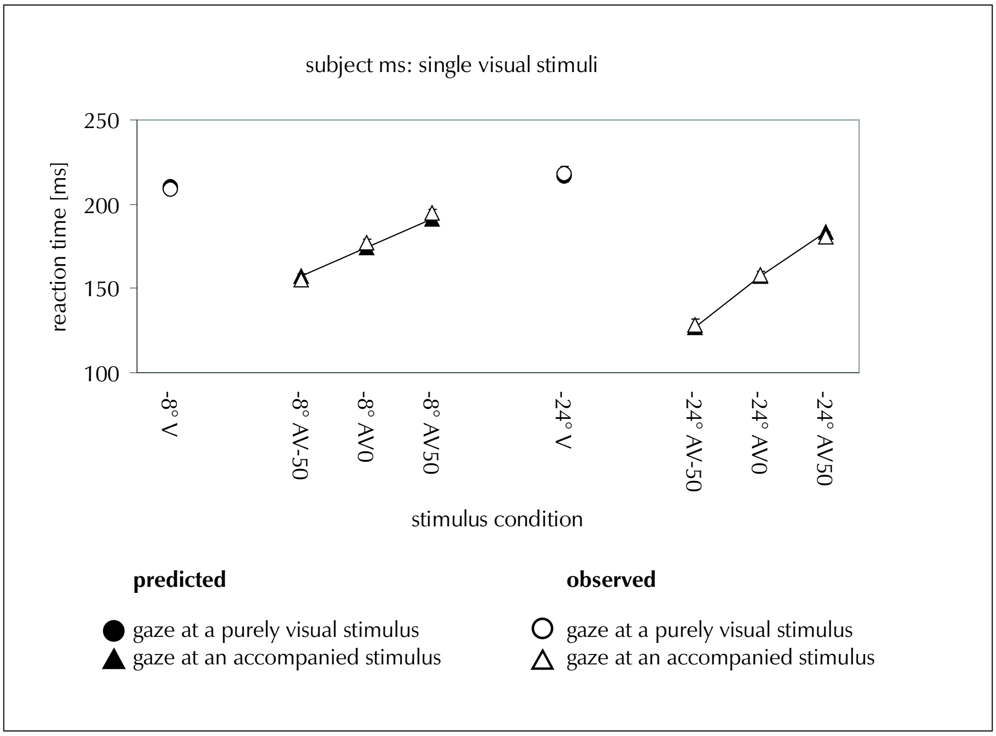

Figure C.35: Subject *ms*: Single target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

C.2 Parameter estimations for the double target conditions

C.2.1 Double Target Condition: visual stimulus pair 8° right/8° left

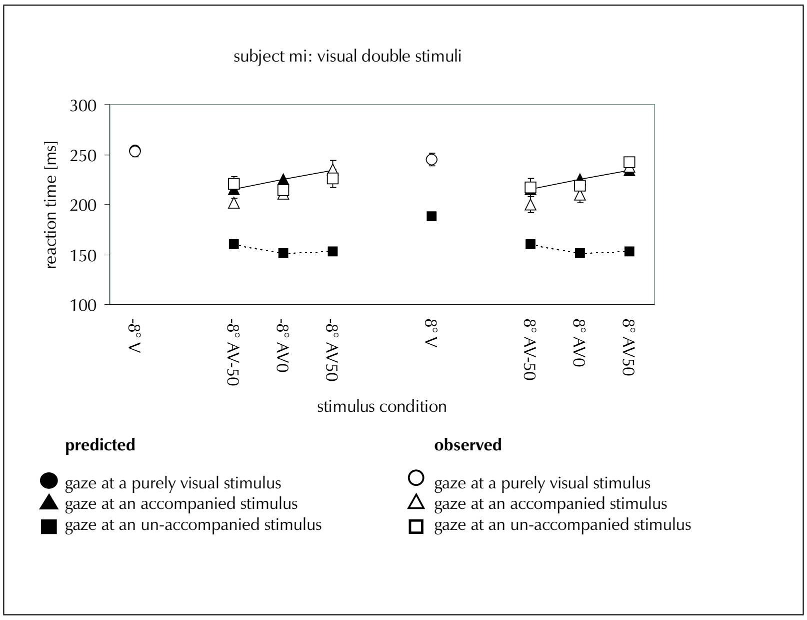

Figure C.36: Subject *mi*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

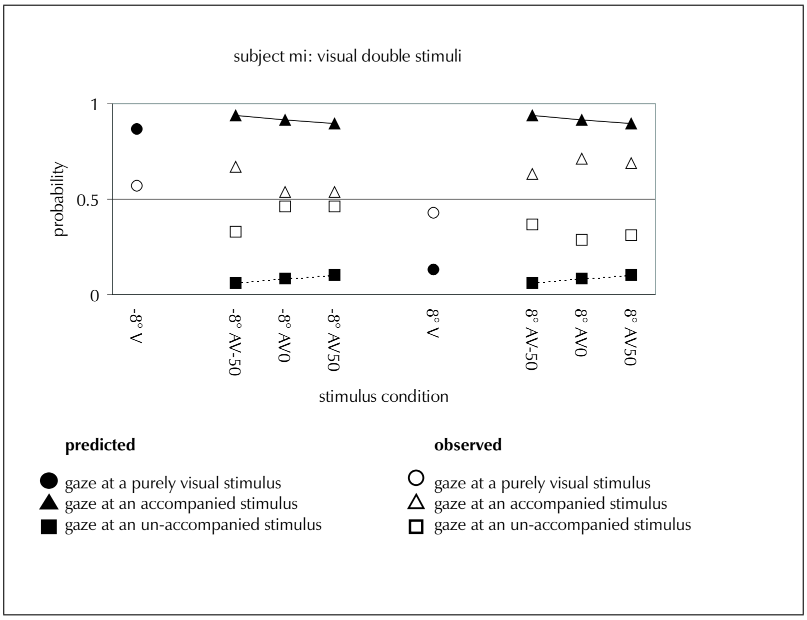

Figure C.37: Subject *mi*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed probabilities for three SOAs.

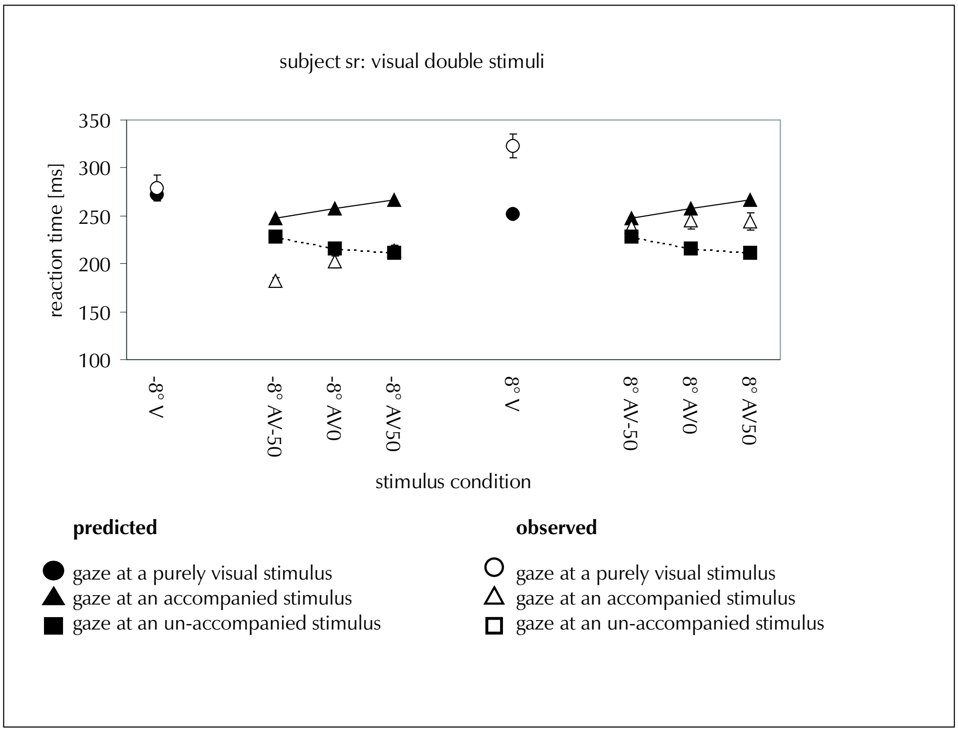

Figure C.38: Subject *sr*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

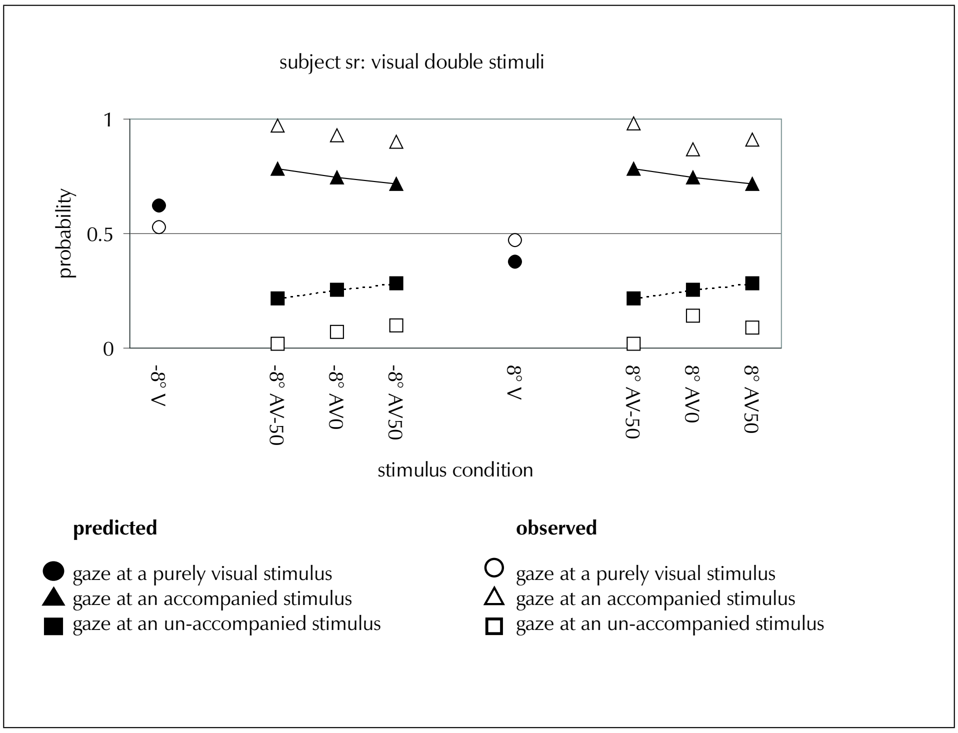

Figure C.39: Subject *sr*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed probabilities for three SOAs.

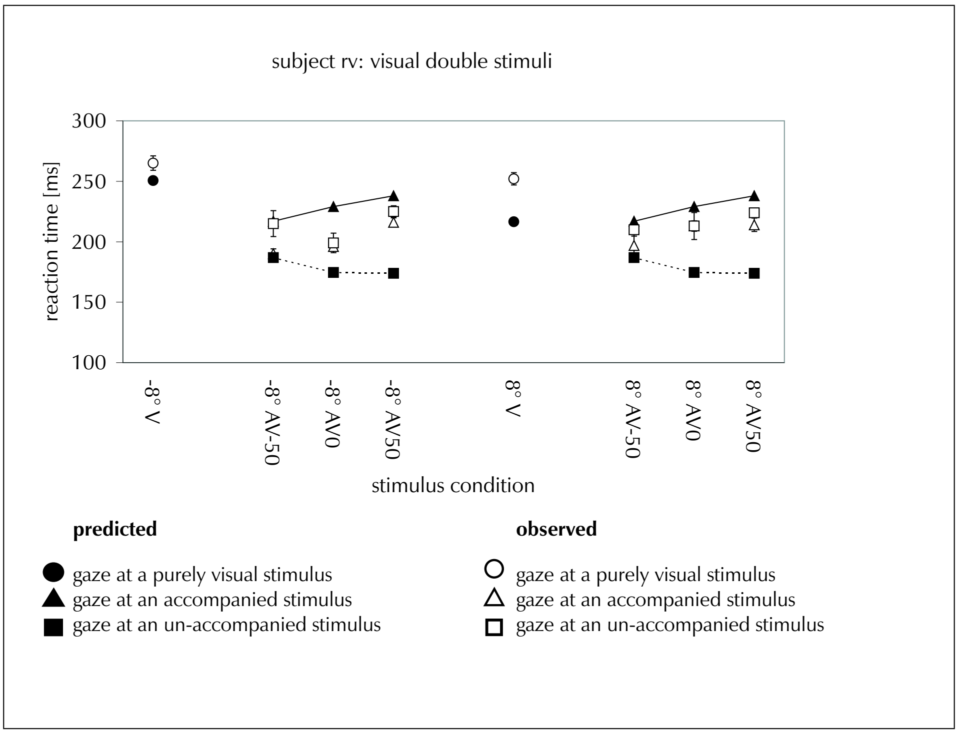

Figure C.40: Subject *rv*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

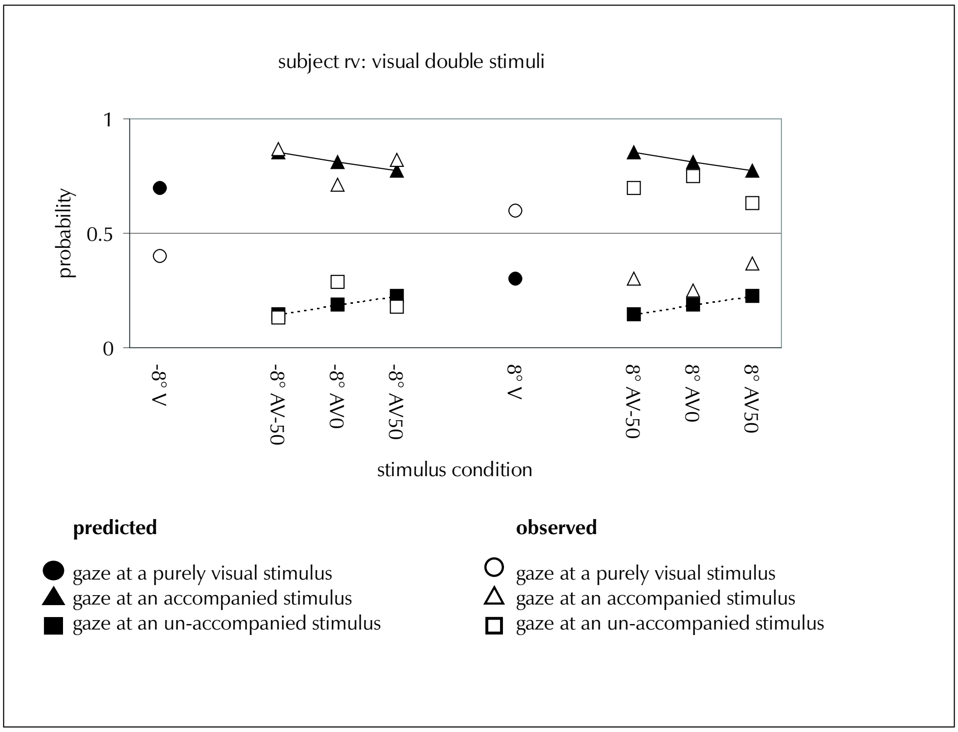

Figure C.41: Subject *rv*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed probabilities for three SOAs.

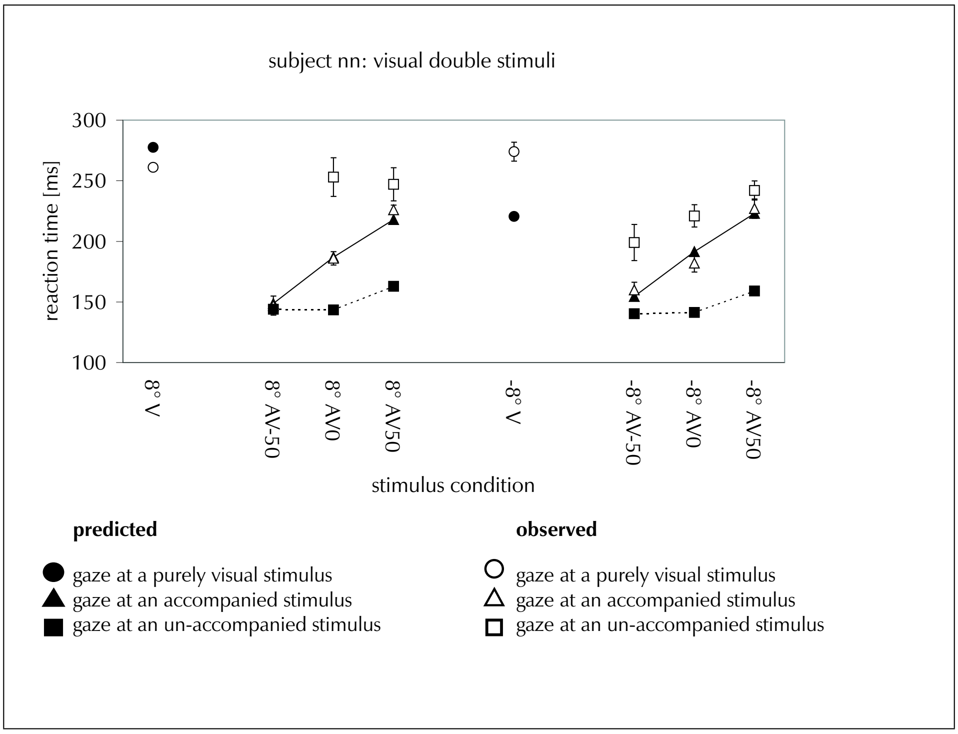

Figure C.42: Subject *nn*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

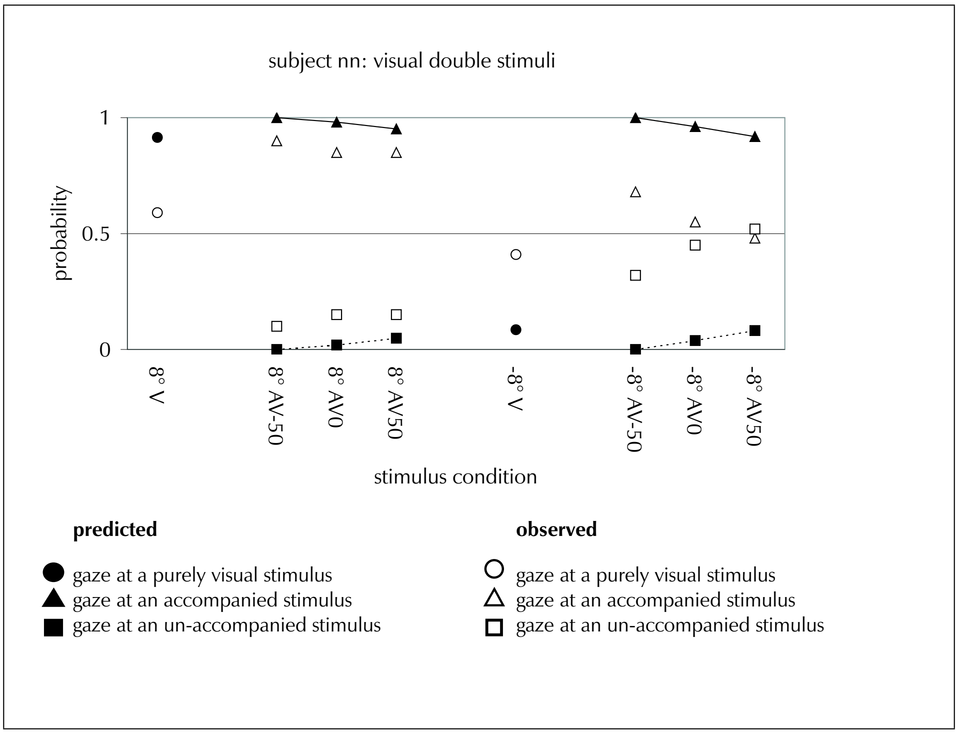

Figure C.43: Subject *nn*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed probabilities for three SOAs.

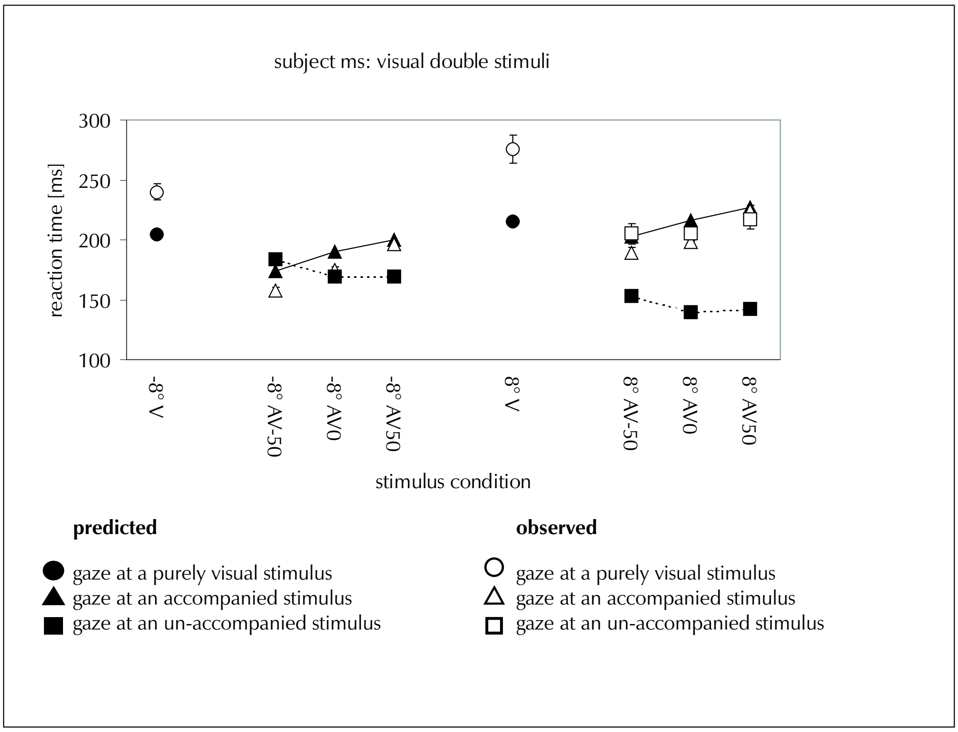

Figure C.44: Subject *ms*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

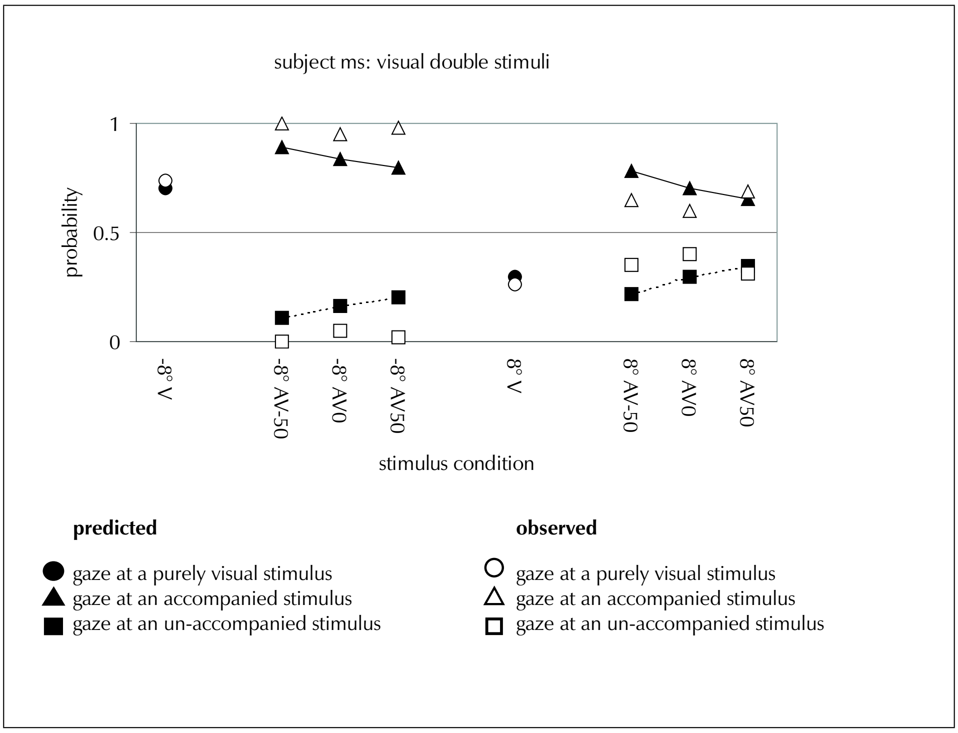

Figure C.45: Subject *ms*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed probabilities for three SOAs.

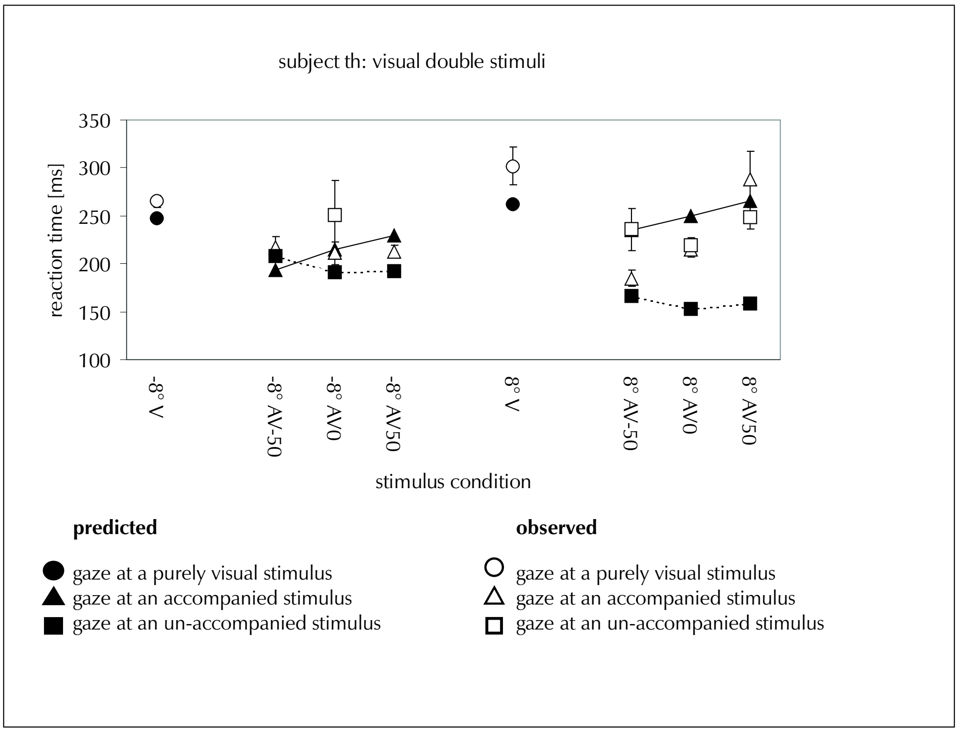

Figure C.46: Subject *th*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

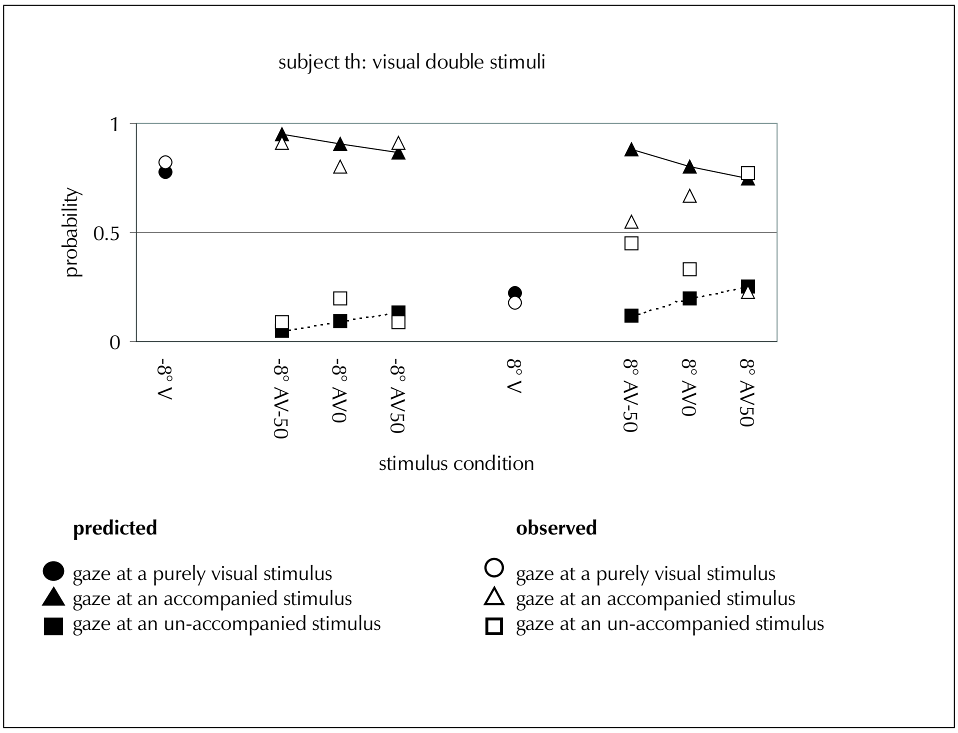

Figure C.47: Subject *th*: Double target condition, visual stimulus pair 8° right/8° left. Given are the predicted and observed probabilities for three SOAs.

C.2.2 Parameter estimations for the double target condition for the visual stimulus pair 24° right/24° left

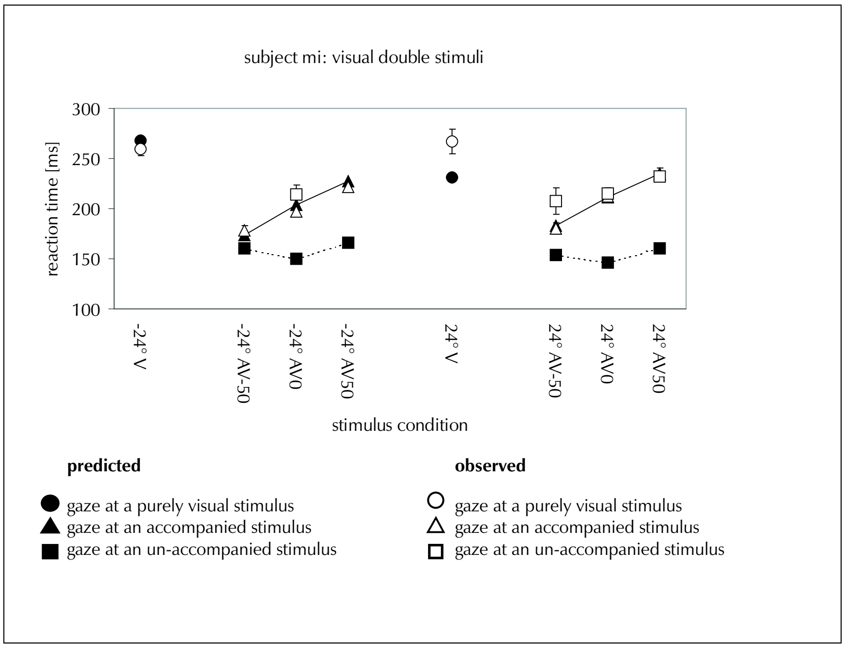

Figure C.48: Subject *mi*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

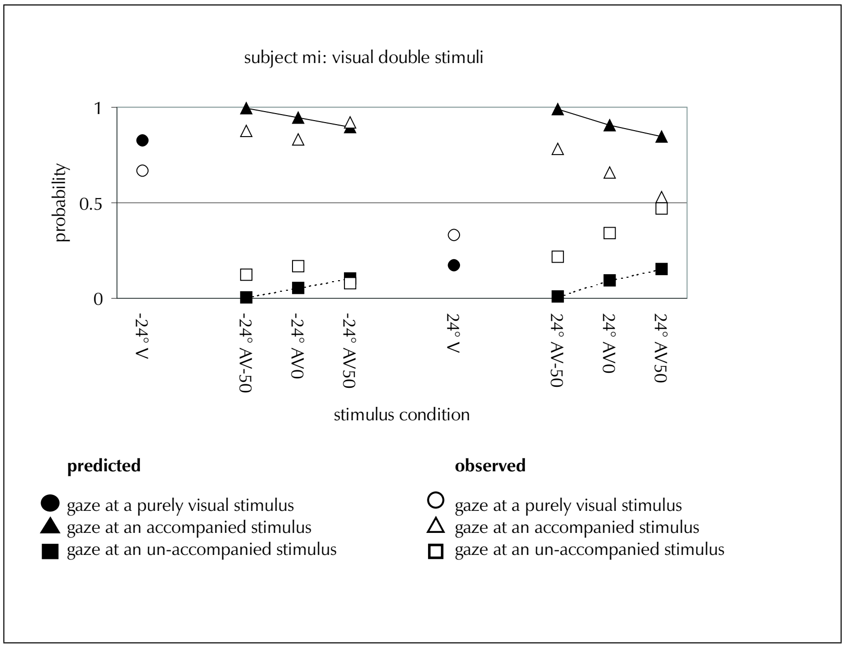

Figure C.49: Subject *mi*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed probabilities for three SOAs.

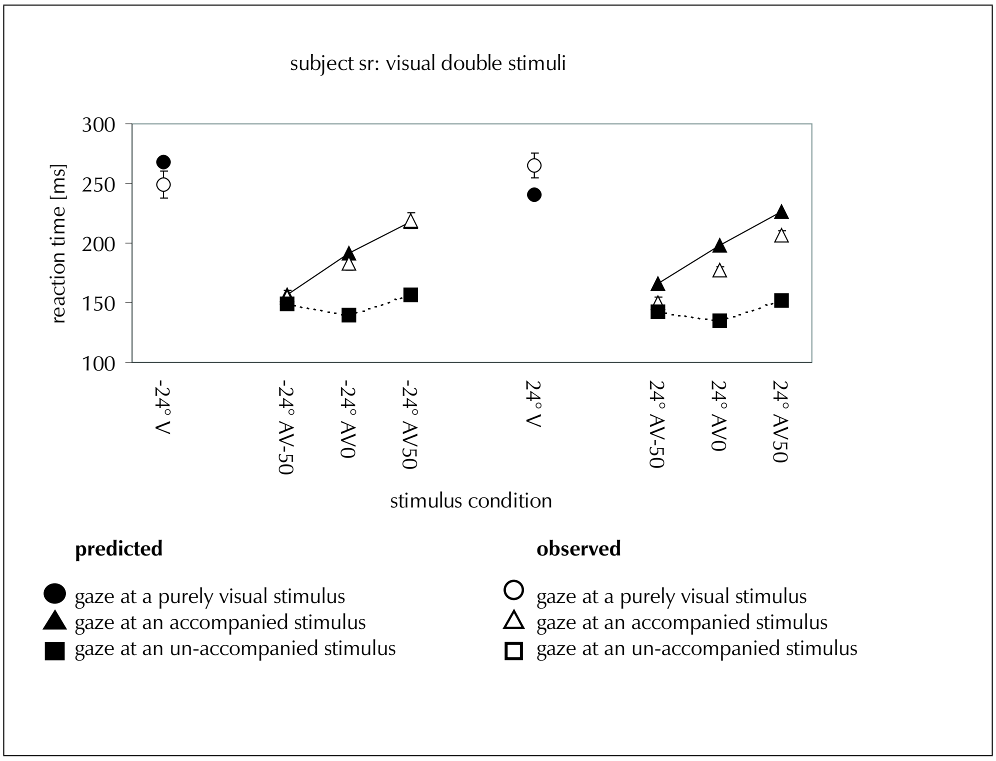

Figure C.50: Subject *sr*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

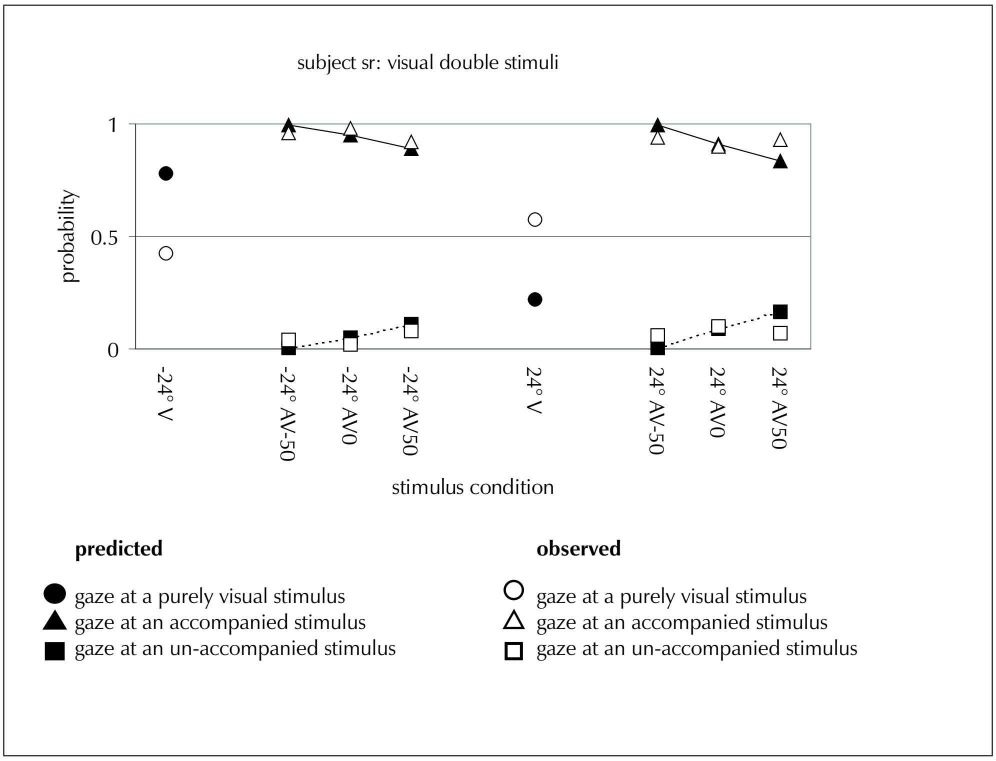

Figure C.51: Subject *sr*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed probabilities for three SOAs.

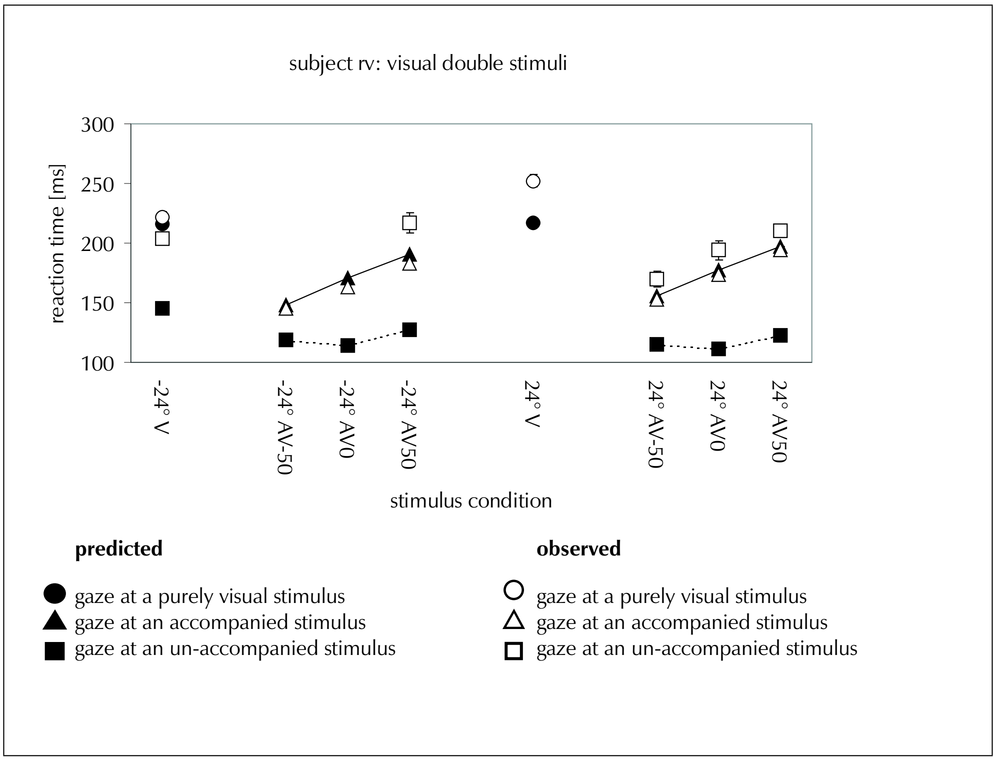

Figure C.52: Subject *rv*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

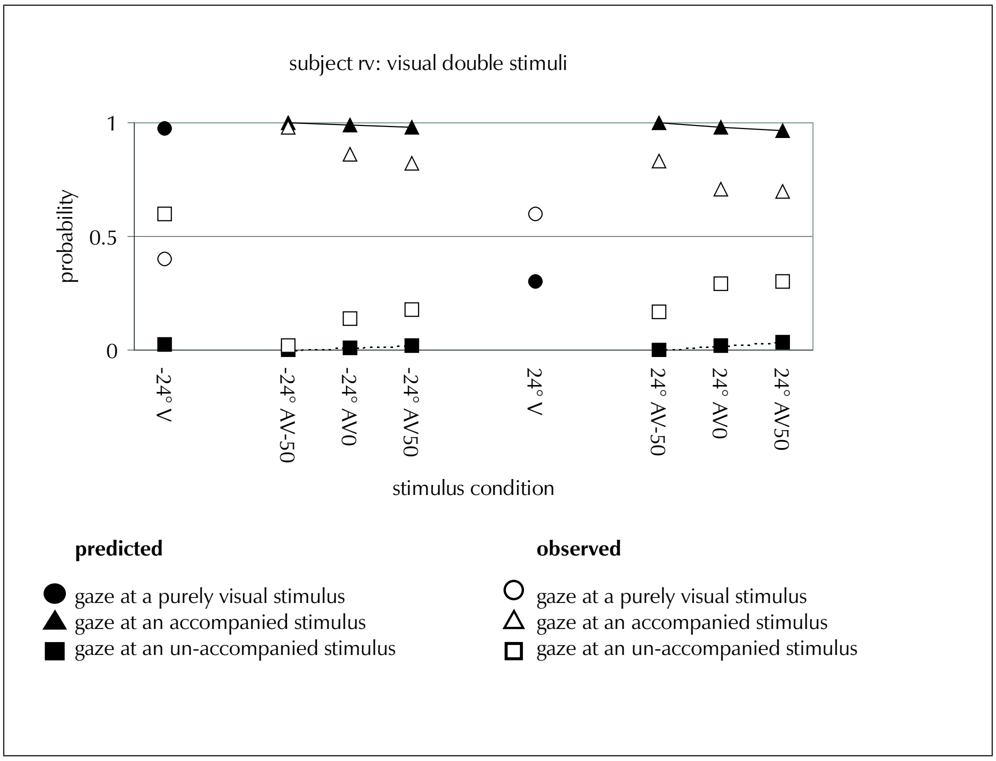

Figure C.53: Subject *rv*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed probabilities for three SOAs.

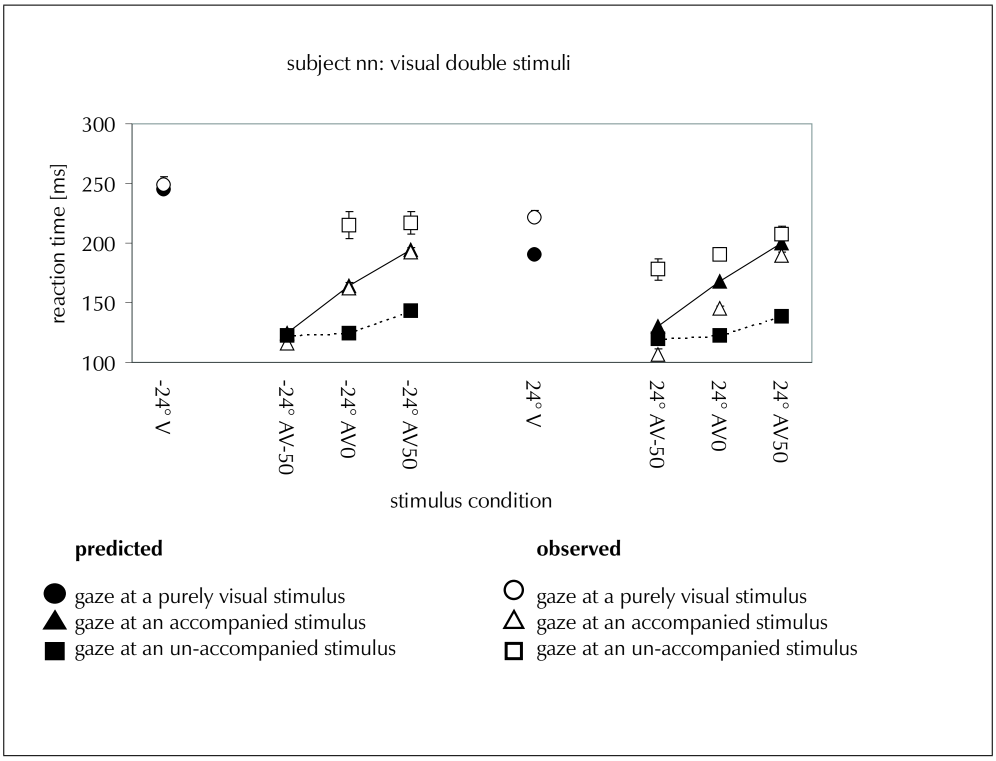

Figure C.54: Subject *nn*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

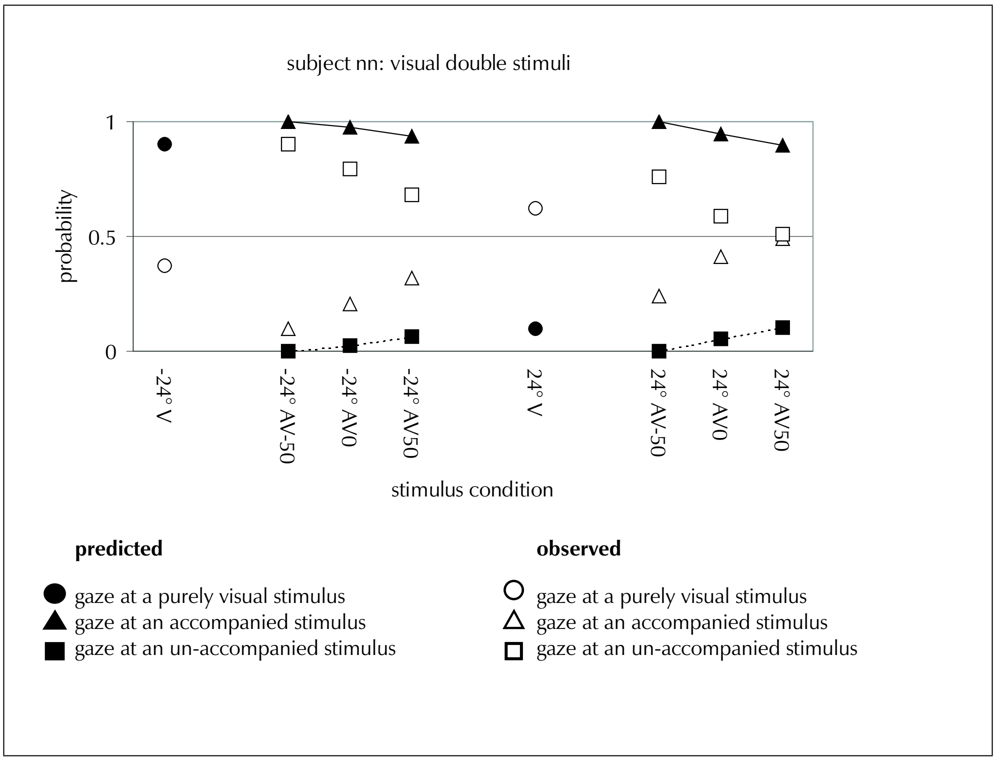

Figure C.55: Subject *nn*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed probabilities for three SOAs.

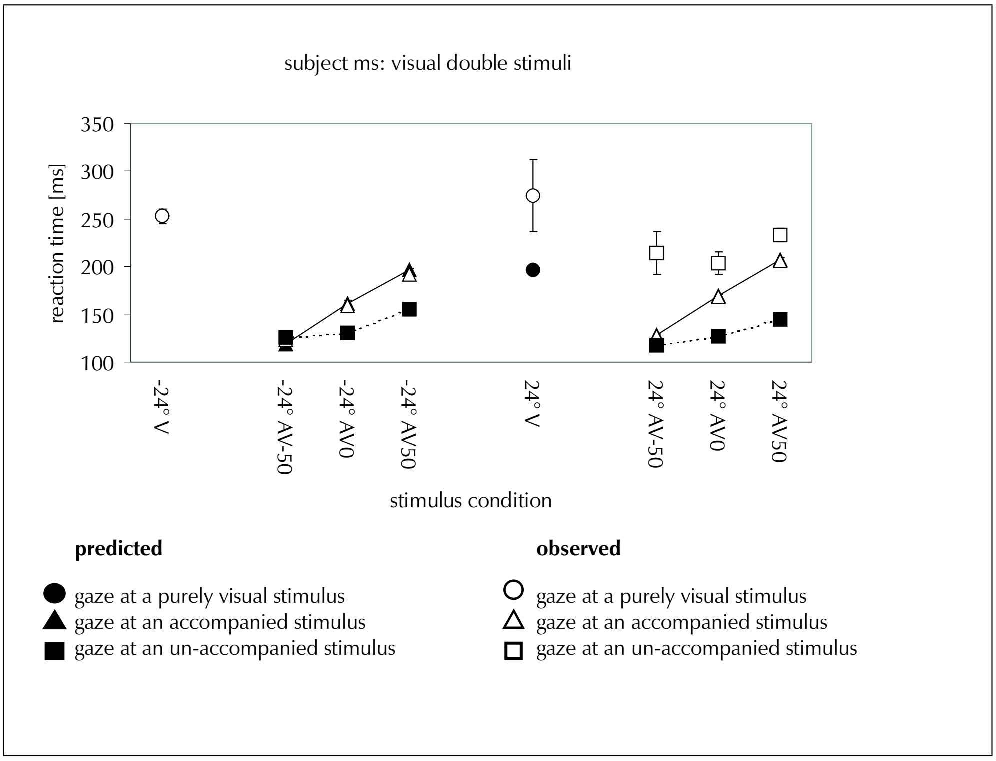

Figure C.56: Subject *ms*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs.

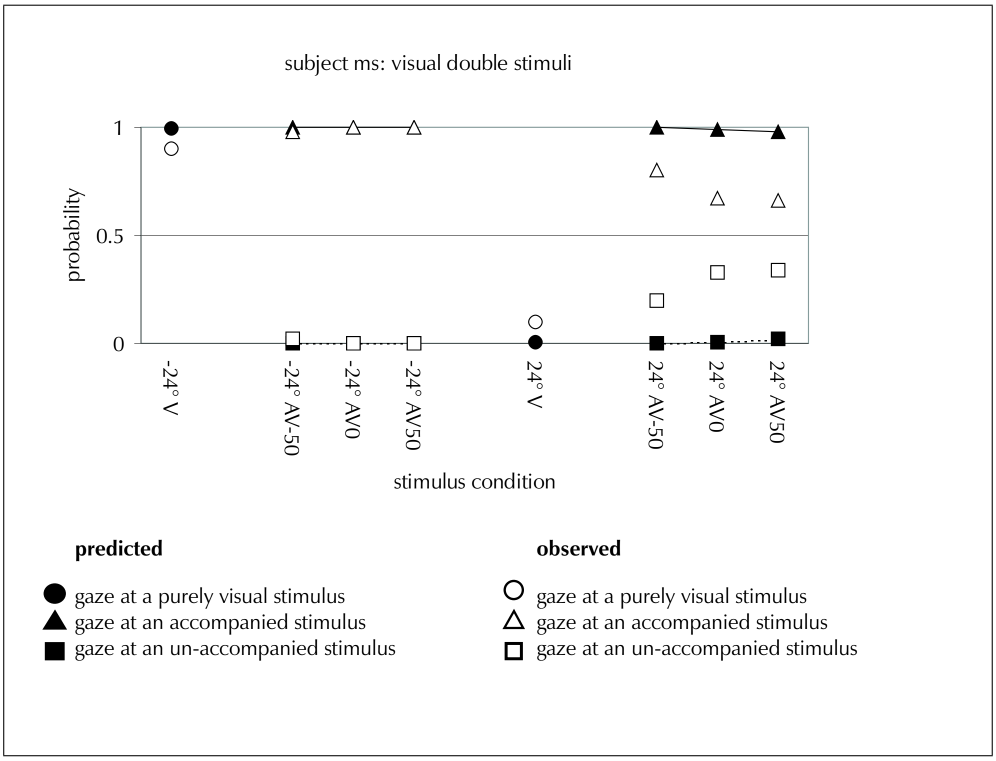

Figure C.57: Subject *ms*: Double target condition, visual stimulus pair 24° right/24° left. Given are the predicted and observed probabilities for three SOAs.

C.2.3 Parameter estimations for the double target condition for the visual stimulus pair 8° right/24° left or 8° left/24° right

C.2.3.1 3-Parameter-Version

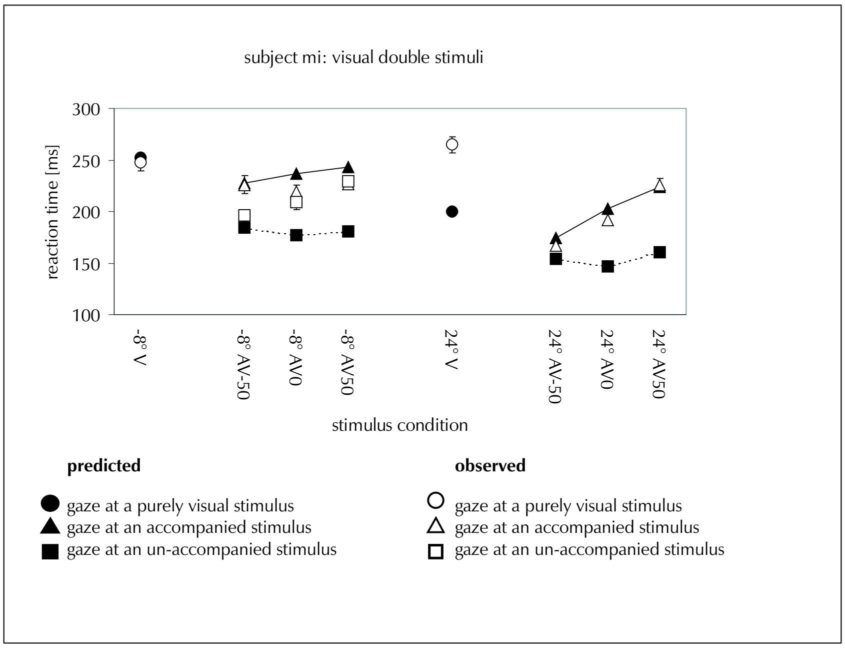

Figure C.58: Subject *mi*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

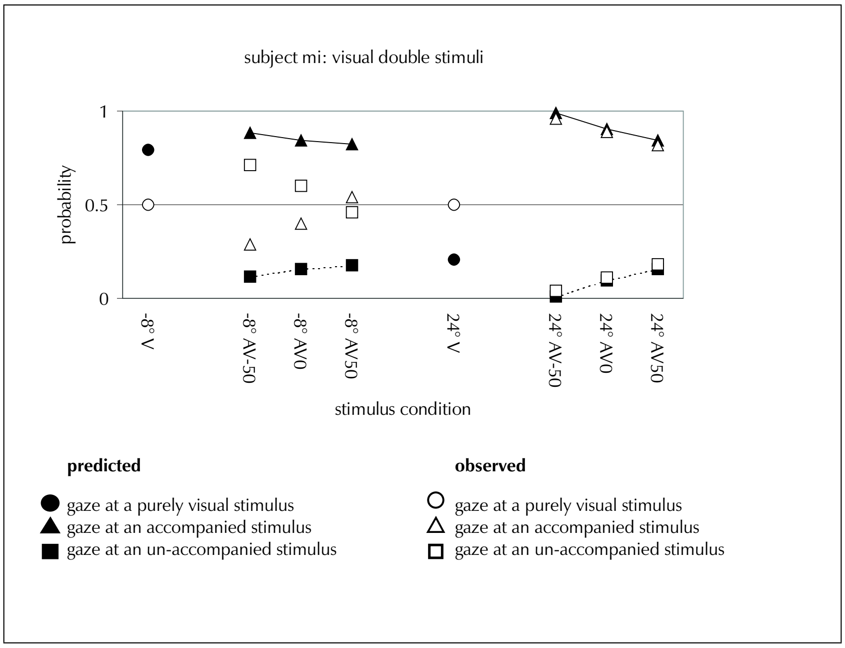

Figure C.59: Subject *mi*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed probabilities for three SOAs (3-Parameter-Version).

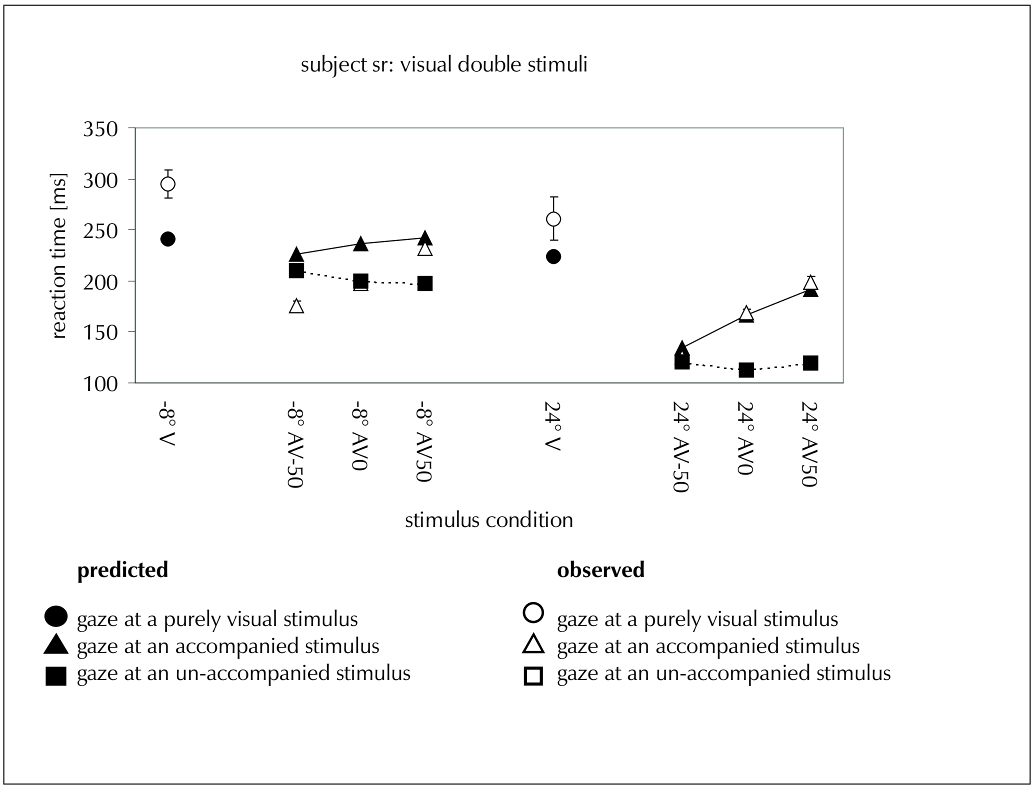

Figure C.60: Subject *sr*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

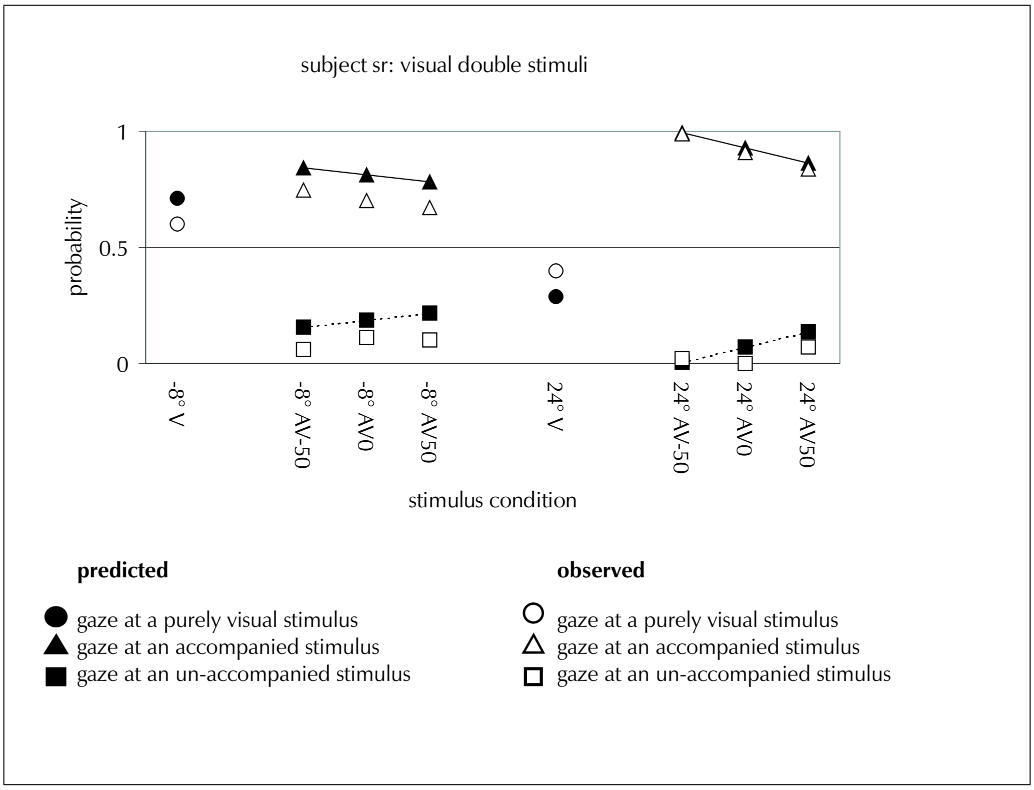

Figure C.61: Subject *sr*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed probabilities for three SOAs (3-Parameter-Version).

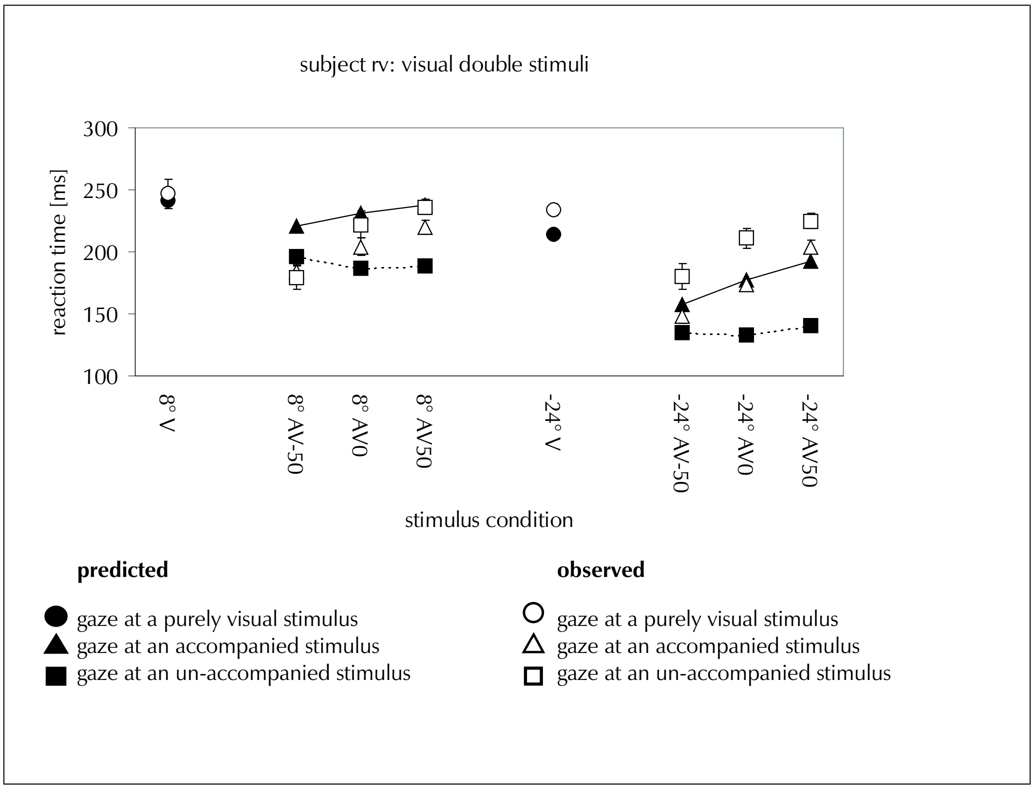

Figure C.62: Subject *rv*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

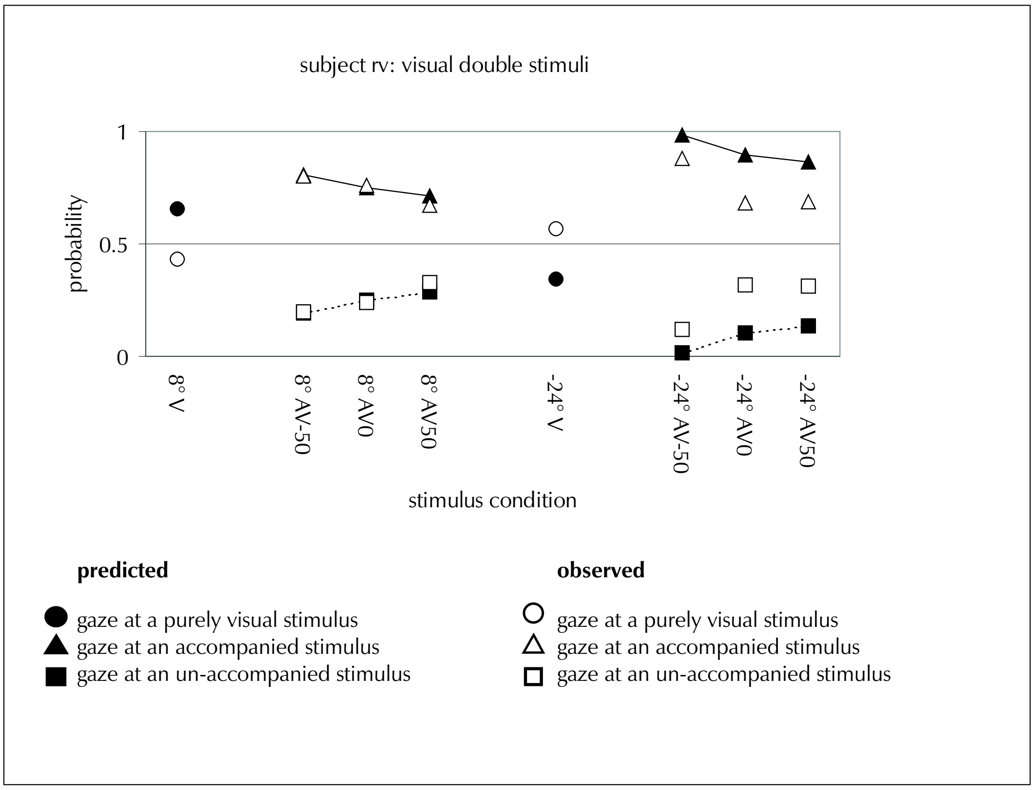

Figure C.63: Subject *rv*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed probabilities for three SOAs (3-Parameter-Version).

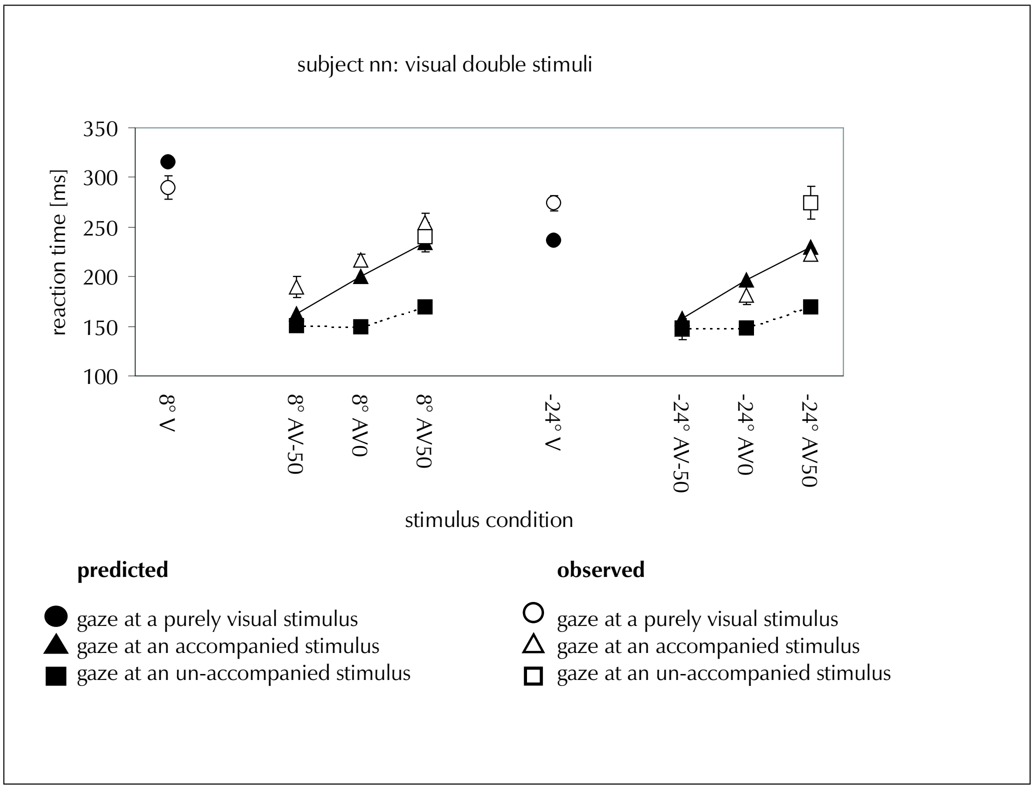

Figure C.64: Subject *nn*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

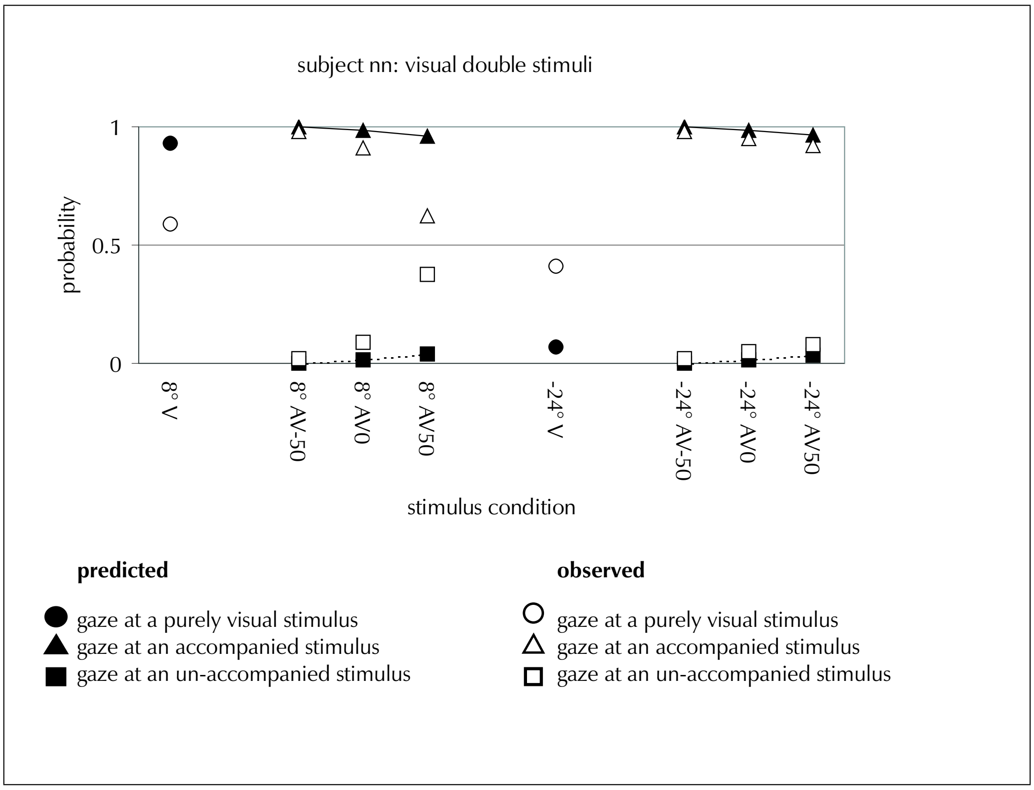

Figure C.65: Subject *nn*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed probabilities for three SOAs (3-Parameter-Version).

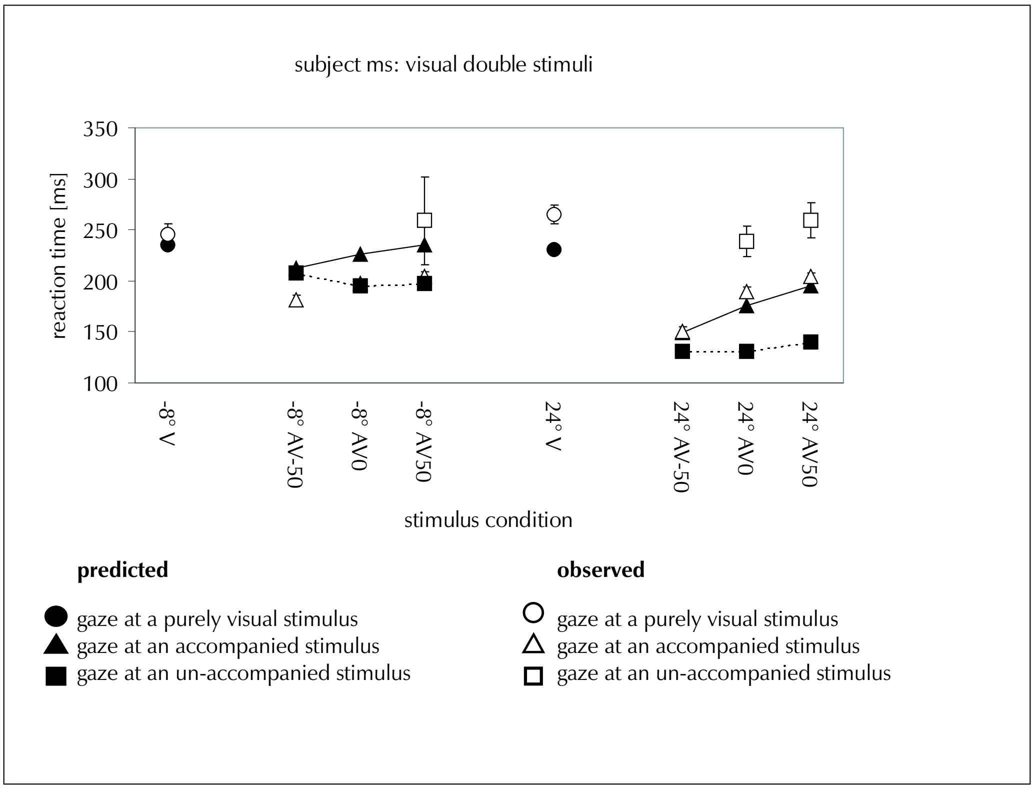

Figure C.66: Subject *ms*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (3-Parameter-Version).

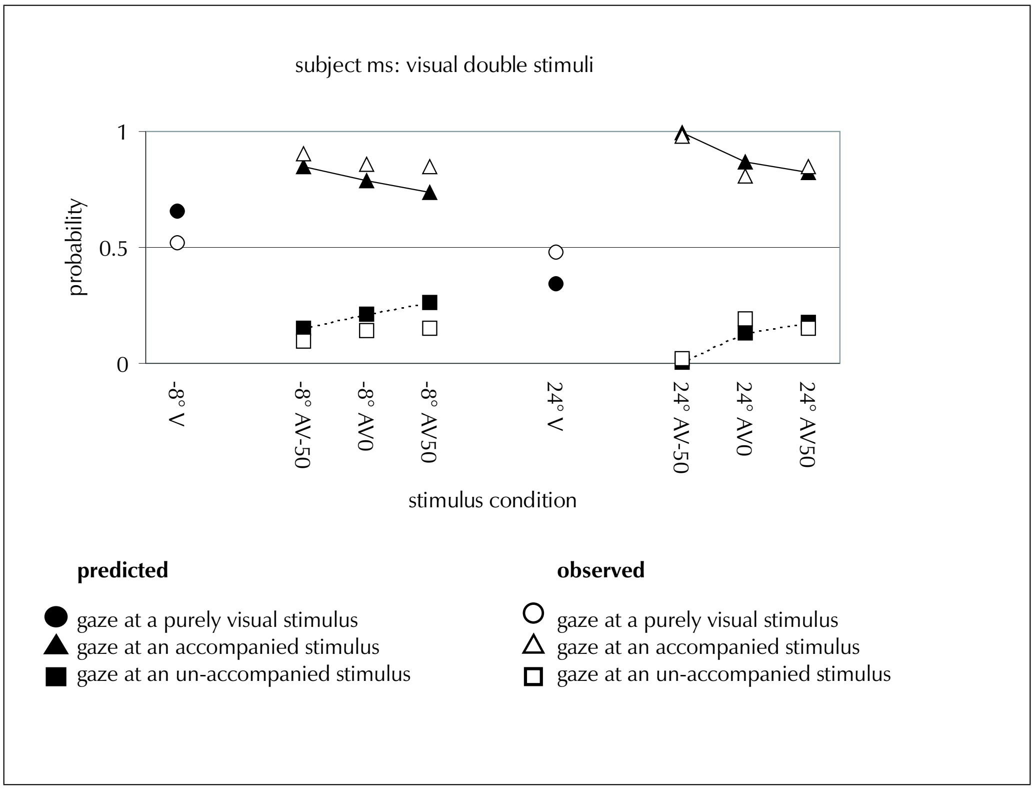

Figure C.67: Subject *ms*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed probabilities for three SOAs (3-Parameter-Version).

C.2.3.2 7-Parameter-Version

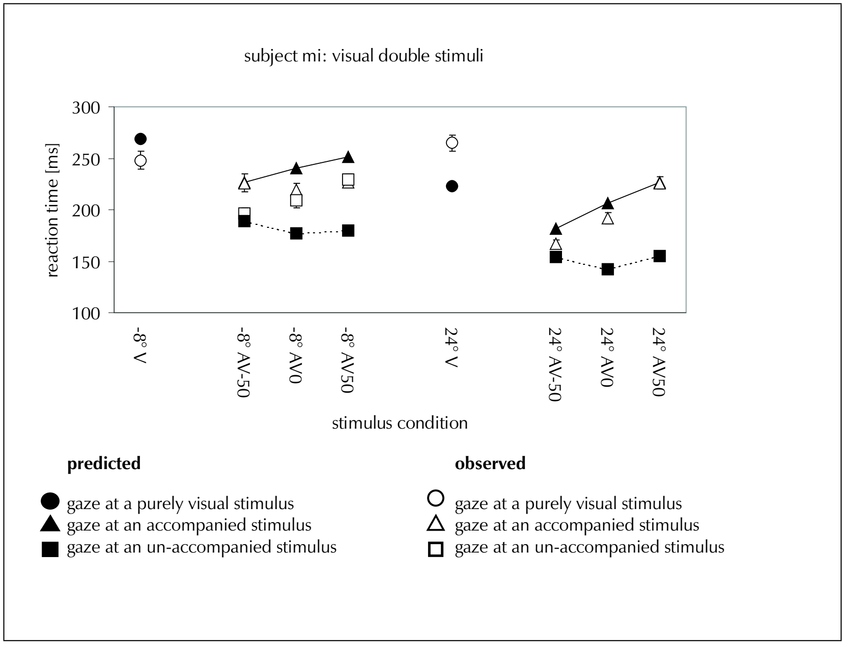

Figure C.68: Subject *mi*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

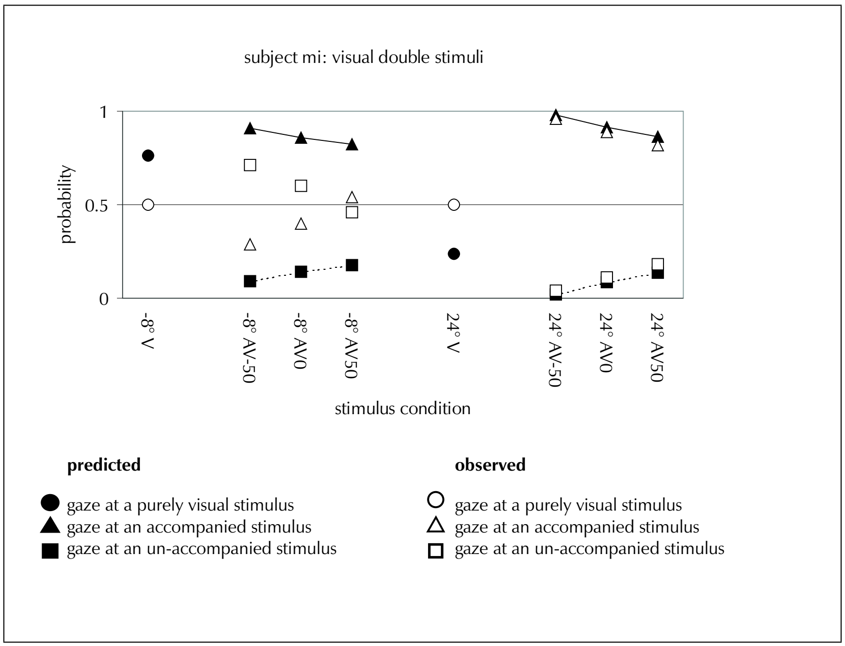

Figure C.69: Subject *mi*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed probabilities for three SOAs (7-Parameter-Version).

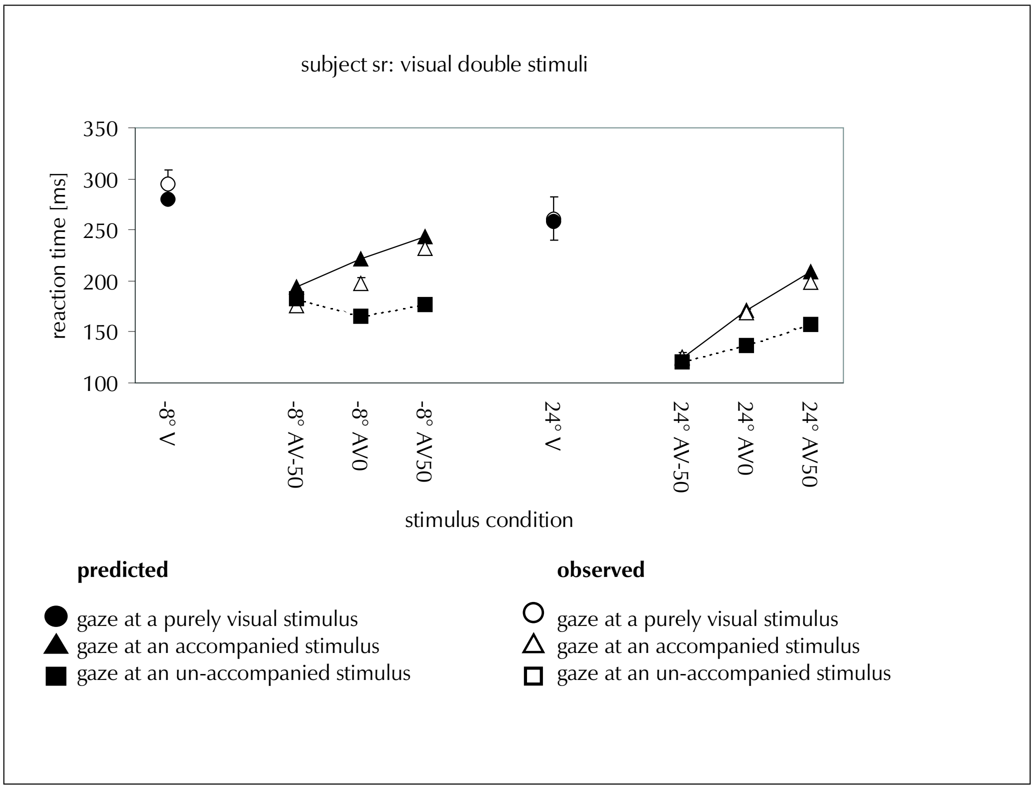

Figure C.70: Subject *sr*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

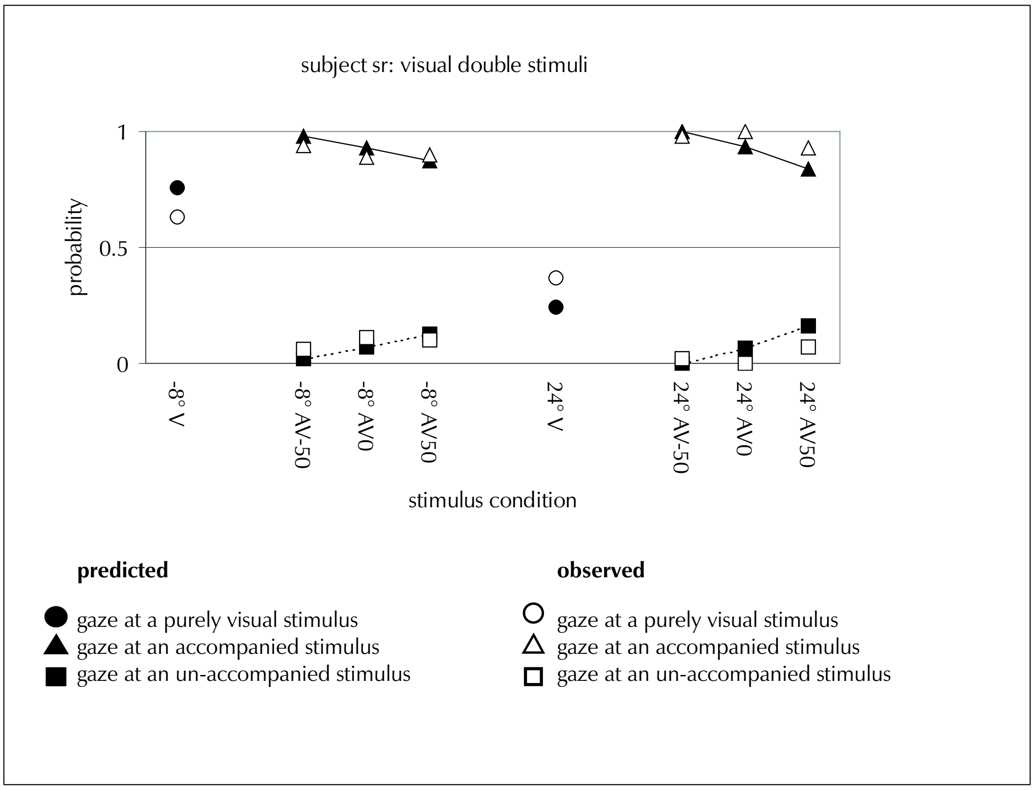

Figure C.71: Subject *sr*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed probabilities for three SOAs (7-Parameter-Version).

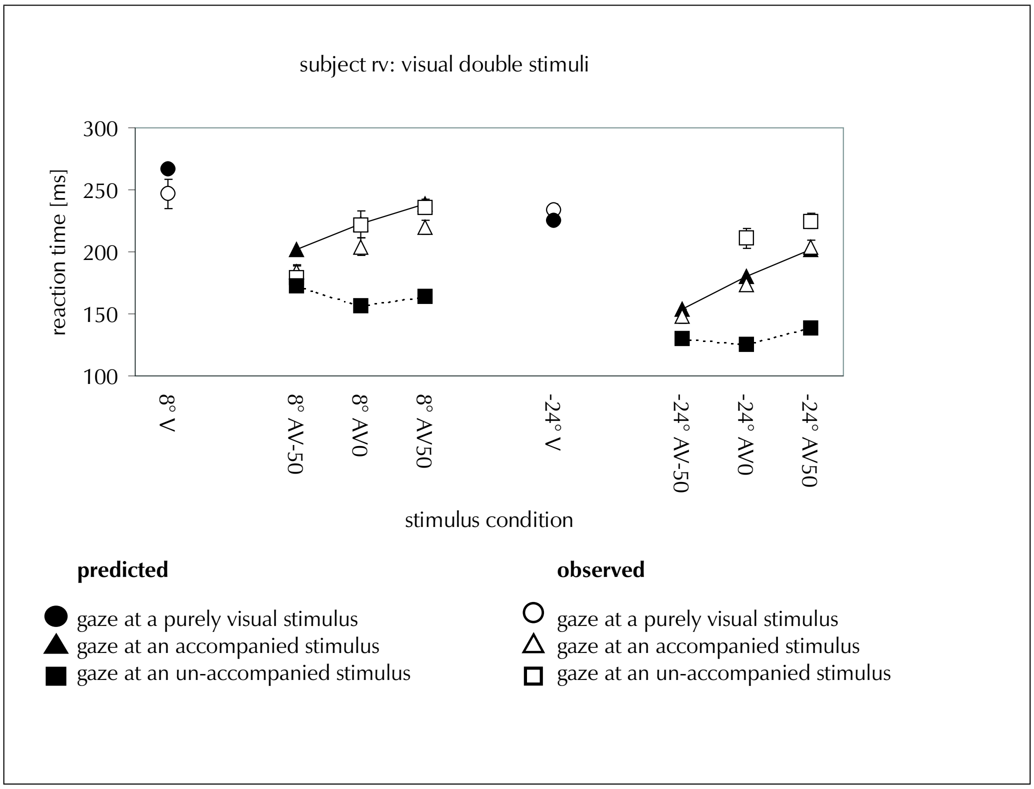

Figure C.72: Subject *rv*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

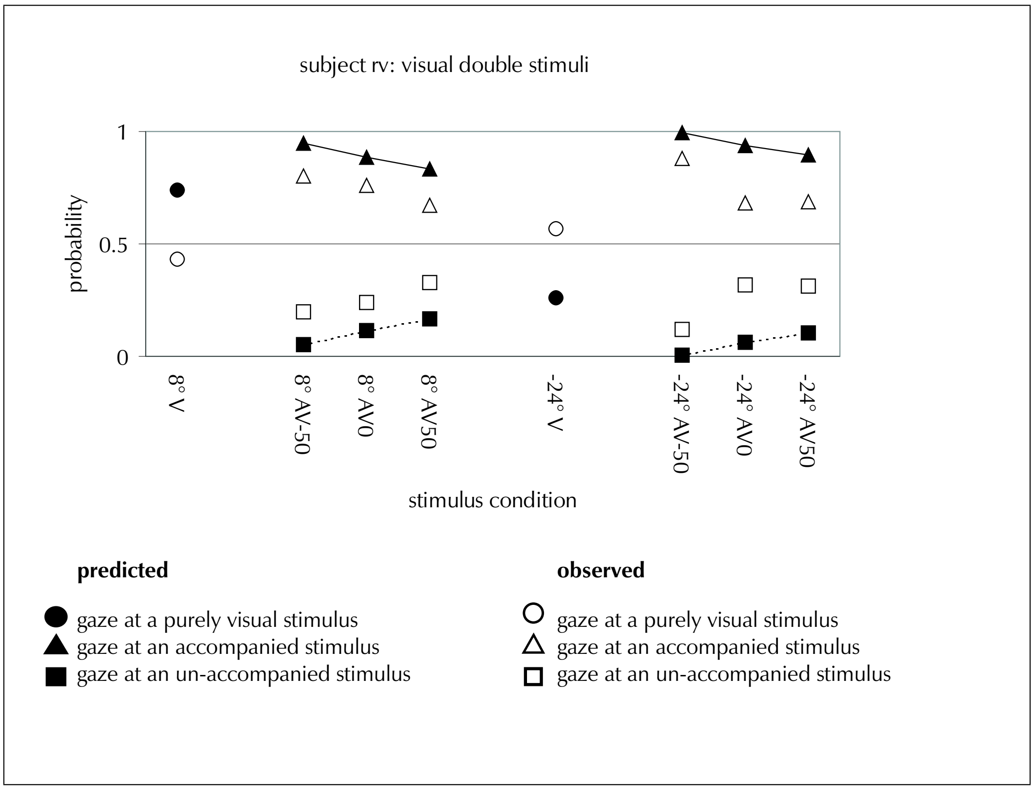

Figure C.73: Subject *rv*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed probabilities for three SOAs (7-Parameter-Version).

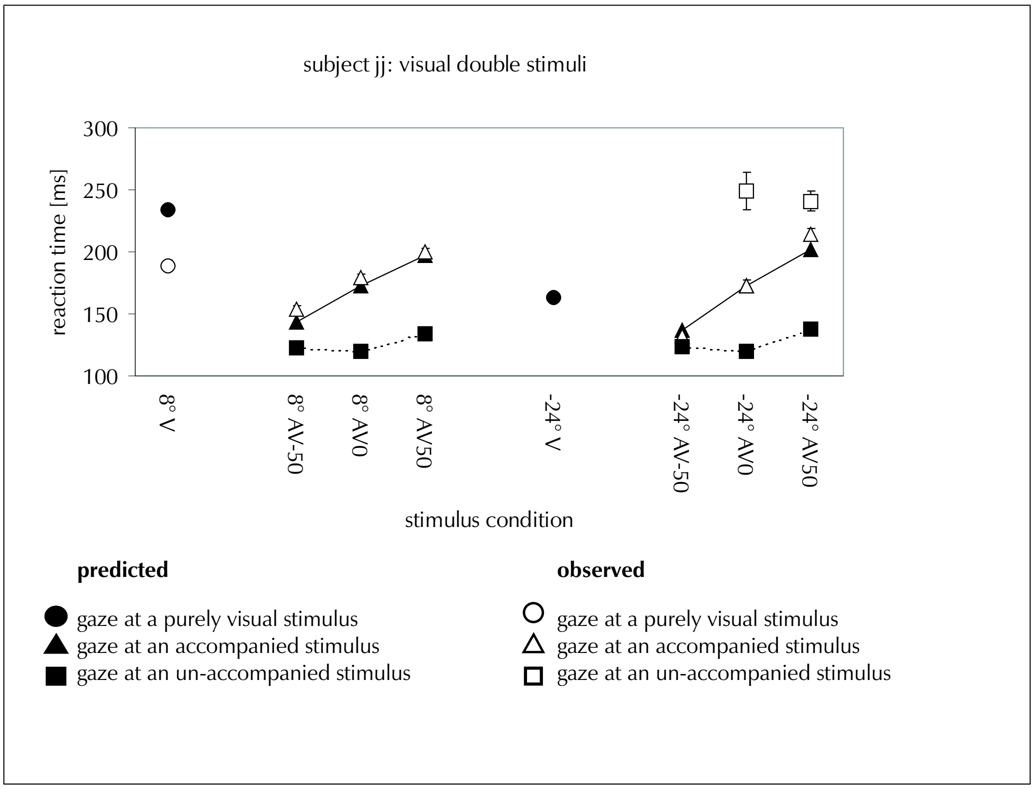

Figure C.74: Subject *jj*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

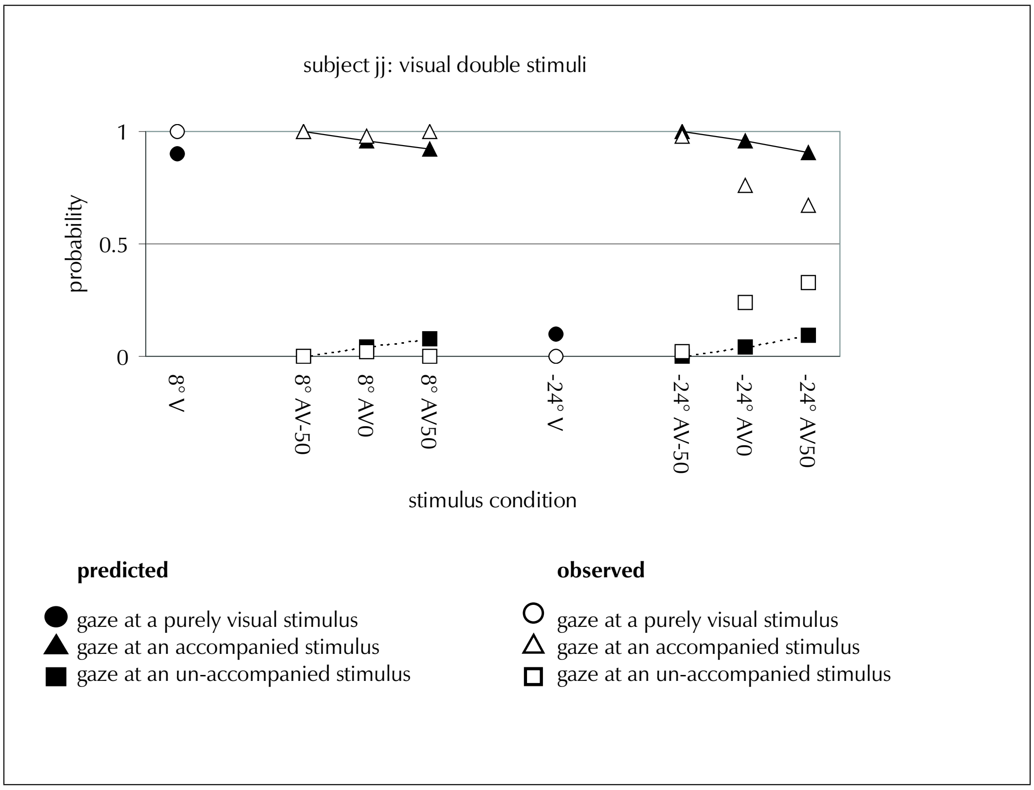

Figure C.75: Subject *jj*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed probabilities for three SOAs (7-Parameter-Version).

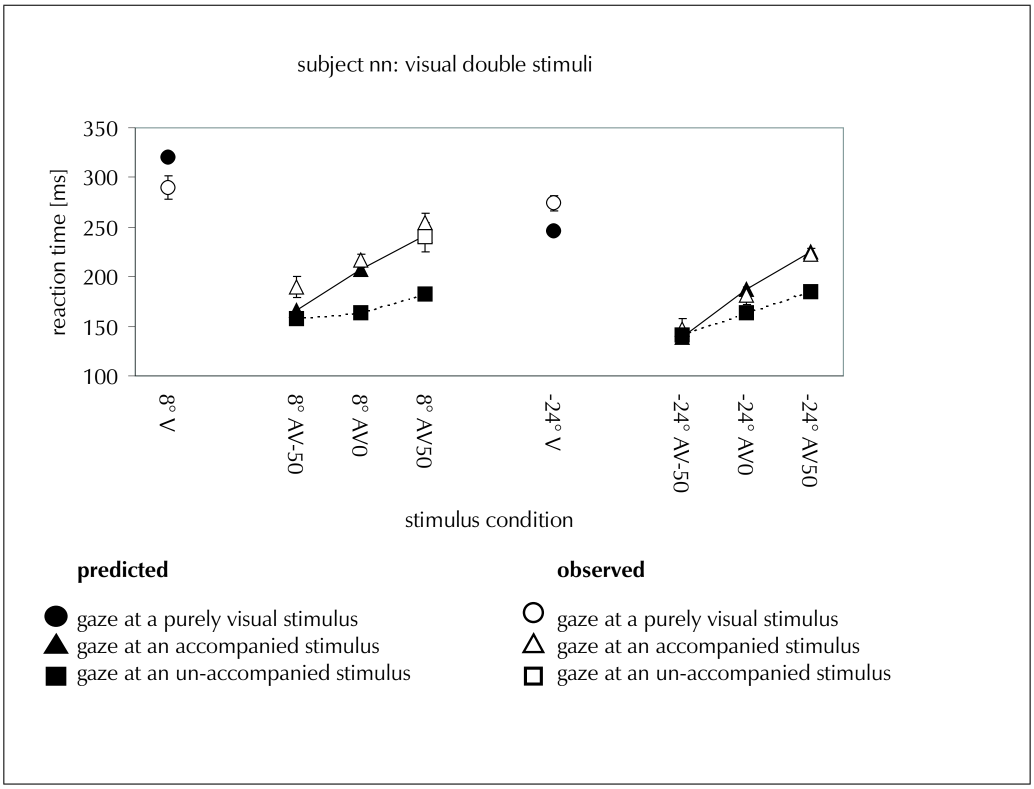

Figure C.76: Subject *nn*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

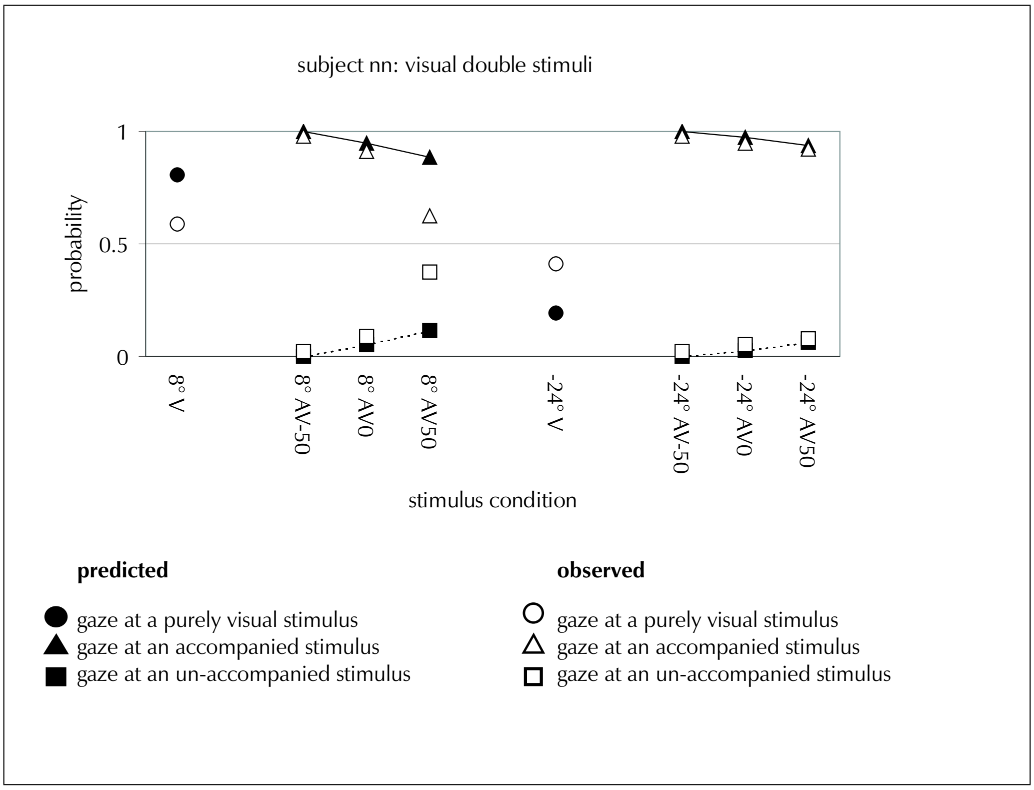

Figure C.77: Subject *nn*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed probabilities for three SOAs (7-Parameter-Version).

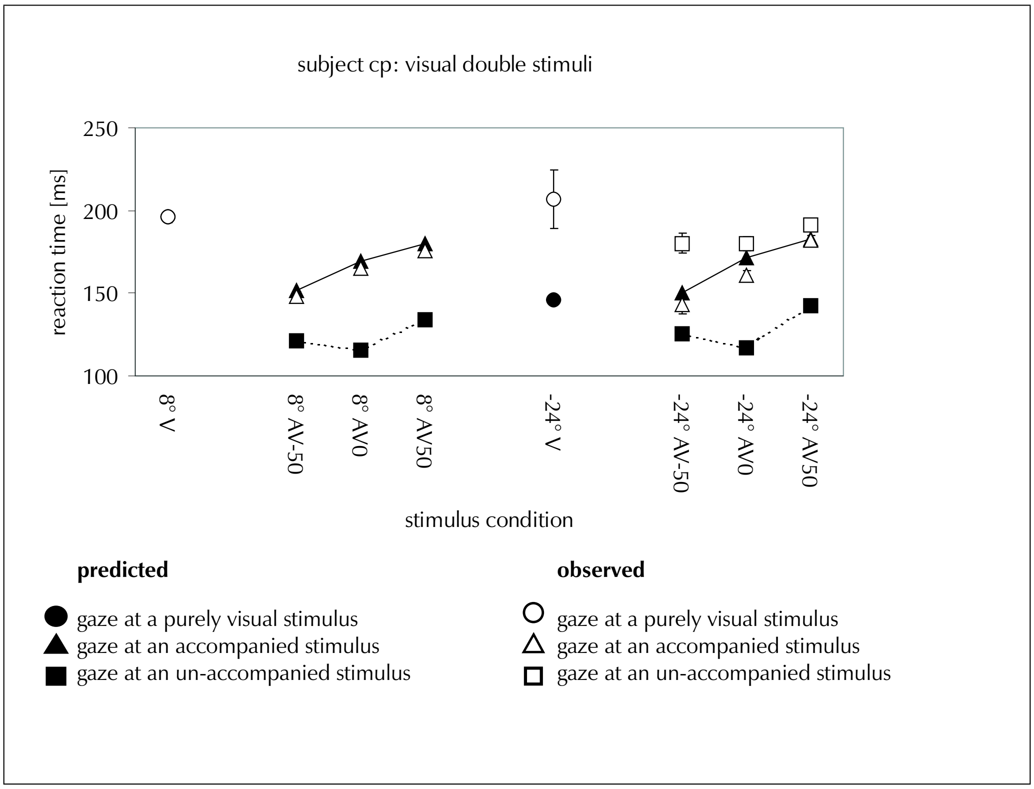

Figure C.78: Subject *cp*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

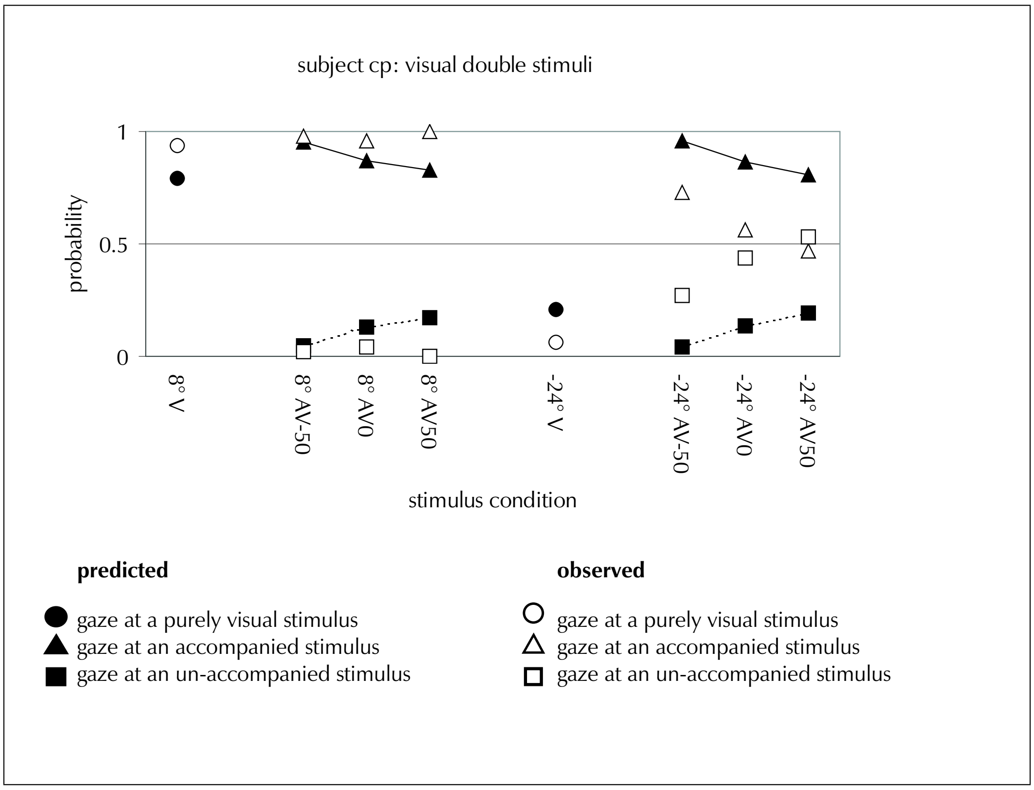

Figure C.79: Subject *cp*: Double target condition, visual stimulus pair 8° right/24° left. Given are the predicted and observed probabilities for three SOAs (7-Parameter-Version).

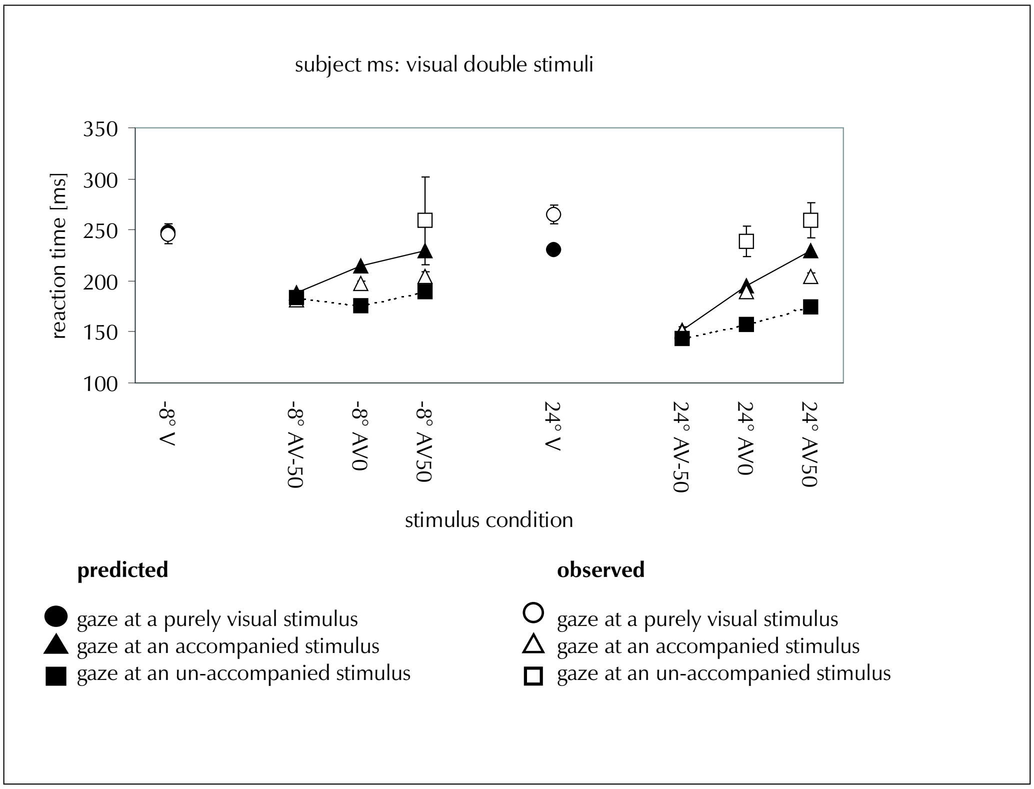

Figure C.80: Subject *ms*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (7-Parameter-Version).

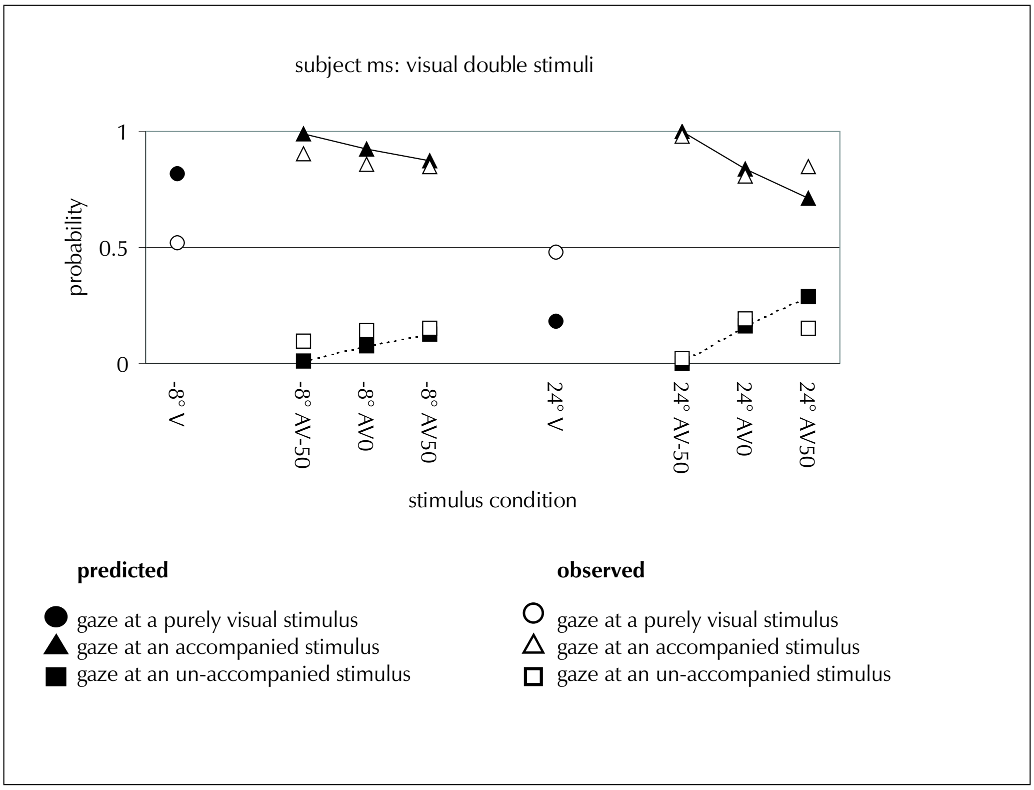

Figure C.81: Subject *ms*: Double target condition, visual stimulus pair 24° right/8° left. Given are the predicted and observed probabilities for three SOAs (7-Parameter-Version).

C.2.4 Parameter estimations for the double target condition for the visual stimulus pair 8° right/24° right or 8° left/24° left

C.2.4.1 2-Parameter-Version

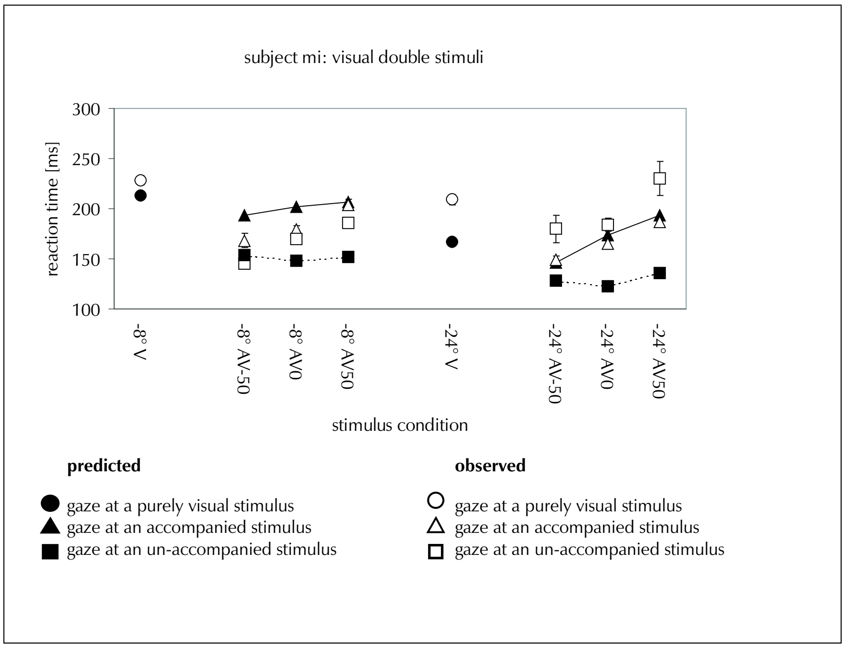

Figure C.82: Subject *mi*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

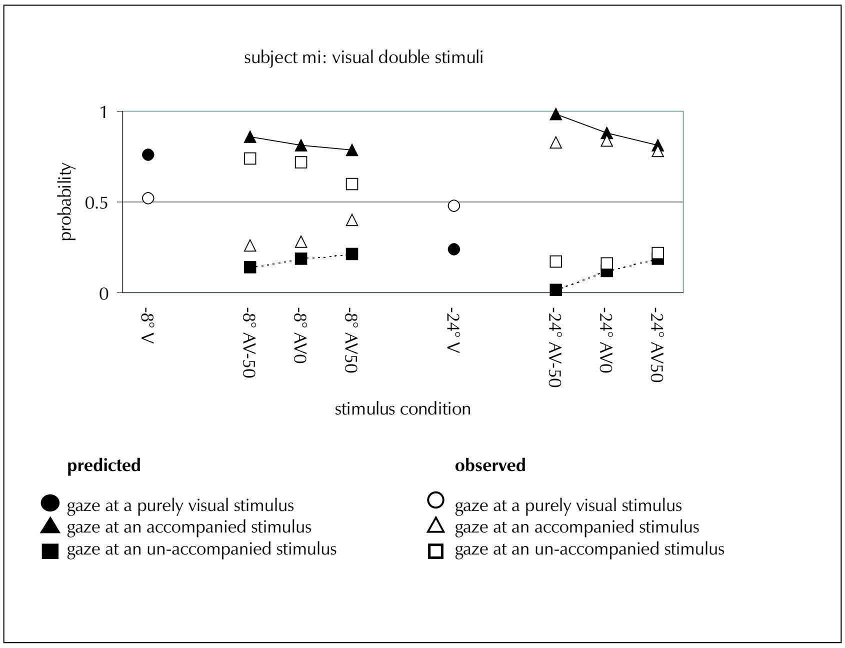

Figure C.83: Subject *mi*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed probabilities for three SOAs (2-Parameter-Version).

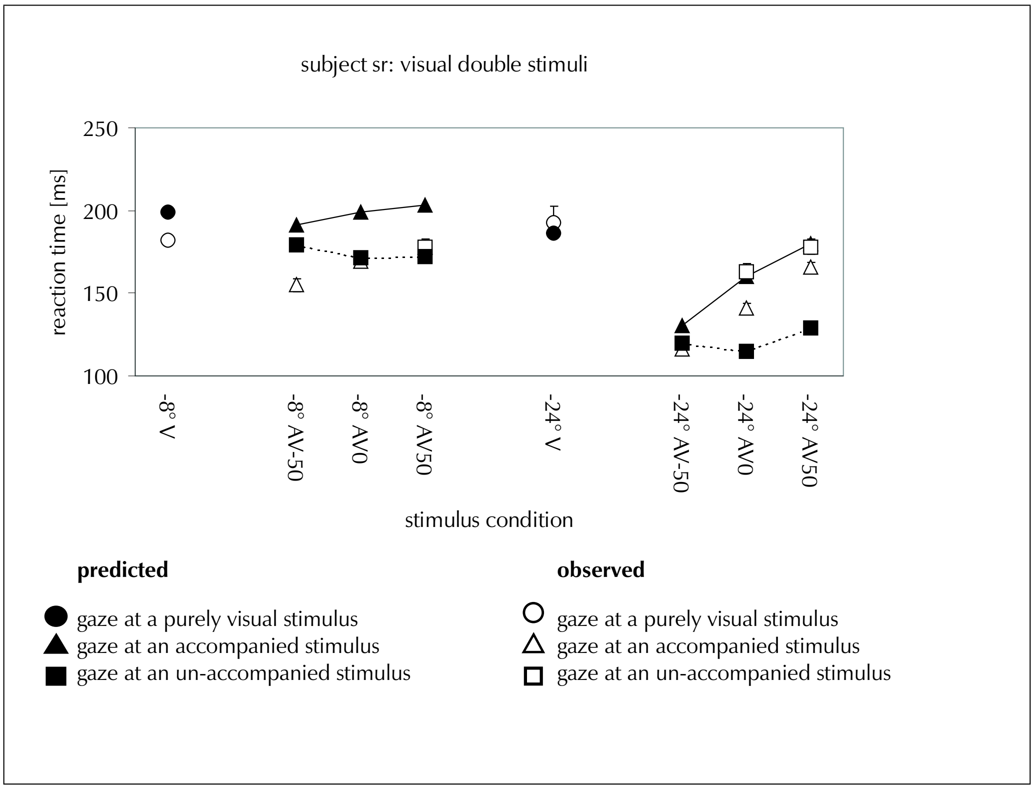

Figure C.84: Subject *sr*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

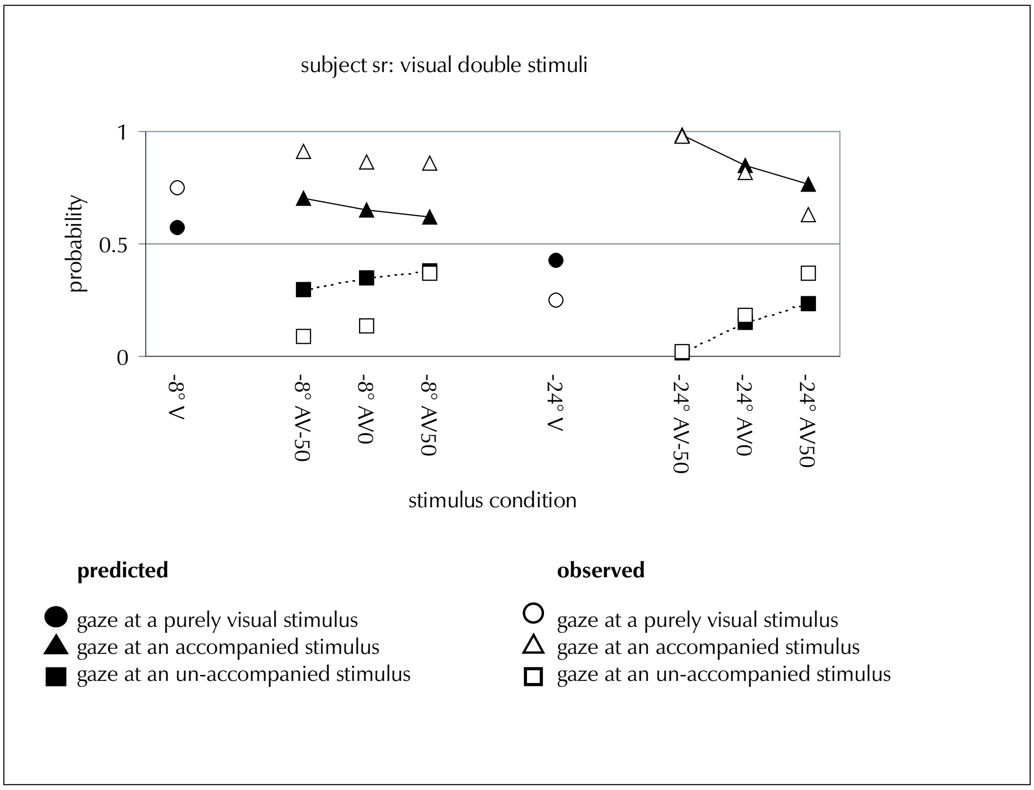

Figure C.85: Subject *sr*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed probabilities for three SOAs (2-Parameter-Version).

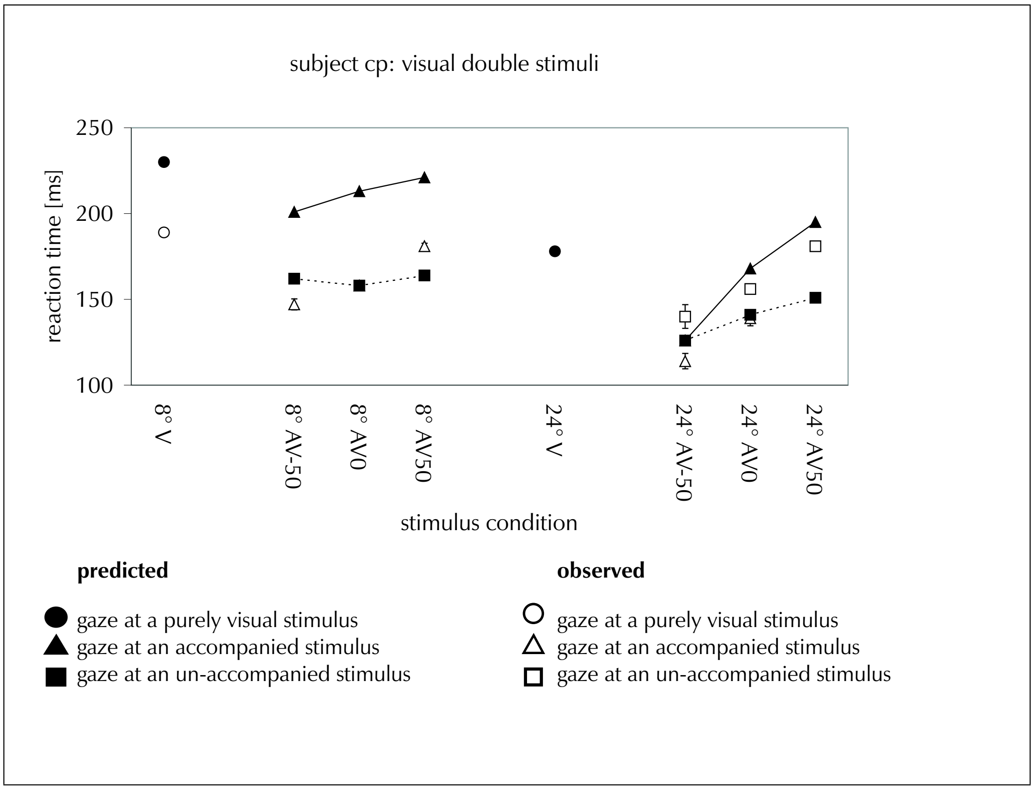

Figure C.86: Subject *cp*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

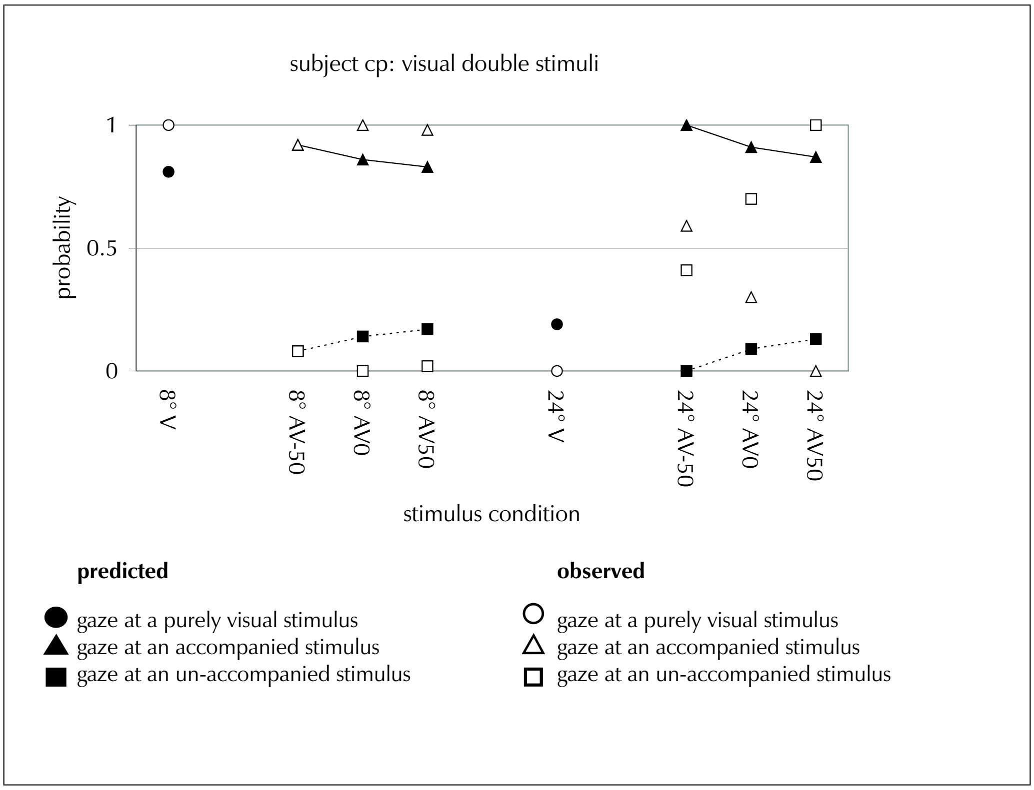

Figure C.87: Subject *cp*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed probabilities for three SOAs (2-Parameter-Version).

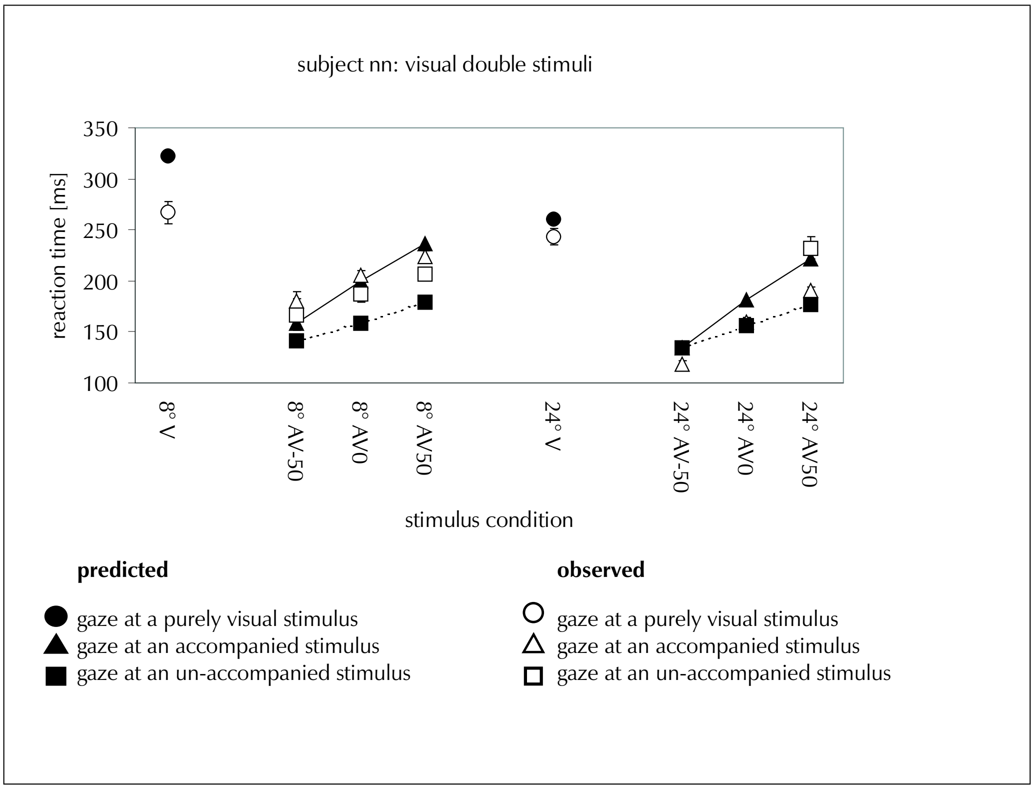

Figure C.88: Subject *nn*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

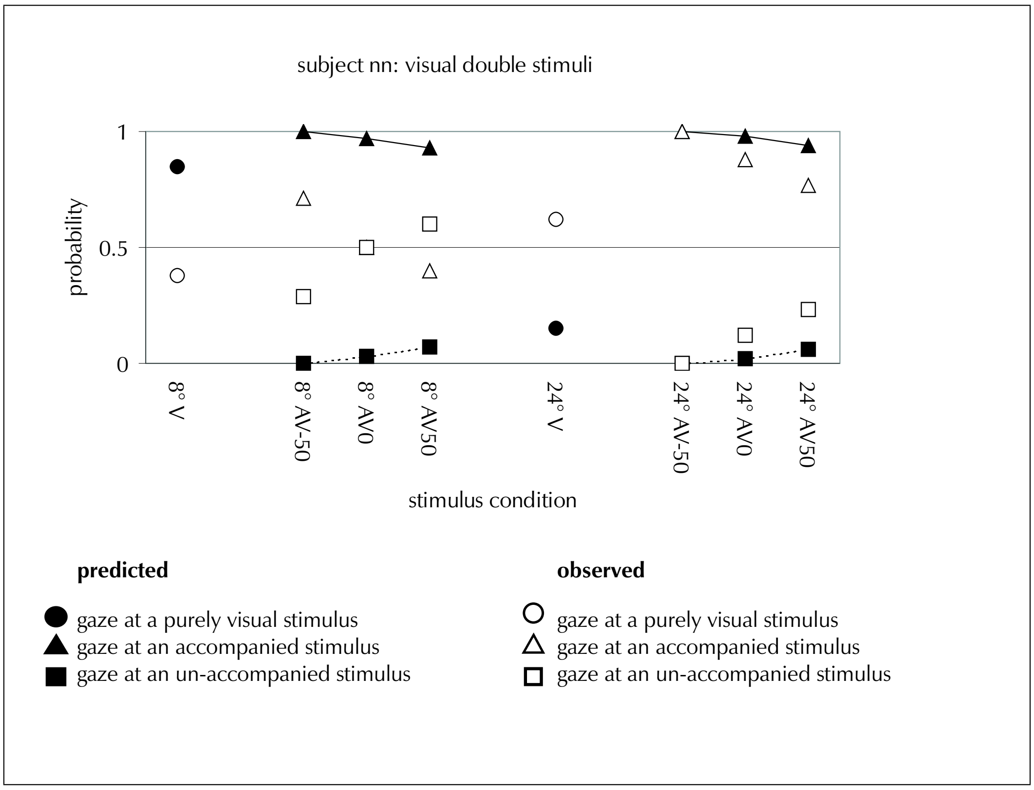

Figure C.89: Subject *nn*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed probabilities for three SOAs (2-Parameter-Version).

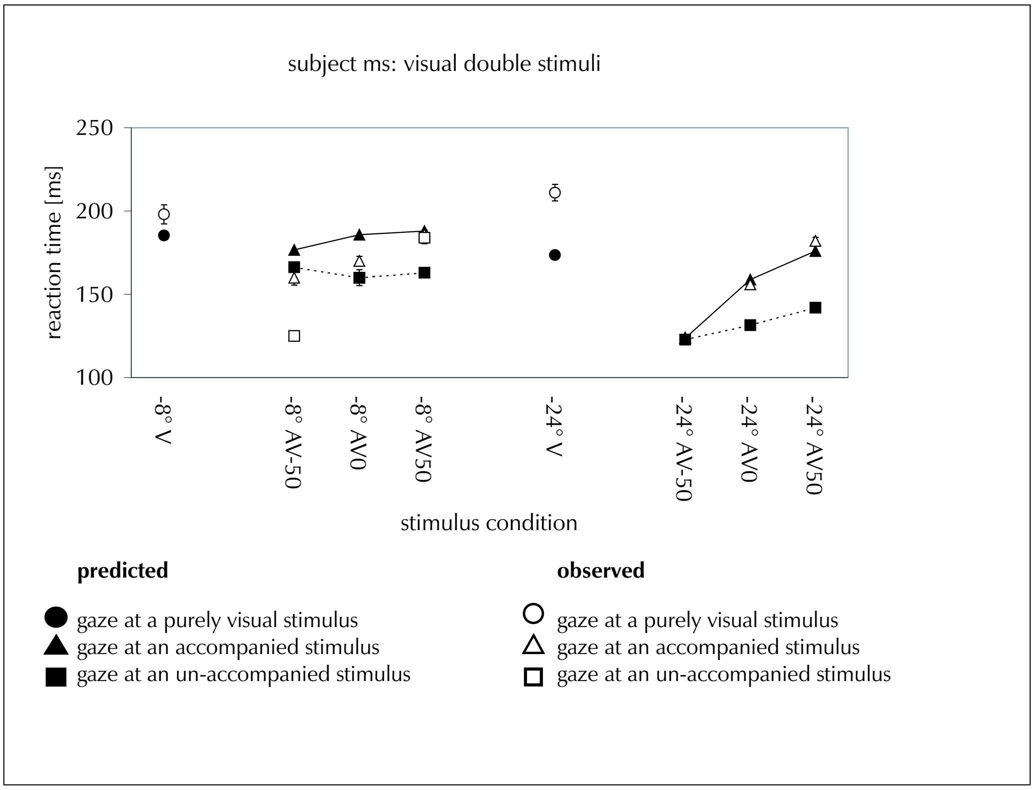

Figure C.90: Subject *ms*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

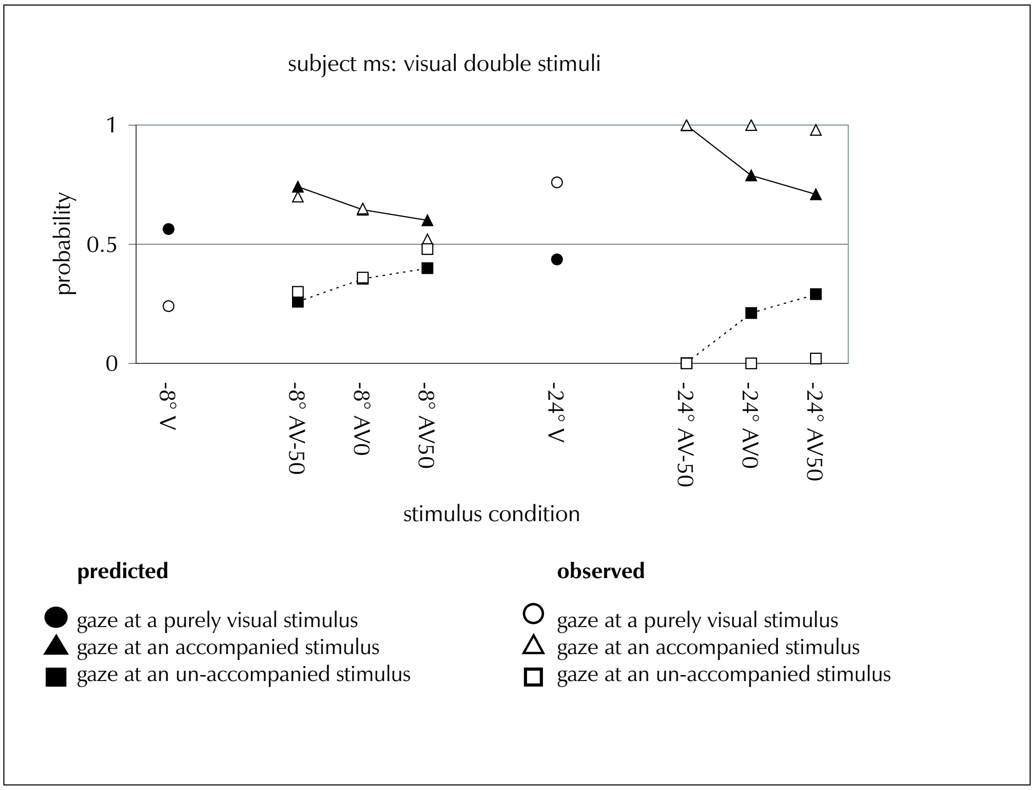

Figure C.91: Subject *ms*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed probabilities for three SOAs (2-Parameter-Version).

C.2.4.2 6-Parameter-Version

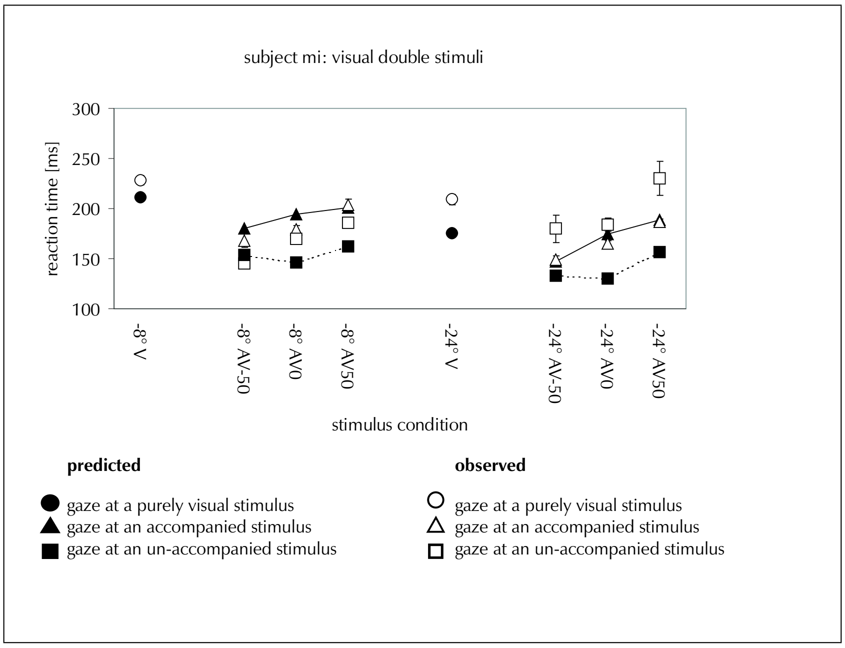

Figure C.92: Subject *mi*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

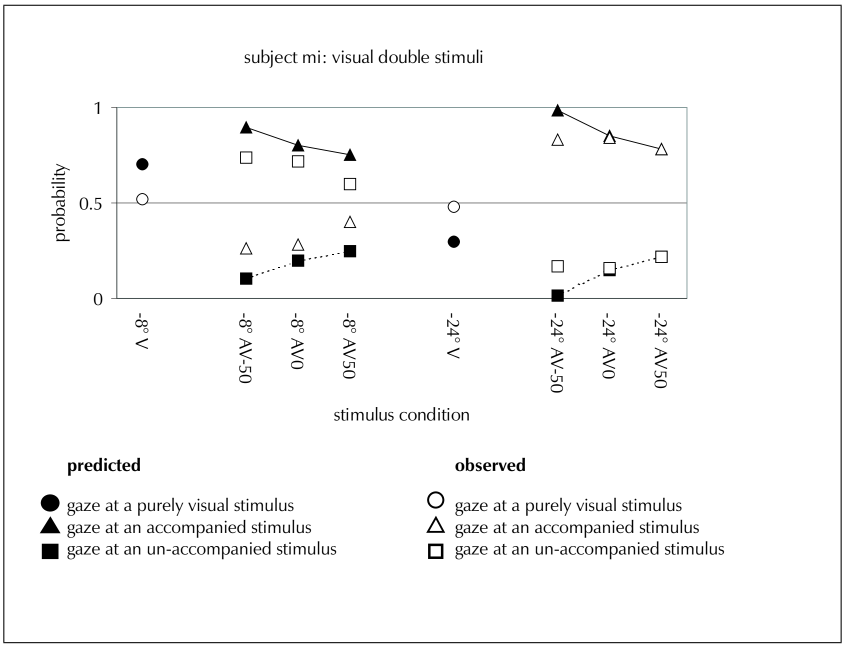

Figure C.93: Subject *mi*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed probabilities for three SOAs (6-Parameter-Version).

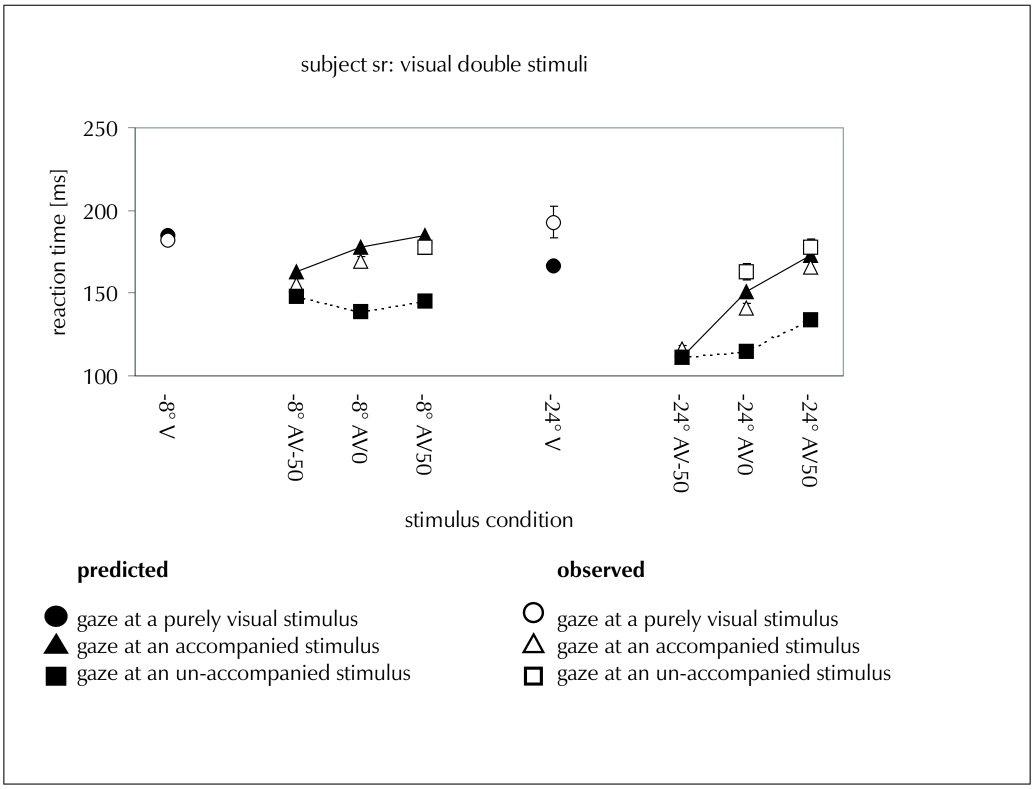

Figure C.94: Subject *sr*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (2-Parameter-Version).

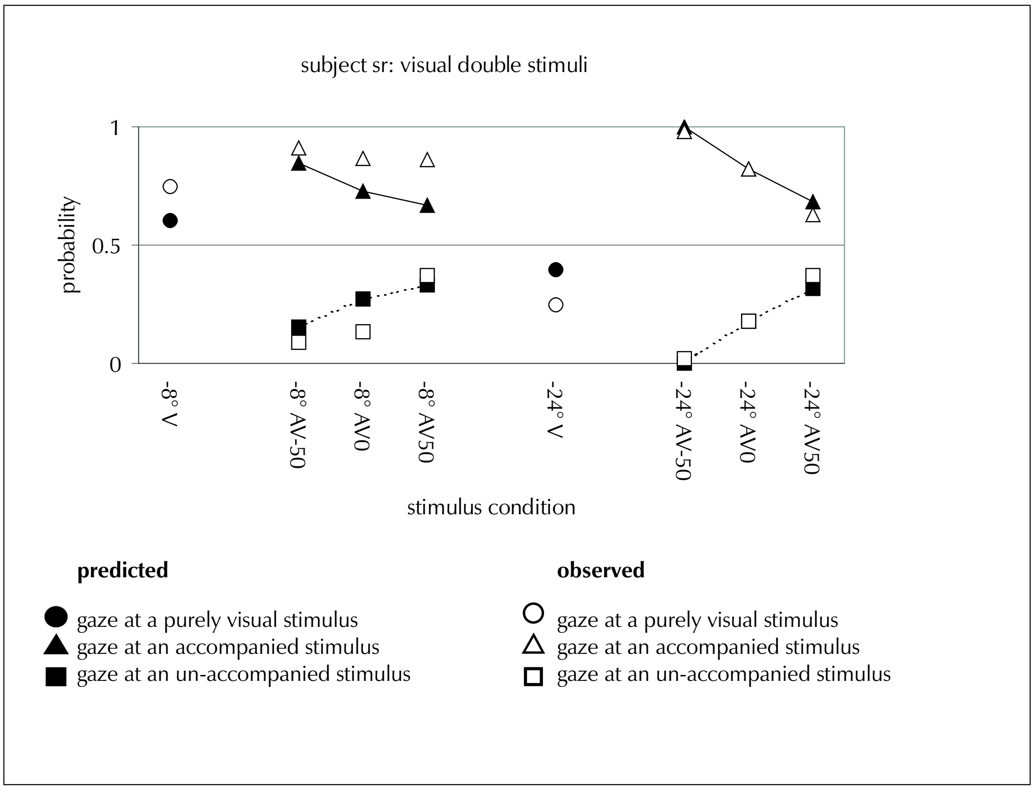

Figure C.95: Subject *sr*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed probabilities for three SOAs (6-Parameter-Version).

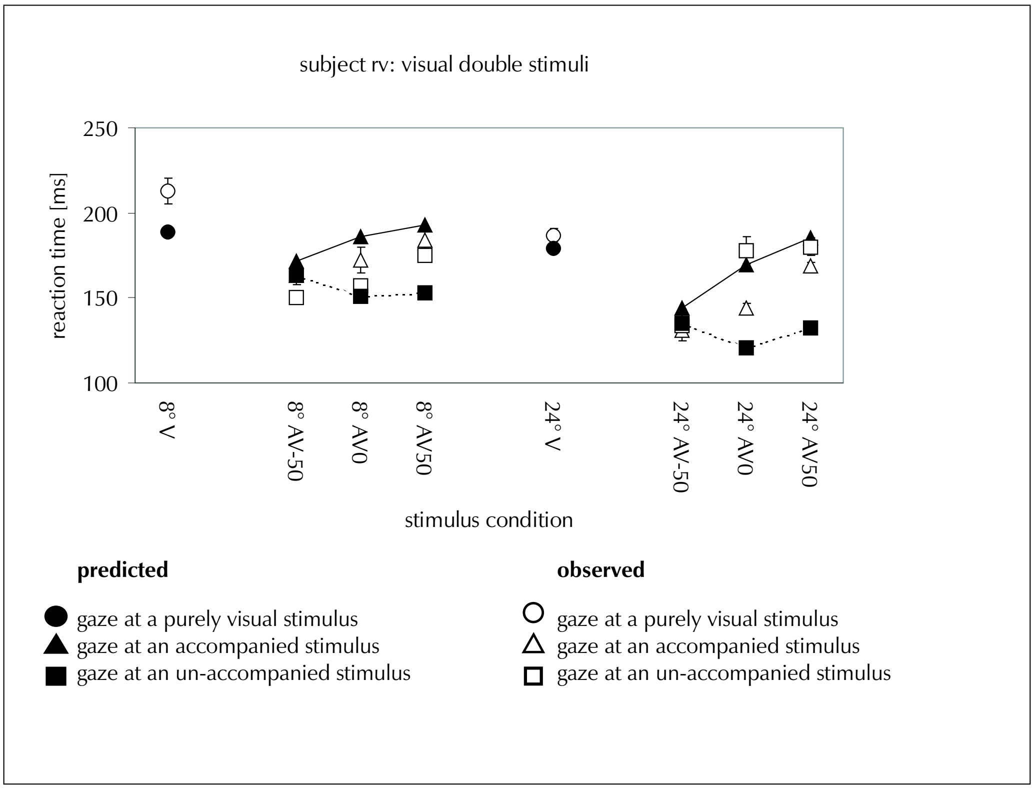

Figure C.96: Subject *rv*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

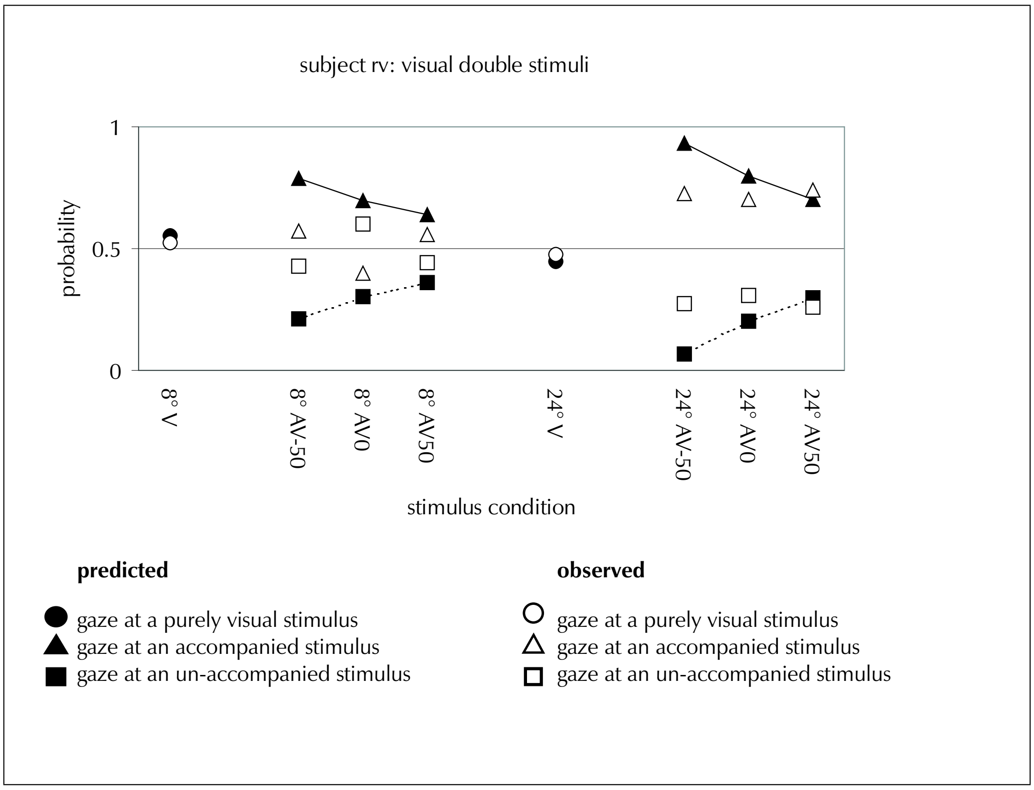

Figure C.97: Subject *rv*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed probabilities for three SOAs (6-Parameter-Version).

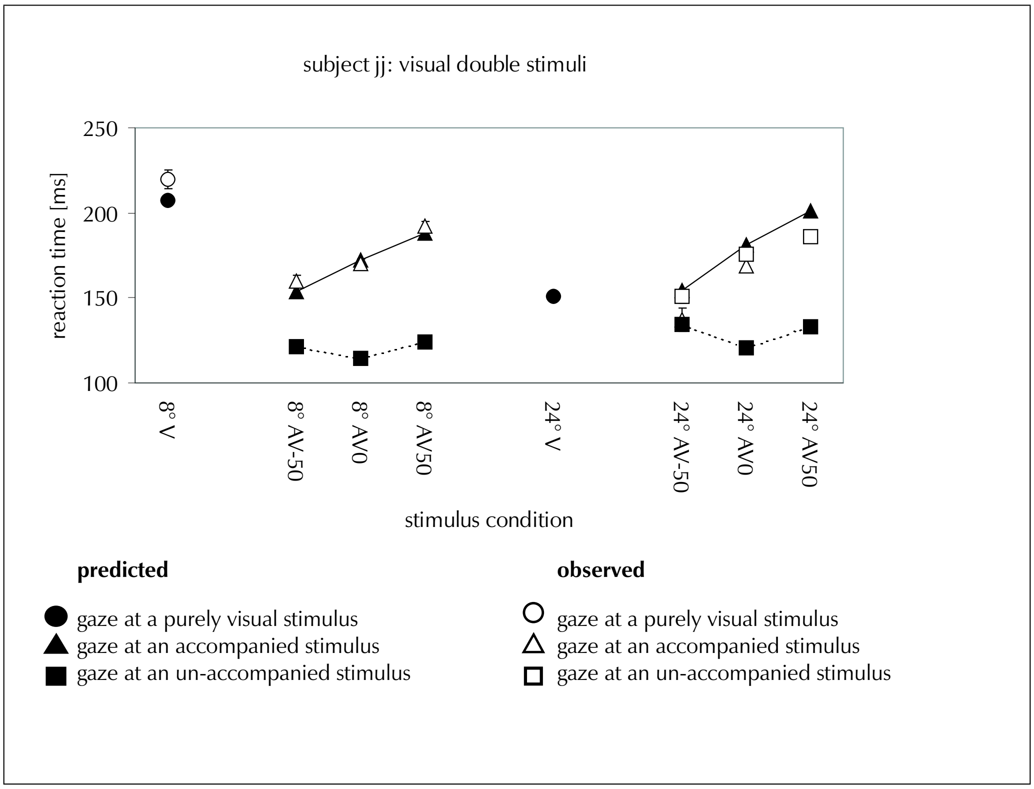

Figure C.98: Subject *jj*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

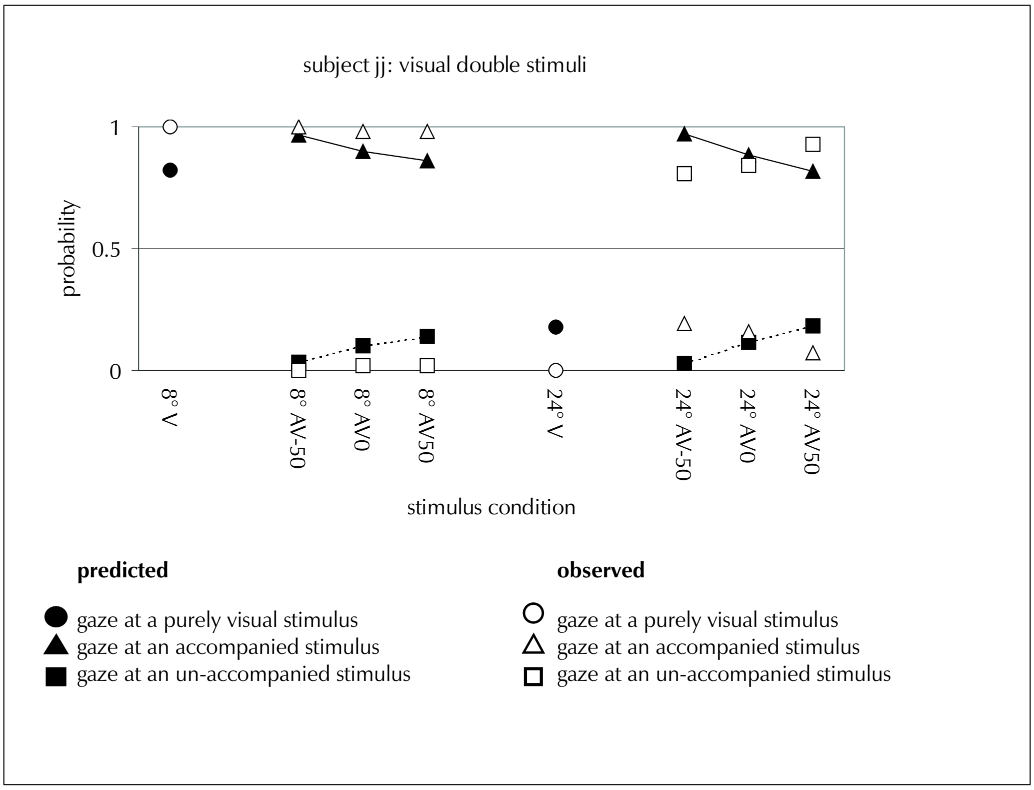

Figure C.99: Subject *jj*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed probabilities for three SOAs (6-Parameter-Version).

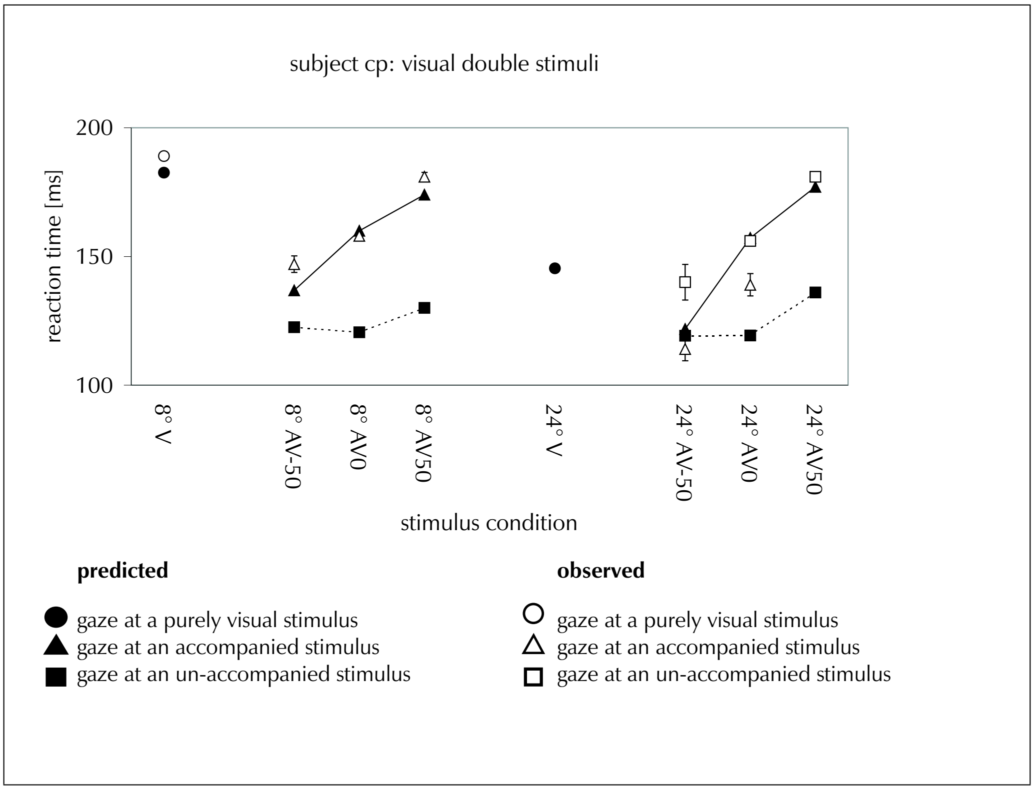

Figure C.100: Subject *cp*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

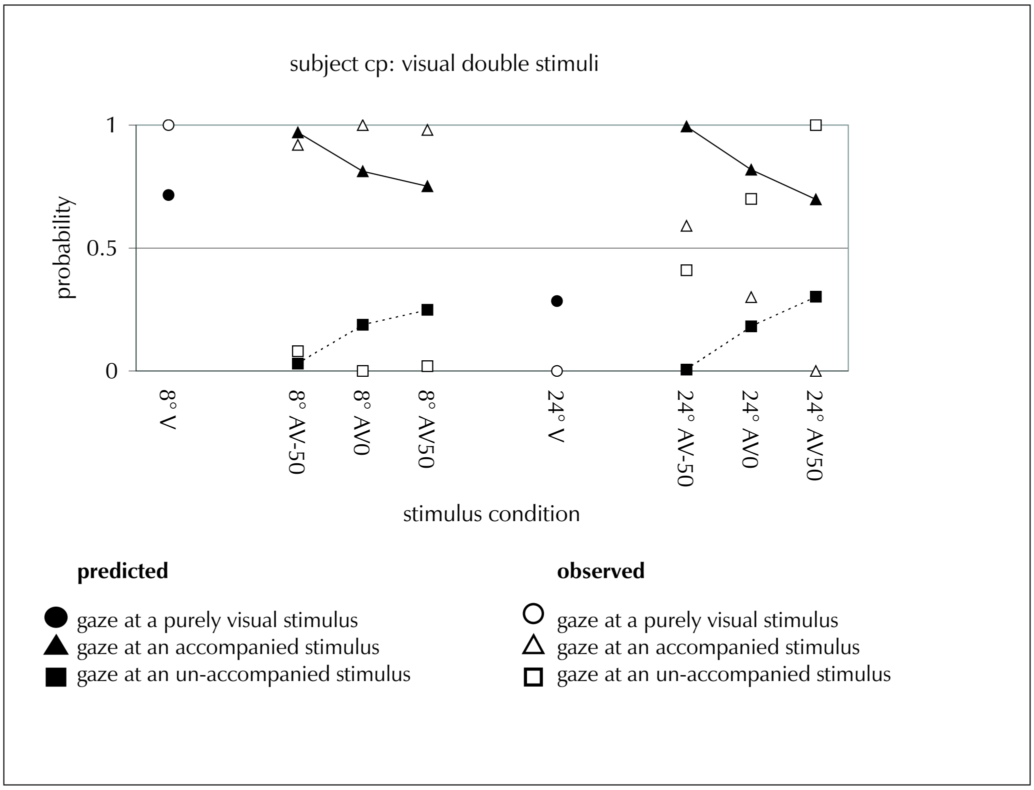

Figure C.101: Subject *cp*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed probabilities for three SOAs (6-Parameter-Version).

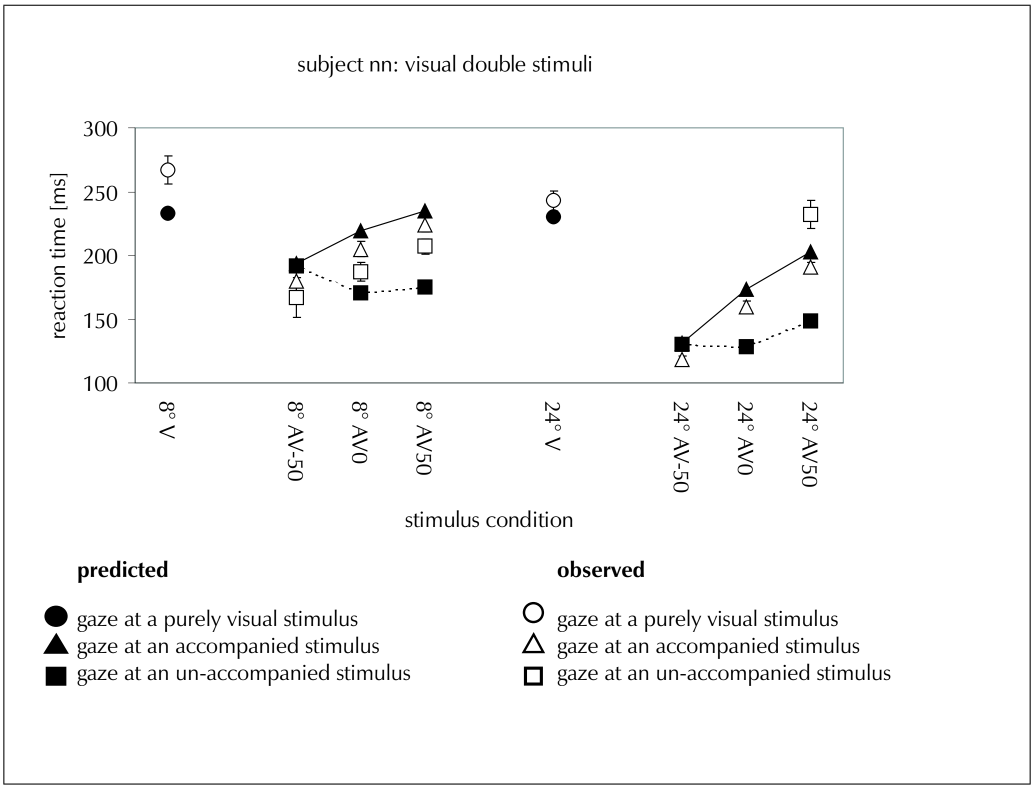

Figure C.102: Subject *nn*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

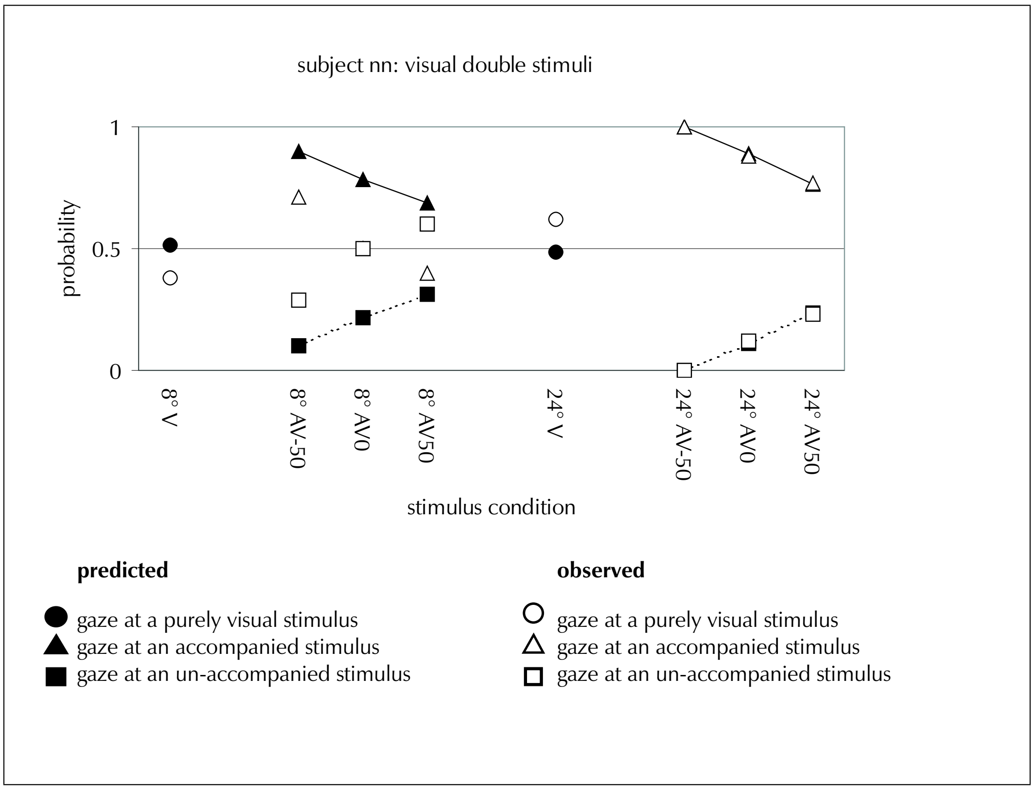

Figure C.103: Subject *nn*: Double target condition, visual stimulus pair 8° right/24° right. Given are the predicted and observed probabilities for three SOAs (6-Parameter-Version).

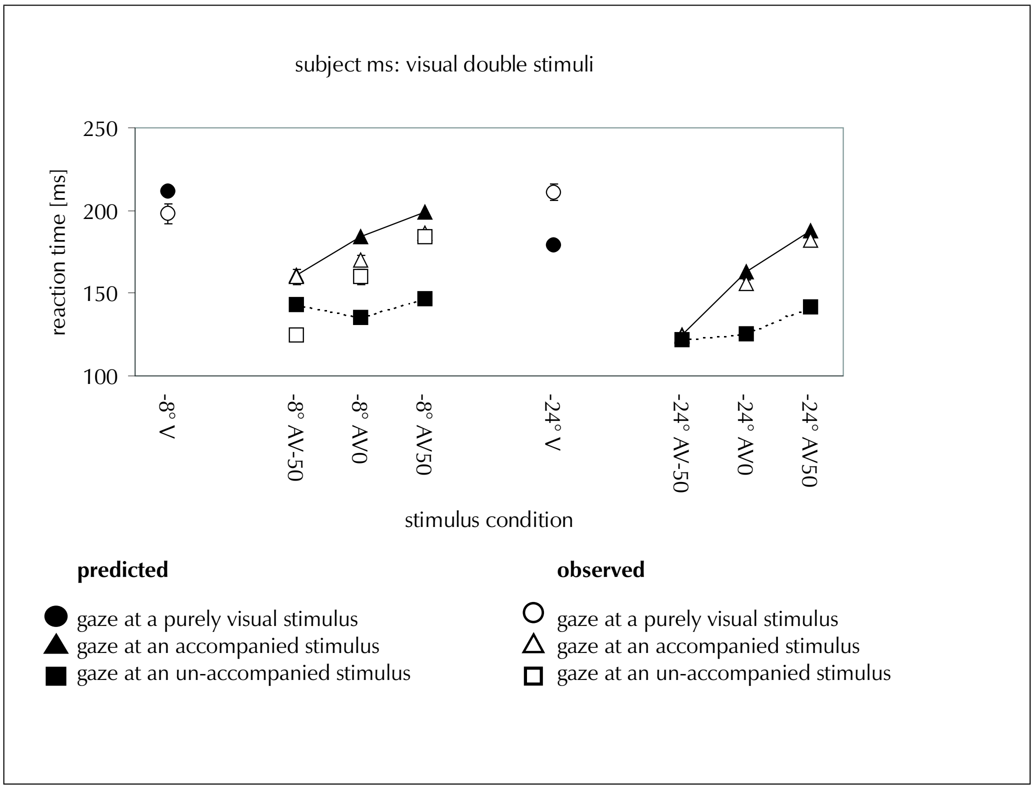

Figure C.104: Subject *ms*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed mean reaction times and standard errors for three SOAs (6-Parameter-Version).

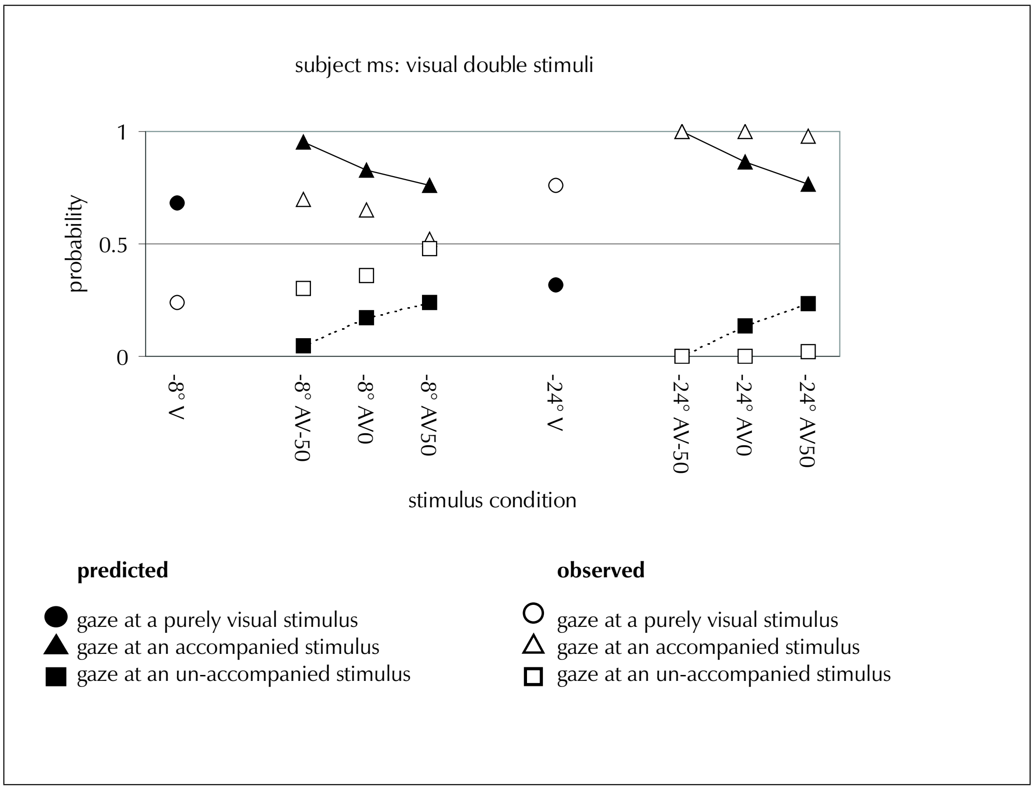

Figure C.105: Subject *ms*: Double target condition, visual stimulus pair 8° left/24° left. Given are the predicted and observed probabilities for three SOAs (6-Parameter-Version).

Eidesstattliche Versicherung

Ich versichere, daß ich meine Dissertation *The influence of an auditory accessory stimulus on target choice and reaction time with two visual stimuli* selbständig ohne unerlaubte Hilfe angefertigt und mich dabei keiner anderen als der von mir ausdrücklich bezeichneten Quellen und Hilfen bedient habe. Die Dissertation wurde in der jetzigen oder einer ähnlichen Form noch bei keiner anderen Hochschule eingereicht und hat noch keinen sonstigen Prüfungszwecken gedient.

Marburg, den 29. Oktober 2001

Danksagung

Diese Arbeit wurde im Rahmen des von der DFG geförderten Graduiertenkollegs Psychoakustik an der psychologischen Fakultät der Carl-von-Ossietzky Universität Oldenburg erstellt.

An dieser Stelle möchte ich mich bei allen Mitgliedern des Graduiertenkollegs, ohne deren Hilfe diese Arbeit nicht zustande gekommen wäre, herzlich bedanken.

Besonderer Dank gebührt dabei:

Professor Dr. Hans Colonius und Professor Dr. Adele Diederich für die engagierte Betreuung meiner Arbeit und ihre wertvolle Hilfe in allen inhaltlichen und organisatorischen Fragen. Durch die intensive Diskussion theoretischer Fragen gaben sie meiner Arbeit viele hilfreiche Impulse.

Dr. Petra Arndt für für Ihre unermüdliche Unterstützung vor allem im experimentellen Teil meiner Arbeit.

Heike Heuermann, Holle Kirchner und allen anderen Mitgliedern des Instituts für Kognitionsforschung, die nicht nur zu einer aufgeschlossenen Arbeitsatmosphäre beigetragen haben, sondern ausserdem durch viele anregende Diskussionen rund um die audiovisuelle Interaktion mein Verständnis diesbezüglich sehr erweitert haben.

Dr. Arno Schilling für seine Unterstützung bei Aufbau und Programmierung der Experimente und Monika Niemann für das Korrekturlesen meiner Arbeit.

Allen Versuchspersonen für das geduldige Mitmachen bei meinen Experimenten.

Meinen Eltern, die mir das Studium der Psychologie ermöglichten und mich immer dabei unterstützt haben.

Dr. Martin Pauly, der mich durch alle Höhen und Tiefen dieser Arbeit begleitete und mir nicht nur zahlreiche gute Tipps sondern auch wertvolle Hilfe in allen technischen und theoretischen Fragen anbot.

Walter Deltgen und allen anderen Freunden, die mich stets darin bestärkten, diese Arbeit erfolgreich zu beenden.

Marburg, den 11. März 2002

Lebenslauf

18.12.1970	Geburt in Nabburg
1977–1981	Grundschule Nabburg
1981–1990	Johann-Andreas-Schmeller-Gymnasium Nabburg
29.06.1990	Abitur
1990–1992	Grundstudium der Psychologie an der Universität Konstanz
02.09.1992	Diplomvorprüfung Psychologie
1992–1997	Hauptstudium der Psychologie an der Justus-Liebig-Universität Gießen
1994–1996	Magisterstudium der Philosophie (Zwischenprüfung 1996)
14.04.1997	Diplomprüfung Psychologie
01.09.1997–31.08.2000	Promotionsstipendium im Rahmen des Graduiertenkollegs Psychoakustik an der Carl-von-Ossietzky-Universität Oldenburg
25.09.2000–30.06.2001	wissenschaftliche Hilfskraft m.A. am Hochschulrechenzentrum der Philipps-Universität Marburg
seit Juli 2001	wissenschaftliche Mitarbeiterin am Hochschulrechenzentrum der Philipps-Universität Marburg