



DISSERTATION

Titel der Dissertation

The role of attention for the flash-lag effect and during
saccadic inhibition of return

Verfasser

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If you want to truly understand something, try to change it.

(Kurt Lewin)

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Abstract

In everyday life, we always pick some visual information while we ignore some other. This is called *selective visual attention*. Selective attention is discussed as the main cause of numerous phenomena and effects, such as prior entry, cueing, inhibition of return (IOR), inattention blindness, change blindness, or the flash-lag effect (FLE). While the contribution of visual attention to some of the effects is undoubted, the picture is not so clear for IOR and the FLE. The current thesis covers tests of the controversial thesis that attention is the origin of these phenomena. To start with the FLE, a visuo-spatial illusion, most theories see its origin in low-level, attention-independent visual processing. In Chapter 2 and 3, I present experiments testing an attentional origin of the FLE. Selective visual attention as the main cause for the FLE leads to new predictions. 1) A spatial FLE should be accompanied by a temporal illusion, a flash-lead effect, 2) under conditions where one illusion (e.g., the spatial illusion) vanishes, the other illusion (e.g., the temporal illusion) should vanish as well, and 3) if a task demands that the observer reverses the order of first attending to a moving object and second to a flash, the visual illusion should be reversed, too. All three predictions could be confirmed. The conclusions of my thesis are indifferent for IOR. From the beginning, researchers linked IOR to a preceding attention shift as one major condition to be met for IOR to be observed. However, other studies revealed different non-attentional origins of IOR. Here I used the well-known top-down contingency of attention on task sets for relevant stimuli to test whether IOR depends on preceding attention capture. If

attention is one major origin of IOR, more attention capture with top-down relevant stimuli should lead to more IOR than less attention capture with top-down irrelevant stimuli. In Chapters 4 to 6, I show that this simple prediction is not corroborated. Whereas attention capture is indeed larger with top-down relevant than irrelevant stimuli (Chapter 6), if anything saccadic IOR is stronger with irrelevant than relevant stimuli (Chapters 4 and 5). Together the results show that IOR is not only the result of attention capture. Further mechanisms have to contribute towards this mechanism.

In conclusion, visual attention could be an origin for the FLE but it fails to explain IOR. The present thesis ends with a discussion of the implications and the limitations of my research.

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Chapter 1: Introduction

Visual attention

Ignoring the facts is key to understanding the world. At least, it is one successful strategy to deal with information overload. Another strategy is picking of only the relevant information. Of course, the trick is to decide beforehand which information is useful and which information could be safely ignored. Selective attention is discussed as one mechanism that does this trick for vision. Early attention theories assumed a *limited processing capacity* of the human mind or brain (Broadbent, 1958). As a consequence input information would have to be reduced to an amount that can be handled by the mind. Contrary to this, the *selection for action* (Allport, 1987) approach regards the selection as a benefit and not as the consequence of a general central processing limitation. According to the selection-for-action view, different actions, such as grasping versus looking, require different input data. For instance, successfully grasping an object definitely requires 3D information about spatial depth. By contrast, in many instances, successfully directing the gaze towards an object can be achieved on the basis of 2D information alone. According to the selection-for-action view, attention enables the use of only the relevant input data that fit into the action plans (Neumann, 1987).

At least since the late 20th century, visual attention is discussed as the main driving force behind many visual phenomena and effects. For example, phenomena such as change blindness (Simons & Levin, 1997) and inattentional blindness (Mack & Rock, 1998) describe situations in which observers fail to detect large changes be-

tween successive images. However, if the observer attends to the area or object that changes, registering the change gets ridiculously easy for the observer (Rensink, 2002). Another effect that reflects attention is the cueing effect (Jonides, 1981; Posner, 1980). If the observer is uncertain about the position of the next relevant target stimulus, a cue that is presented before the target and at the position of the target (or a cue pointing towards the target) facilitates finding the target. This advantage of cues at the same position (SP) as the target is observed relative to a condition with a cue presented at a different position (DP) than the target (cf. Posner, 1980; Eriksen & Hoffmann, 1972). The cueing effect probably reflects attention. Attention is necessary to see a visual stimulus in full (Treisman & Gelade, 1980; Wundt, 1896). Thus, if the cue allows attention to be directed towards the visual target and before target onset, discriminating, identifying, and seeing the target is facilitated (Neumann & Niepel, 2004; Scharlau, 2002; Scharlau, Horstmann, & Ansorge, 2006). This facilitation is typical for so brief intervals between cue and target that an eye movement as an origin of the cueing effect is unlikely (cf. Nakayama & Mackeben, 1989). (In fact, as we will see below, with an increasing cue-target interval the results drastically change, at least with unpredictable cues that are uninformative with respect to the target's most likely position.) The fact that the eyes do not have to be moved for a cueing effect is regarded as an indication that the cueing effect relies on covert attention shifts (where eye movements would be overt attention shifts).

Besides, these effects in which attention figures as a relatively uncontroversial standard explanation for a phenomenon or an effect, in other areas of research it is hotly debated whether attention is truly contributing to a phenomenon or an effect in question. Already Helmholtz (1895) wanted to state explanations of visual processing with well formalized concepts and aimed at eliminating relatively vague and yet powerful concepts, such as attention, from his explanations. Helmholtz only accepted attention as a placeholder for yet to be developed more precise conceptions. The same is true with regard to the explanation of many *visual illusions* where researchers prefer to provide explanations in terms of basic neurophysiological concepts rather than referring to attention (Kirschfeld & Kammer, 1989; Krekelberg & Lappe, 2000). Visual illusions are core concepts in vision research because they very likely show the relatively fix and inflexible constraints of visual processing that are shared by many individuals. Illusions thus allow deep insight into the underlying architecture of vision (Pylyshyn, 1984). Here, I focused on research about the *flash-lag effect* (FLE). When a moving stimulus is presented aligned with a flashed static stimulus at only one position, observers typically see the flash as shifted against motion direction (cf. Nijhawan, 1994; Nijhawan, Watanabe, Khurana, & Shimojo, 2004). The flash seems to “lag behind”, therefore, the name of the illusion. The effect might owe to attention (cf. Baldo & Klein, 1995; but see Khurana & Nijhawan, 1995) because, as stated above, attention could be a gateway to visual perception (cf. Wundt, 1896). According to the attentional explanation, the flash captures attention. As a consequence, as long as

attention is with the flash, the moving stimulus would not be updated for visual perception. Once attention is withdrawn from the flash and directed to the moving stimulus, this moving stimulus would have travelled further on its motion trajectory. As a consequence, attention would update the moving stimulus for perception at a position slightly shifted relative to the objective flash position and the flash would be seen as shifted against the motion (Baldo & Klein, 1995). However, besides attention, a wide range of different non-attentional explanations have been given for the FLE. According to the most prominent account of Nijhawan (1994), for example, any moving stimulus would be seen at an extrapolated position to compensate for the delay of the neuronal responses to moving stimuli.

Another controversial effect that I studied during my PhD research was *inhibition of return* (IOR). Different from the FLE, with IOR, it was the other way round in that during the early research attention was considered a top candidate for explaining IOR (Posner & Cohen, 1984). IOR denotes slower responding to SP than DP targets if the cue-target interval is extended to values above ca. 300 ms (cf. Klein & MacInnes, 1999; Lupiáñez, 2010; Taylor & Klein, 1998). Posner and Cohen (1984) were the first to observe IOR found it for target positions, largely independently of the direction of concomitant eye movements. These authors therefore concluded that IOR reflected the participants' reluctance to redirect their covert attention to a position that had first captured attention in the past (when a cue was presented) but that was later actively disregarded because no target could be found at this position. Therefore, the name of the effect: *inhibition of return* (of atten-

tion). However, later results challenged this conclusion and found evidence for a stronger connection between IOR and eye movements than between IOR and covert shifts of attention (Rafal, Calabresi, Brennan & Sciolto, 1989). Relatively early after its first description by Posner and Cohen (1984), Rafal et al. found that IOR was present when a cue in the periphery of the visual field afforded a saccade towards its position but that IOR was absent when an arrow as a cue was presented in the center of the screen. Based on the fact, that the central cues did not afford a saccade in so direct a way as the peripheral cue, Rafal et al. (1989) speculated that overt movements of the eyes rather than covert shifting of attention was the major driving force behind IOR. This conclusion was backed up by findings showing that IOR and attention capture of a cue could be two effects that develop at the same time rather than in succession (cf. Tassinari & Berlucchi, 1993), and that capture and IOR are differentially affected by diverse experimental manipulations intended to target an attention-system vs. a saccade-steering mechanism (Hunt & Kingstone, 2003; but see, e.g., Souto & Kerzel, 2009). The following studies contained in my thesis shed light on the questions whether visual attention contributes to the origin of visual illusions like the FLE and whether visual attention accounts for IOR.

In the following paragraphs, I will briefly introduce the general background of my PhD research. Firstly, I will sketch the logic behind the experiments on the FLE (Chapters 2 to 3). Secondly, I will introduce different conceptions of attention, with an emphasis on the way that attention is driven – that is, whether it is stimulus-driven attention or goal-driven. Together, these paragraphs set the stage for the

major rationale underlying the conclusions from the IOR research (Chapters 4 to 6).

Two different ways to examine visual attention

In this thesis, two different experimental protocols are used to study visual attention: visual illusions and spatial cueing. We will start with visual illusions. Visual illusions are very powerful demonstrations of the constructive nature of vision. With the help of visual illusions, the observer is able to directly experience the effects of the limitations imposed by the underlying mechanisms of visual perception themselves. These limitations might be adaptive in some sense but they are definitely leading to a non-veridical illusory representation of the environment (Shepard, 1990). Think of cinema, where a succession of still images is seen as the display of real continuous motion. While visual illusions have the immediate advantage of seeing what one gets as a result of the architecture of the visual system, it is often difficult to track down an illusion to one specific underlying principle, such as attention. This is the case for spatial misperceptions, such as the flash-lag effect (FLE). One aim of my thesis was to test an attentional explanation of the FLE.

The flash-lag effect

If two objects are presented in perfect objective alignment, one would usually see these objects also as aligned. However, the subjective perception can drastically

differ from objective alignment if one of two objects moves and the other one is briefly flashed, aligned with the moving object. In this situation, the flashed object seems “to lag” behind the moving object – that is, the flash is seen as shifted against the direction of motion. This subjective impression is the reason why this illusion is called the flash-lag-effect (FLE; Nijhawan, 1994). According to Kerzel (2010), the FLE was first described by Fröhlich (1923) as a variation of the Fröhlich effect, and re-discovered twice, by Metzger (1932) and Nijhawan (1994). To date, the cause of the FLE is still unclear but most theories explain the effect with attention-independent principles, such as low-level neuronal mechanisms (e.g., Berry, Brivanlou, Jordan, & Meister, 1999). For instance, Fröhlich attributed the effect to a neuronal dwell time for every perceived object. This dwell time leads to a longer stationary visibility of the flashed object while the moving object shifts in space (see also Gauch & Kerzel, 2009). Nijhawan (1994) gave a different explanation. He assumed that a low-level correction signal is computed on the basis of the motion trajectory of the moving stimulus and that perception is based on this corrected signal that extrapolates the perceived position of the moving stimulus to a future position. Nijhawan (1994) assumes that this correction mechanism compensates for the neuronal delays during motion processing and thus allows synchronization of perceived positions with real objective positions during stimulus motion. As a consequence of this extrapolation, a predictable moving object is not perceived at its current veridical but at a future position. Because the static flash does not move, its perception is also not corrected. As a consequence, the

flash would be perceived at its veridical position – that is, as lagging behind the extrapolated moving stimulus.

A number of alternative explanations have been given for the FLE (cf. Eagleman and Sejnowski, 2000, 2007; Purushothaman, Patel, Bedell, & Ogmen, 1998). I will not discuss these alternative theories in any detail here and the reader can find more information on these theories in Chapters 2 to 3. Important for the current context, one mechanism that has been discussed as a potential origin of the FLE is visual attention. This view was formulated by Baldo and Klein (1995; Baldo, Kihara, & Namba, 2002) and Müsseler and Aschersleben (1998). According to these authors, the flashing stimulus captures attention. As a consequence, attention is not on the moving stimulus at the time of objective alignment with the moving stimulus and has to be shifted towards the moving stimulus at a later point in time. Yet attention is crucial for the perception of the moving stimulus. Thus, the perception of the moving object is shifted by the time it takes to redirect attention from the flash to the moving object. As a consequence, the perceived spatial position of the flash is compared with the perceived spatial position of the moving object at a later point in time. At this time, the moving object has traveled towards a position further down its motion trajectory. As a consequence, both objects are perceived as displaced relative to one another.

The flash-lag effect and attention capture

In my thesis, I tested new hypotheses that I derived from the attentional account of the FLE. If it is true that the FLE reflects sequentially shifting attention first to the flash and then to the moving stimulus and if perception depends on attention, it follows that a change of the moving stimulus at the time of the flash should also be seen as temporally trailing behind the flash's onset. In other words, the spatial FLE should be accompanied by a temporal illusion "in the opposite direction" – meaning, spatially the flash should be seen to "lag behind" the moving stimulus but temporally a change of the moving stimulus should be perceived as "lagging behind" the flash. This prediction was tested and confirmed in Chapters 2 and 3. Chapters 2 and 3 tested additional predictions of the attentional explanation of the FLE. All of the predictions were confirmed. Thus the attentional explanation of the FLE was supported (see also Becker, Ansorge, & Turatto, 2009; Chappell, Hine, Acworth, & Hardwick, 2006).

Mechanisms of spatial attention

The second part of my thesis was concerned with IOR. IOR is observed with long cue-target intervals and is interesting because of its potential to inform attention theories. Most critically, IOR figured prominently in one of the hot debates of attention, namely whether attention is stimulus-driven or top-down contingent.

To start with the stimulus-driven view, if an object captures attention, regardless of the current goals, intentions, or top-down control settings of the viewer, the corre-

sponding attention shift is regarded as *stimulus-driven* (Theeuwes, 1991). Stimulus-driven attention capture is a fast and transient process (Egeth & Yantis, 1997). However, humans are also capable of shifting their attention at free will to any location in the visual field. In this case the attention shift is called *goal-driven*. Goal-driven attention shifts emerge later but they can last for a longer time (Müller & Rabbitt, 1989).

Stimulus-driven attention

Eye- or attention-catching objects have one or more features that help distinguishing between the object and its immediate surroundings. Among the helpful features are sudden luminance changes (such as in a flash or an abrupt onset), and clear color differences to the background (i.e., when a red berry is on a background of green foliage). Objects that show one or more of the above mentioned feature differences to their surroundings are called *salient*. Salient objects seem to capture attention automatically (Itty & Koch, 2000). Also, stimulus-driven attention capture could be a short-lived process, initially strong but only of a transient duration (Donk & van Zoest, 2008, Egeth & Yantis, 1997). Importantly, if attention is stimulus-driven, the goals of the viewer are of little relevance. Stimulus-driven attention capture occurs with respect to the salient stimulus and thus stimuli with useful information have the same potential to capture attention as stimuli without useful information.

Goal-driven attention

According to William James, “my experience is what I agree to attend to” (1890, p. 402). This passage highlights that attention is at least to some degree under voluntarily control. Active shifts of attention by the viewer are *goal-driven*. Goal-driven attention shifts follow a different time course than stimulus-driven attention shifts. Voluntarily shifts start later but last for a longer time (Müller & Rabbitt, 1989).

Contingent capture

Top-down contingent capture or briefly *contingent capture* (Folk & Remington, 1998) is a third mechanism combining both, characteristics of stimulus-driven and of goal-driven attention. Contingent capture is stimulus-driven in the sense that a searched-for stimulus elicits the capture of attention automatically, once this stimulus is presented in the visual field. However, according to contingent-capture theory it is not the salience of the stimulus that is responsible for the attention capture. Instead the top-down search settings play a critical role. Any feature of a stimulus in the visual field would be weighted by the actual goals of the observer. Searched-for features would be highlighted and/or irrelevant features suppressed. This leads to a new, top-down weighted map of “salience”. As a result, only stimuli with a searched-for relevant feature capture attention. A red object in front of a green background would only capture attention when an observer searches for red objects. If the observer searches for blue objects, an otherwise salient red object would become inconspicuous. The predictions of the contingent-capture theory have been borne out by experimental results in numerous cueing studies (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; for a review, see Burnham,

2007). For example, if participants search for green targets, green cues will capture attention but red cues will fail to capture attention. This situation reversed when the participants have to search for red targets. To note these top-down contingencies of attention capture effect were found where all of the cues were color singletons – that is, all color cues stood out by their salient colors from the background of more color-homogenous distractors. This means that the experiments supporting the contingent-capture theory at the same time seemed to falsify the stimulus-driven capture theory because according to the latter, the color-singleton cues should have captured attention regardless of the participants' current active top-down search settings.

Inhibition of return (IOR)

I have already explained that with longer cue-target intervals, IOR occurs. Originally, IOR was thought to reflect preceding covert attention shifts (Posner & Cohen, 1984). This state of affairs, however, has drastically changed over the past years. Starting with the work of Rafal et al. (1989), an increasing number of articles has demonstrated that IOR might be not so tightly coupled to preceding covert attention shifts as has originally been believed. Among the evidence against attention being a precursor of IOR is the observation that inhibitory and facilitatory cueing effects can develop in parallel and are both present with very small cue-target intervals (cf. Tassinari & Berlucchi, 1993).

Yet, the rationale of some studies relies on a tight connection between covert attention shifts and IOR. This is true of research in the domain of contingent capture. To start with, researchers that believe in stimulus-driven attention capture explained the findings of more attention capture after top-down matching cues (with a feature similar to the searched-for target features) than non-matching cues (with a feature different from the searched-for target features) with the help of attentional disengagement (Theeuwes, Atchley, & Kramer, 2000). According to the disengagement or deallocation theory, every salient stimulus initially captures attention and this is also true of the non-matching color singleton-cues in the studies of Folk et al. (1992) and others. However, the participants are able to quickly register that a non-matching cue is not a target. Therefore, the participants are also able to swiftly withdraw their attention from these cues. As a consequence, with a small interval between cue and target, attention can be first captured by the non-matching cue in a stimulus-driven way but then quickly be deallocated from this cue so that no capture effect is evident in a comparison between SP and DP conditions. The situation is different with the top-down matching cues. These are harder to discriminate from the targets. As a consequence, attention still lingers on the cue at the time of target onset, and a capture effect can be found.

One can clearly see the connection between this theory and IOR: If it is true that attention is the precursor for IOR, with even longer cue-target intervals than have been used in Folk et al. (1992), it should be possible to find IOR with the non-matching cues. It should also be possible to find IOR after the matching cues, alt-

though with yet a further delay – that is, an even longer cue-target interval than is necessary for IOR in the non-matching cueing conditions. When these predictions were tested, however, the findings were at variance with the deallocation theory. There was no IOR after color-singleton cues whatsoever and IOR was restricted to the top-down matching conditions when an abrupt-onset cue was used (Gibson & Amelio, 2000).

As explained, however, the IOR findings have only bearings on theories about attention capture if it can be shown that IOR is a reflection of attention capture in the first place. When I set out to test the question of IOR in top-down matching versus non-matching conditions in the present research, I was able to find (1) partly support for the assumptions of Theeuwes et al. (2000) but (2) also could demonstrate that IOR was inconclusive with respect to the initial capture phase. In Chapters 4 and 5, I used saccades – the quick jumping movements of the eyes – to test whether IOR could be found after color singletons and to understand whether IOR would be stronger after non-matching than matching cues. Both of these possibilities were supported by my findings and – in line with prior research (e.g., Rafal et al., 1989) – my findings suggest that questions regarding the role of deallocation are better studied with the more sensitive overt-attention system of eye movements than with only covert attention shifts. Also, when I went on to test whether the IOR effects are indicative of what goes on during early initial capture, I was unable to find a strong connection (Chapter 6). In this experiment, I used the N2pc to measure attention early after cue onset and eye movements to investigate subsequent IOR.

The N2pc is a component of event-related potentials in the parietal-occipital regions of the human brain that is more negative contralateral to a covert attention shift than ipsilateral to the shift (Luck & Hillyard, 1994). The N2pc has the great advantage to provide a continuous track of attention, from stimulus onset onwards. I used it to test whether attention capture of non-matching and matching cues was the same at the time of cue onset (cf. Eimer & Kiss, 2008). This was not the case. I observed a stronger around 200 ms after the matching than after the non-matching cue. This was the case although IOR was more similar for both types of cues. In fact, if anything IOR was stronger after the non-matching cue. Although this finding alone indicated that Theeuwes et al. (2000) might have been taken a valid point, in combination with the early effects on the N2pc, the conclusion would be more cautious and the connection between IOR and a preceding attention shift could be less tight than thought.

In conclusion, my thesis deals with attentional origins of two effects, IOR and FLE, but the results only supported a contribution of attention to FLE while results were mixed regarding a role of attention for IOR.

Chapter 2: What you see is what you set: The position of moving objects.

The following manuscript was published in *Proceedings of the 32nd Annual Conference on Artificial Intelligence*.

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What you see is what you set – the position of moving objects.

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Abstract. Human observers consequently misjudge the position of moving objects towards the direction of motion. This so called flash-lag effect is supposed to be related to very basic processes such as processing latencies in the human brain. In our study we show that this effect can be inversed by changing the task-set of the observer. A top-down change of the observers attentional set leads to a different perception of otherwise identical scenes. Cognitive theories regard the misperception of the moving object as an important feature of attention-mediated processing, because it reflects the prioritized processing of important objects.

1 Where do we see moving objects?

If human observers look at moving objects and judge their position at a specified point in time, they misjudge their positions towards the directory of motion. This effect is called flash-lag and known since 1931 [1]. Most theories agree that this effect is related to processing latency. The human visual system has a processing latency of about 80 ms [2]. We do not see the world as it is, but as it was about 80 ms ago. In a static world this would not be much of a problem, but in a dynamic world, objects can change positions during this time. If, for example, the tennis player Andy Roddick is to serve, he accelerates the ball up to 250 km/h [3]. In 80 ms, this ball travels 5.5 meters. Seeing the ball 5.5 meters displaced is no beginning for a successful return. A more up-to-date representation of the environment would enhance the chance to return the ball.

The same is true for technical systems. A football robot consequently misjudging the position of the ball with about 80 ms could only interact with very slowly moving footballs. Real-time representations of the outer world would enhance attempts to interact with the world. On the other hand, real-time processing is not possible, neither for robots nor for humans. How does the human visual system cope with a considerable slower processing speed? Attentional accounts answer: by having a clue

what is important. If attention is deployed to a specified area in the visual field, objects inside this particular area are processed faster than objects outside this area [4]. According to the attentional view, the misperception of the moving object is not a bug but a feature.

But how does the visual system know what is important? One object could be important in one situation but totally useless in another situation. If observers have the difficult task to count passes between random moving basketball players, the ball and the players are very important. A moonwalking bear, crossing the scene would be very unimportant although moonwalking bears could be assumed to be important. If observers watch the same scene without a particular task, the player would be less important and the bear comparatively more important. Studies show that human observers consequently miss salient objects when busy with another task, but have no problem in detecting them without a demanding task [5]. In the following study, we will show that the relative importance of objects sets the perceived position of moving objects at a specified point in time.

We use a standard flash-lag paradigm with a moving stimulus and a static stimulus. The static stimulus is used as a time marker. Our setup looks like a clock face with a seconds hand traveling on the outer rim of the clock (see figure 1). The time marker is an inner clock hand that can be seen on four different positions, 3 o'clock, 6 o'clock, 9 o'clock and 12 o'clock. We realized three conditions in which the position of the moving object was to judge. The seconds hand was always visible and moving smoothly with 25 rpm around the clock. The inner clock hand was also moving with 25 rpm but only visible on four positions. It started at the 12 o'clock position, jumped to the 3 o'clock, the 6 o'clock, the 9 o'clock and again to the starting position.

In condition 1, the inner clock hand was only visible for 13.3 ms. The observer's task was to adjust the position of the seconds hand in a manner that it was aligned to the 3 o'clock position, the moment the inner clock hand was visible. The onset of the inner hand (the time marker) triggers the onset of the comparison task. One cannot judge the relative position of two objects when only one is visible. So the position of the moving object is relatively unimportant while it cannot be compared to the time marker. The time marker has to be attended-to first and afterwards the moving object.

In condition 2two, the task stays the same but the setup changes a bit. The inner hand is always visible and the seconds hand gets a head start of $\frac{1}{4}$ revolution. The task is to adjust the position of the moving stimulus that both objects are aligned when the inner hand catches up with the outer hand. To solve the task, one has to wait until the inner hand jumps and compare the new position of the inner hand to the actual position of the outer hand. Again, the time marker has to be attended-to first and afterwards the moving object.

In condition 3, the inner hand gets a head start of $\frac{1}{4}$ revolution. Now the seconds hand has to catch up with the inner hand. The task is to adjust the position of the seconds hand so that the inner hand jumps to the next position the moment both objects are aligned. Priority changes in this condition. The inner clock hand is unimportant until the seconds hand reaches its position. In this condition the moving object has to be attended-to first and afterwards the time marker.

2 Results

Figure 1 shows the average results of five observers (one author and four naïve observers) at Paderborn University. The seconds hand was seen as displaced in direction of motion when the inner clock hand triggered the onset of the task. The seconds hand was seen as displaced contrary to the direction of motion when the onset of the task was triggered by itself. The setup and the average results are depicted in Figure 1.

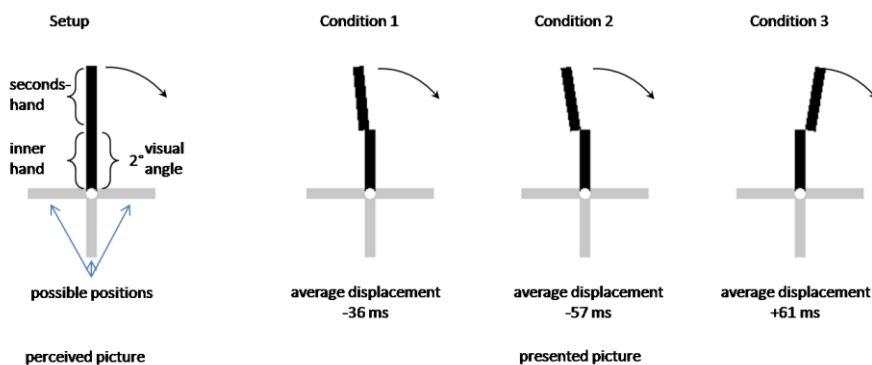


Fig. 1. In each condition the perception of the moving bars should look like the reference picture depicted under “setup”. The actually presented picture did not match the subjective perceived picture. In conditions 1 and 2, the seconds hand was lagging behind the inner hand while perceived as aligned. In condition 3, the seconds hand was leading the inner hand while perceived as aligned.

These findings indicate sequential encoding of first the object that heralds the beginning of the task and second the reference object. Such a task-dependent, top-down sequence was predicted by the attentional explanation of the flash-lag effect. The point is: It is not the bottom-up properties of the presented objects which modulate the percept, but the task the observer performs.

The moving object could be seen either as leading or as lagging. Transferred to the tennis player, this would mean a more up-to-date representation of the ball if the task is returning the ball. The exact position of the opponent would be less important and could be processed later. The perception of the exact position of the tennis player has not been investigated yet. However, there are some studies on football players which are perfectly in line with our attentional explanation. If the linesman is to judge offside he has a bias towards judging offside even if there was no offside [6]. And indeed the linesman’s task reminds of a flash-lag task. One has to judge the position of a moving object (the player) at a specified time (when the pass was shot). The onset of the linesman’s task is triggered by the pass, so attention is first deployed to the ball and after the pass was recognized deployed to the player. Unfortunately (for the attacking team) the player has moved during this time and is being seen in an offside

position after the ball was passed. Deploying attention first to the player (is he in an offside position?) and then to the ball carrier (is he passing?) should inverse the bias into less offside judgments even when the attacking player is in an offside position. Unfortunately (for the linesman) players are often in passive offside positions. In this case the linesman has to do nothing. So the strategy of first attending the player and then the ball carrier would result in much useless cognitive work.

To sum up: Our experimental results with human observers demonstrated that attention speeds up the perception of an attended object quite a bit (36 to 61 ms). Such latency effects have been reported with other tasks such as temporal-order judgments and can be regarded as a very reliable consequence of visuo-spatial attention [7, 8]. We thus can conclude that attention does not only allow for more detailed processing, object-level representations or even conscious perception, but also to faster processing [9]. As far as we know, this advantage has not yet been included in computational models of attention. An exception might be the model by Hamker [10].

We also showed that attention is top-down-mediated. It was the task, not the saliency of features which determined whether the seconds hand trailed or led the inner hand in perception. Again, this is in line with current experimental results in psychology. During the last years, an increasing amount of studies has shown that, at least in human observers, it is task-relevance, not salience, which controls attention [11, 12, 13], or that the effects of salience are at best very short-lived and replaced by top-down influences after about 200 to 300 ms [14]. According to these accounts, if salience controls attention, it does so not by default, but because salience is task-relevant in the present context. Again, this important finding has not been incorporated into computational models of attention. Although many of the current models include some top-down information, this influence is not as weighty and basic as in experimental psychology.

At first sight, attending to task-relevant objects seems to be a reasonable strategy for human observers. But what are the advantages in more detail? If processing capacity is limited, such a strategy could ensure the processing of relevant features, that is, features which are important for the current actions of tasks at hand. Another side effect of prioritization is shielding against interfering information. If for example a football robot is tracking an orange football in order to score a goal, this football has to be processed with priority. The orange t-shirt of an audience member would get less attention because it is not related to the task and although it might be equally salient) and would get less of a chance to interfere with the tracking of the football. We might also speculate that task-relevant objects very often are the objects to be acted upon – for example the object were are fixating, manipulating, tracking, grasping etc. Attention would thus serve a very important function in action control. This idea is most directly included in the premotor theory of attention [15]. In this theory covered attention shifts involve the mechanisms for saccade programming. Both, attention shifts and saccades utilize motor control circuits. All these findings and notions – attention is top-down controlled, attention is tightly coupled to the control of eye movements, attention is vital for current actions and tasks at hand – corroborate the belief that computational modeling of attention will take a major step if attention is implemented in autonomous systems.

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Chapter 3: Spatial mislocalisation as a consequence of sequential coding of stimuli.

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Spatial mislocalization as a consequence of sequential coding of stimuli

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Abstract In three experiments, we tested whether sequentially coding two visual stimuli can create a spatial misperception of a visual moving stimulus. In Experiment 1, we showed that a spatial misperception, the *flash-lag effect*, is accompanied by a similar temporal misperception of first perceiving the flash and only then a change of the moving stimulus, when in fact the two events were exactly simultaneous. In Experiment 2, we demonstrated that when the spatial misperception of a flash-lag effect is absent, the temporal misperception is also absent. In Experiment 3, we extended these findings and showed that if the stimulus conditions require coding first a flash and subsequently a nearby moving stimulus, a spatial flash-lag effect is found, with the position of the moving stimulus being misperceived as shifted in the direction of its motion, whereas this spatial misperception is reversed so that the moving stimulus is misperceived as shifted in a direction opposite to its motion when the conditions require coding first the moving stimulus and then the flash. Together, the results demonstrate that sequential coding of two stimuli can lead

to a spatial misperception whose direction can be predicted from the order of coding the moving object versus the flash. We propose an attentional sequential-coding explanation for the flash-lag effect and discuss its explanatory power with respect to related illusions (e.g., the Fröhlich effect) and other explanations.

Keywords Attention · Visual illusions · Prior entry

At every moment in time, a multitude of visual stimuli impinge on the human retina, but only a few of these stimuli are selected for purposes such as perception, in-depth processing, or action control. Attending to different visual locations, stimuli, features, or dimensions boosts the perception and discrimination of fine visual detail (cf. Bashinski & Bacharach, 1980; von Helmholtz 1894) and speeds up processing of visual stimuli at the focus of attention, as well as subsequent saccades to the attended stimuli (cf. Posner, 1980; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). At the same time, attending can prolong the perceived duration of the attended stimuli (cf. Enns, Brehaut, & Shore, 1999; Mattes & Ulrich, 1998).

Apart from these effects, visuospatial attention can also contribute to visual illusions. As everyday observers, we are barely aware of these illusions. We naively presume that the temporal and spatial features that we perceive reflect the physical properties of distal objects. Beginning with the early days of experimental psychology, however, visual illusions have shown that spatial features of distal objects can be misperceived (e.g., Fröhlich, 1929), and related research has suggested that attention could be (partly) responsible for these effects (Müsseler & Aschersleben, 1998). Fröhlich observed that the starting position of an abruptly onsetting moving stimulus was not veridically perceived. Instead, it was perceived at a position shifted

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farther along its motion trajectory. According to Müsseler and Aschersleben, visual perception of the onset position of the abruptly onsetting moving stimulus depends on allocating attention to its position and is therefore beset with a delay corresponding to the time it takes for attention to focus on the moving stimulus. As a consequence, the moving stimulus will have a perceived onset location that is shifted in the direction of the stimulus movement (cf. Fröhlich, 1929). In line with this assumption, several studies have shown that the Fröhlich effect is reduced when attention is allocated earlier to the motion onset—for instance, when the position of the abruptly onsetting motion stimulus is precued (cf. Ansorge, Carbone, Becker, & Turatto, 2010; Müsseler & Neumann, 1992; Müsseler, Stork, & Kerzel, 2008).

These results reveal that perceptual illusions caused by visuospatial attention may be the flip side of the advantageous effects of visuospatial attention: Because the focusing of visuospatial attention is a necessary precondition for an in-depth representation of a visual stimulus, attention can also delay the perception of a stimulus if it is initially misdirected elsewhere. This role of attention as a gatekeeper for perception is also supported by another type of illusion: Selective attention can also modulate visual illusions concerning the temporal features of visual objects. In this case, the misperception caused by attention is often even more difficult to detect. For example, in the complication experiments, Wundt (1896) noted that his subjects perceived predictable rhythmic stimuli faster than unforeseeable stimuli. In these experiments, participants saw a clock with a rotating hand and had to rate the time at which they heard or felt a stimulus by indicating the clock hand position at the time of the perception of the heard or felt stimulus. Perceptual latency was lower when the stimuli were repeatedly presented at a rhythmic interval. Wundt and other researchers ascribed this effect to prior entry: Focusing attention on a stimulus facilitates stimulus perception so that an attended stimulus is perceived earlier than an unattended stimulus. Because attention can be focused better on an expected rhythmically repeated stimulus than on a stimulus that cannot be anticipated, perception of the rhythmic stimulus is faster than that of the unanticipated stimulus. Already in Wundt's times, this interpretation was criticized as reflecting a judgment bias (cf. Dunlap, 1910), but it was later rehabilitated in light of more rigorous experiments (e.g., Shore, Spence, & Klein, 2001; Stelmach & Herdman, 1991).

The transient focusing of visuospatial attention could thus be a mechanism for modulating temporal, and possibly also spatial, misperceptions or illusions. The mere duration of the attention shift from A to B might be responsible for a spatial misperception—for example, when stimulus B is a moving stimulus and moves along its trajectory while

attention is first focused on A, such that attention can only catch up with B at a later point on its motion trajectory (cf. Baldo & Klein, 1995; Müsseler & Aschersleben, 1998). However, it is also possible that attention has a different effect and creates illusions by serving as a temporal marker for a point of reference for the beginning of a visual representation that is integrated over a certain duration X (e.g., Becker, Ansorge, & Turatto, 2009). According to this line of thinking, attending to one stimulus A provides the starting point for the integration of visual information from this (e.g., moving) stimulus, such that the representation of the position of a moving stimulus would be defined by a time window of some minimal duration (e.g., 80 ms) after the focusing of attention on A (cf. Eagleman & Sejnowski, 2007). This kind of temporal marking of a reference point by attention plus the integration of visual evidence over time elegantly explains the Fröhlich effect, that the position of a moving stimulus is misperceived in the direction of motion and can also account for the flash-lag effect (cf. Nijhawan, 1994). The latter effect denotes the misperception of a moving stimulus as shifted in the direction of its motion when it is in fact objectively aligned with a visual flash (Eagleman & Sejnowski, 2000b).

However, it should be noted that factors besides attention can contribute to sequential coding and spatial misperceptions. For instance, in the Fröhlich effect, the initial position on the motion trajectory (and, in fact, each subsequent position on the motion trajectory alike) is not only difficult to attend to: The perception of this position is also delayed because it is subject to visual backward masking or metacontrast masking (cf. Breitmeyer & Ogmen, 2006) by the subsequent visual stimulus at the next adjacent position along the motion trajectory, which could result in a decreased visibility of the onset position (cf. Carbone & Ansorge, 2008; Kirschfeld & Kammer, 1999). Hence, the Fröhlich effect could also be a consequence of masking; that is, the initial position of a moving stimulus is seen as shifted in the direction of motion because the initial position is backward masked and does not benefit from prior position priming by a preceding adjacent stimulus on the trajectory, as would be the case for all subsequent positions but the initial position of the moving stimulus. Likewise, in the flash-lag effect, factors such as the exact contrast of the flash as compared with that of the moving stimulus, and the resultant temporal head start of the processing of one stimulus over the other, determine the extent of the spatial illusion (Purushothaman, Patel, Bedell, & Ogmen, 1998). The uniting principle of all of the different mechanisms, however, seems to be the principle that the temporal precedence of the processing of one stimulus, position, or feature over the other can lead to spatial misperceptions, and that attention is but one way in which this sequential coding could be brought about. In the

present study, we tested the possibility that sequential coding in general (Exps. 1 and 2) and attention in particular (Exp. 3) could be responsible for spatial misperceptions.

Experiment 1

If a spatial misperception, such as the flash-lag effect, is indeed due to the sequence of the participants' coding first the flash and subsequently an aligned moving stimulus (here, a bar), then we would expect to find that the participants also perceive the flash as temporally preceding the aligned moving stimulus at the same position, even if the two stimuli are presented synchronously at this position. This prediction will be tested in Experiment 1, in which we adapted a procedure for the measurement of the flash-lag effect (Kerzel, 2010; Nijhawan, 1994).

In studies on the flash-lag effect, participants have to judge the position of a moving bar relative to that of a flash. In this situation, despite the fact that the two stimuli, flash and moving bar, are objectively exactly aligned, the flash is usually perceived to be "lagging" behind the moving bar (flash-lag effect; Nijhawan, 1994). To test whether under these conditions the flash is also (mis)perceived to precede the moving bar in time, we had to introduce a visual change of the moving bar. The time of this change could then be compared with the time that the flash was presented. For that purpose, the moving bar changed its appearance near the time of the flash. As a consequence, we were able to ask our participants for their judgments about the spatial position of the moving bar relative to the flash in one block, and to report the temporal order of the time of the change of the moving bar relative to the presentation of the flash in another block.

If the sequential coding first of the flash and then of the moving bar is responsible for the spatial misperception of the moving bar, we should find (a) a spatial flash-lag effect in the spatial judgment task, with the moving bar perceived as shifted in the direction of its motion relative to the position of the flash, when in fact the moving bar and the flash are objectively exactly aligned, and (b) a temporal flash-lead effect in the temporal judgment task, with the flash perceived as appearing earlier than a change of the moving bar, when in fact the onset of the flash and the change of the moving bar are objectively exactly synchronous.

Method

Participants A group of 15 participants participated in the temporal and spatial judgment tasks of Experiment 1. All participants had normal or corrected-to-normal vision, based on prior testing. Two of the participants had to be

excluded because their judgments did not vary as a function of the stimulus onset asynchrony (SOA) between flash and change of the bar. Participants were naïve with respect to the experimental hypotheses, and all gave informed consent.

Materials An Intel Core 2 Duo 2.80-GHz computer with a 19-in. color monitor (Iiyama HM903DT Vision Master Pro) controlled the timing of events and generated the stimuli. Stimuli were presented with a resolution of $1,024 \times 768$ pixels and a refresh rate of 75 Hz. Participants viewed the screen from a distance of 57 cm, with the head supported by a chinrest. For registration of manual responses, we used a standard keyboard. Event scheduling and response measurement were controlled by MATLAB and the Psychophysics Toolbox (Brainard, 1997).

Stimuli See Fig. 1 for a depiction of the procedure in a trial. The rotating bar was a black (0.5 cd/m^2) bar centered on the gray (4 cd/m^2) screen. It had a length of 10.7° and a width of 0.5° . The bar rotated with a speed of 50 cycles per minute, with its axis of rotation at screen center. With every refresh of the monitor (13.3 ms), this bar rotated by 4.0° angle of rotation. The rotating bar had two gaps, one near each of its ends. At one point during the revolutions of the bar, flashes were presented within these gaps. The gaps had a length of 1.1° and were located with an eccentricity from the gap's center of 3.4° . Because the diameters of the circular flashes were equal to the gap lengths, each flash fitted into the gap if it was presented aligned with the rotating bar. The flashes were two white disks (118 cd/m^2), both with a diameter of 1.1° and presented with the same eccentricity as the gaps: With respect to screen center as a point of reference, the two flashes were presented at point-symmetrically opposite positions for a single refresh of the computer screen.

For the visual change of the rotating bar, this bar was repeatedly fragmented and completed: During one revolution, two segments of the rotating bar with lengths of 0.4° vanished near the gaps of the rotating bar, and during the next revolution, these segments reappeared. A demo of Experiments 1 and 2 can be found at http://pptypo3.univie.ac.at/fileadmin/usermounts/priessh9/FLE_TOJ/FLE_TOJ.html (Priess 2011).

Design and procedure The experiment consisted of two blocked conditions, a temporal judgment task and a spatial judgment task, that were identical with respect to the stimuli. The blocks were counterbalanced across participants. In each trial of both the spatial and temporal judgment tasks, participants had to fixate on a small white dot at the center of the screen, and they initially saw one to two revolutions of the rotating bar. After this, the flashes

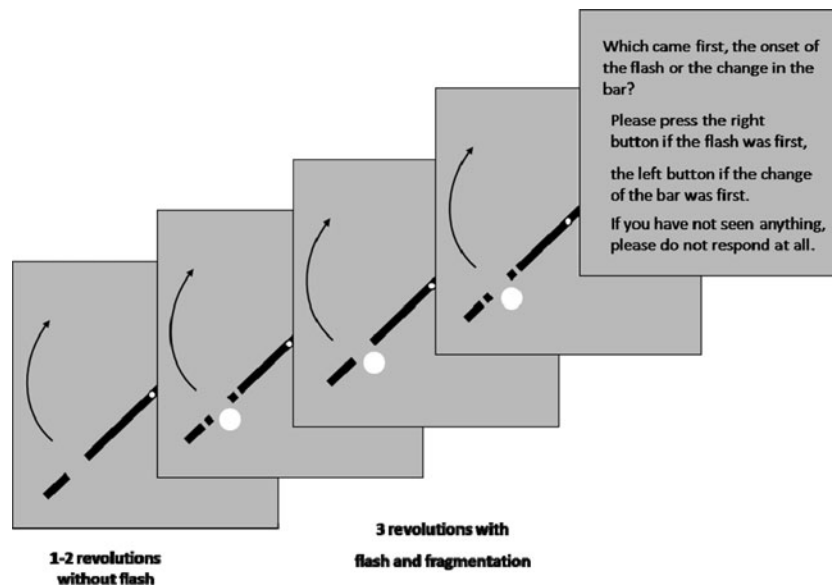


Fig. 1 Depicted is a schematic illustration of the sequence of displays (frames from left to right) in a trial of Experiment 1. A trial started with the presentation of the moving bar (in the frame on the lower left of the figure). After a variable time (one or two revolutions of the rotating bar), two flashes (white disks) were shown. At or near the flash-onset time, the rotating bar was fragmented or completed (depending on how the bar looked at the beginning of the trial). This is depicted in the second frame from left. A trial continued with another three revolutions, during which the flash was repeated and the

bar was fragmented and completed in turn (in the third and fourth frames from the left). Participants had to either judge the spatial position of the flash relative to the rotating bar—this was the spatial task (not depicted)—or judge the temporal sequence between the onset of the flash and the change (segmentation or completion) of the rotating bar. An example of the concluding display in the temporal task is depicted (in the frame on the upper right). The arrows indicate the direction of motion. The stimuli are not drawn to scale

and the changes of the rotating bar were presented repeatedly for the three concluding full revolutions of the rotating bar during a trial. In this manner, participants were able to base their spatial and temporal judgments on their perception of one particular repeated temporal interval or spatial distance during all three concluding revolutions of the rotating bar in a trial.

The flashes were presented either spatially aligned with the rotating stimulus (0°) or with a spatial distance of an angle of rotation of 4.0° , 12.0° , 24.0° , or 48.0° away from the rotating bar. The unaligned flashes were equally likely to be shifted in the direction of the movement of the rotating bar or against it. In both blocks, orthogonally to the spatial distance manipulation, the flash could either temporally lead or lag the change of the rotating bar. Within a trial, the interval between the onset of the flash and the change of the rotating bar was fixed. The interval had a duration of 0, 13.3, 40, 80, or 160 ms. Each temporal interval thus exactly corresponded to one of the spatial distances—that is, the bar moved 4° in 13.3 ms, 12° in 40 ms, and so forth—to allow for comparisons between the magnitudes of the expected temporal and spatial illusions.

On half of the trials, the rotating bar was initially shown in complete fashion, and the first change of the rotating bar consisted of an offset of two small segments of the rotating bar (i.e., a fragmentation) during the first of the final three revolutions in this trial. On the other half of the trials, the

rotating bar was shown segmented at the onset of rotation, and the first change consisted of the onset of the two missing segments (i.e., a completion). Across all conditions, onsets and offsets of segments alternated during subsequent revolutions (i.e., in the order onset, offset, onset or offset, onset, offset).

In the temporal judgment task, participants had to judge whether the flash was perceived temporally before the change of the rotating bar, or whether the rotating bar changed before the flash was presented. In the spatial judgment task, participants had to judge whether the flash was perceived at a position spatially shifted in the direction of the motion of the rotating stimulus or opposite to the direction of this motion. In the spatial judgment task, we used the nine different spatial distances for the calculation of the points of subjective equality (PSEs)—that is, the points of equal frequencies of the two judgments. In the temporal judgment task, we used the nine different temporal equivalents of the spatial distances for the calculation of the PSEs. Because every condition was tested 30 times, participants completed 270 trials in the temporal and spatial conditions, respectively.

Results

We used *psignifit* 2.5.6 to fit data to psychometric curves and to calculate the PSE for each participant and condition

individually (Wichmann & Hill, 2001). Thereafter, two-tailed *t* tests were used to assess whether the spatial and temporal PSEs showed a perceptual illusion (i.e., significant deviations from zero).

As can be seen in the upper panel of Fig. 2, when flash and moving bar were presented spatially and temporally aligned, the flash was judged to spatially lag behind the moving stimulus on a majority of the trials. This corresponds to a spatial misperception in the form of a flash-lag effect: The flash had to be spatially located 10.3° ($SE = 4.3^\circ$) ahead of the rotating bar in order to be perceived as being aligned at the same position as the bar, $t(12) = 8.42$, $p < .001$. This spatial shift of 10.3° corresponded to a delay of perception of the rotating bar relative to the flash of 34 ms ($SE = 14$ ms).

In the temporal judgment task, participants saw the change of the rotating bar as temporally lagging the onset of the flash: When the flash onset and the change of the moving stimulus were objectively simultaneous, the probability of reporting that the flash preceded the change of the rotating bar exceeded the expectancy value of $P = .5$. On average, the flash had to be presented 39 ms ($SE = 29$ ms) after the change of the rotating bar to be perceived as simultaneous. This temporal misperception—a temporal flash-lead effect—was also significant, as indicated by a mean PSE different from zero, $t(12) = 4.78$, $p < .01$.

If both the spatial and temporal misperceptions reflected the same underlying sequence of coding first the flash and then the rotating bar, the two misperception effects should be of equal magnitude. To test whether the temporal flash-lead and spatial flash-lag effects were of equal magnitude, we calculated the individual differences between the two misperception effects by subtraction of their time equivalents and performed a *t* test against zero with the difference values. The result of the *t* test was not significant: $t(12) = 0.55$, $p = .59$.

As can be seen in Fig. 2, however, the temporal task was more difficult than the spatial task. This is indicated by the fact that the average slope of the function was steeper in the spatial task (70 ms/inner quartile) than in the temporal task (15 ms/inner quartile). This slope difference was significant: $t(12) = 4.96$, $p < .01$. The steeper slope in the spatial task indicated better adherence with ideal performance (i.e., a step function) in that task than in the temporal task.

Discussion

In Experiment 1, we did indeed show that the same stimulus conditions that produced a spatial flash-lag effect also produced a temporal flash-lead effect. These results are in line with a sequential-coding explanation of the flash-lag effect: that participants first code the flash and delay coding of the moving object until it has moved farther along its

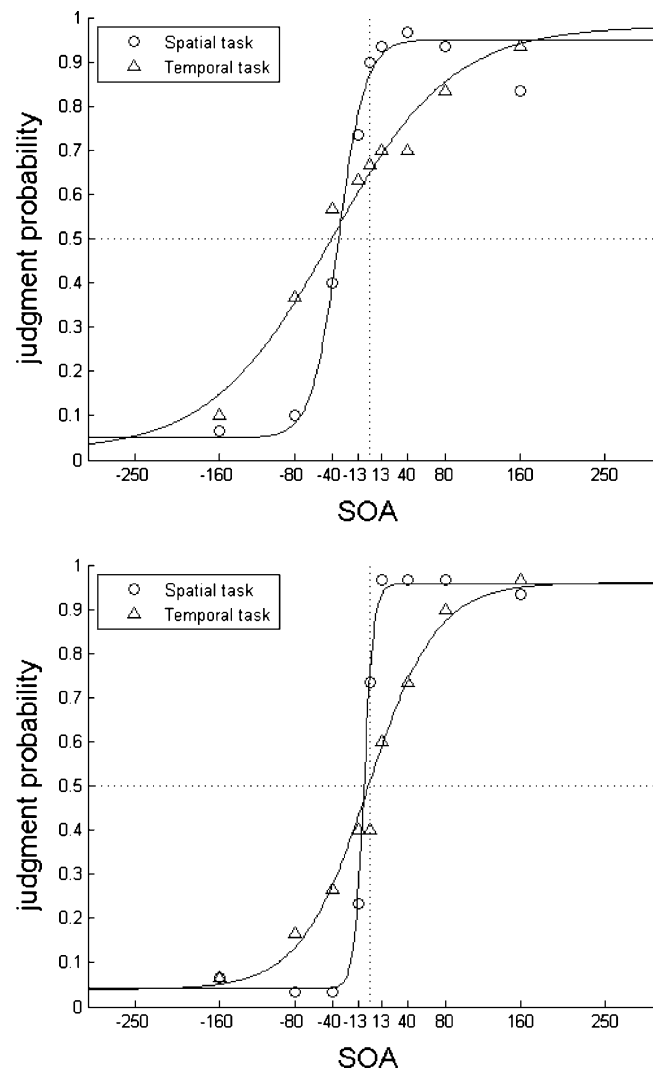


Fig. 2 Psychometric functions relating judgment probabilities on the *y*-axis to stimulus onset asynchronies (SOAs, in ms) on the *x*-axis, as a function of task (spatial or temporal) and experiment (Exp. 1, upper panel; Exp. 2, lower panel). In the spatial task, the *y*-axis depicts the probability of the judgment that the rotating stimulus was seen as shifted in motion direction (= flash was seen as shifted against the direction of the rotating stimulus), and the *x*-axis indicates the objective interval between the onset of the flash and the presentation of the rotating stimulus at the position of the flash. On the *x*-axis, a negative objective SOA in the spatial task means that the rotating bar objectively preceded the flash at the position of the flash. As can be seen, at the point of subjective equality (PSE; i.e., a judgment probability of $P = .5$) the SOA was negative in Experiment 1 (upper panel) but not in Experiment 2 (lower panel). This means a misperception in the form of a spatial flash-lag effect obtained in Experiment 1, but not in the control conditions in Experiment 2. In the temporal task, the *y*-axis depicts the probability of the judgment that the onset of the flash preceded the change of the rotating stimulus, and the *x*-axis shows the objective interval between the onset of the flash and the change of the rotating stimulus. On the *x*-axis, a negative objective SOA in the temporal task indicates that the visual change of the rotating stimulus objectively preceded the onset of the flash. As can be seen, at the PSE (judgment probability of $P = .5$) the SOA was negative in Experiment 1 (upper panel) but not in Experiment 2 (lower panel). This means a misperception in the form of a temporal flash-lead effect, obtained in Experiment 1 but not in Experiment 2

trajectory, which creates the impression that the flash lags behind. However, it is not yet certain whether sequential coding was indeed responsible for the spatial misperception. It could be argued that the sensory features of the rotating bar's motion (or position), on the one hand, and of the changes of the rotating bar, on the other hand, were not the same. For instance, theoretically, judgments about the position of the moving bar could always be based on the onset of the flash, but temporal judgments had to be based on the bar's offset at least for one revolution of the bar. Given the differences in the sensory features that could be used for the two different judgments, it is possible that the two illusions are based on different underlying mechanisms. At least, these differences make it difficult to link the temporal misperception of the change of the rotating bar closely to the spatial misperception created by the motion of the rotating bar.

Moreover, comparisons between the conditions are complicated by low-level feature differences between the conditions: First, note that the flash in Experiment 1 was white, whereas the bar was black. If processing a white flash is faster than processing a (change in a) black bar, the temporal precedence of the sensory processing of the white flash over the change in the bar could also account for the coding of the flash before the change of the bar. Second, the flash consisted of a fast onset–offset sequence, whereas the onsets and offsets of the bar were separated by a longer interval. If processing of an onset was faster than processing of an offset, or vice versa, participants could have always based their spatial judgments about the flash on the faster of these two features (e.g., onset of the flash), but would have been forced to base their temporal judgments about the change of the bar on the slower of the two features at least once per each trial (e.g., offset of segments).

What is needed to show that the temporal and spatial misperceptions are based on the same underlying mechanism is an additional joint manipulation of the illusions, this time with identical low-level features for the spatial and temporal decisions. This was done in Experiment 2.

Experiment 2

Experiment 2 critically tested whether the two misperceptions of a spatial flash-lag effect and a temporal flash-lead effect can be also manipulated in a predictable similar fashion (cf. Eagleman & Sejnowski, 2000a). Specifically, we expected that the sequence of first attending to the flash and then to the rotating stimulus should no longer be a preferred strategy when the moving bar stops at the time of the flash. This holds because if both flash and moving stimulus vanish at or near the point of their spatial

alignment, the offsets of both stimuli can equally serve as a signal to start encoding the relative positions of these stimuli. This should eliminate the temporal flash-lead effect and, as a consequence, the spatial flash-lag effect.

In line with the second of these predictions, Eagleman and Sejnowski (2000b), among others, showed that the spatial flash-lag effect indeed disappears when a rotating stimulus stops its motion (and offsets) near or at the very moment that the flash appears and disappears. However, Eagleman and Sejnowski (2000b) did not test whether a temporal flash-lead effect was also absent under these conditions. If we are right that the more variable sequential-coding strategies (of either first the flash and then the rotating bar, in some trials, or first the offset of the rotating bar and then the flash, in other trials) are responsible for the absence of the spatial illusion in stopped-motion conditions, the temporal flash-lead effect should be abolished together with the spatial flash-lag effect.

In Experiment 2, we tested this prediction by assessing temporal order judgments and spatial judgments when the flash was presented close to the offset of the moving bar. Deviating from the procedure of Experiment 1, the bar was always completely visible (never fragmented), and participants had to base their temporal order judgments and position judgments on the same event: the stopping of the bar.

In sum, according to the sequential-coding account, we expected that the flash-lead effect in the temporal judgments and the flash-lag effect in the spatial conditions would be eliminated in Experiment 2, because there would be no incentive to prioritize the flash (or the moving object) first and to always encode the position of one particular stimulus first. On the other hand, if the temporal misperception is unrelated to the spatial misperception, there would be no reason to expect that a manipulation that affected (here, eliminated) the spatial misperception should also similarly affect (here, eliminate) the temporal misperception.

Method

Participants A group of 15 new participants took part. All of them did the temporal and the spatial judgment tasks and had normal or corrected-to-normal vision, based on prior testing. Again, 2 participants had to be excluded because their judgments did not vary as a function of the SOA between the flash and the stopping and offset of the bar. The participants were naïve with respect to the experimental hypotheses and gave informed consent.

Apparatus, stimuli, design, and procedure These were identical to those aspects of Experiment 1, except for the following differences: The rotating bar did not change its

appearance but instead stopped its motion and vanished at or near the time of the onset and offset of the flash. In the temporal judgment task, the participants judged the onset of the flash relative to the stopping (or offset) of the bar.

Results

The data were treated as described in Experiment 1. Figure 2 (lower panel) depicts the results of the spatial and temporal judgment tasks. There was a small spatial flash-lead effect of 5.32 ms ($SE = 7.33$ ms) in the spatial judgment condition, and also a small temporal flash-lead effect of 4.88 ms ($SE = 17.81$ ms) in the temporal judgment condition. The spatial flash-lead effect was significant, $t(12) = 2.62$, $p = .02$, but the temporal flash-lead effect was not, $t(12) = 0.99$, $p = .34$. Both effects are too small to explain the results of Experiment 1 and are not within the range (or direction) of the typical flash-lag illusion.

Again, we found that the temporal task was more difficult (slope = 40 ms/quartile) than the spatial task (5 ms/quartile). This difference was significant, $t(12) = 3.76$, $p < .01$.

Discussion

According to the sequential-coding explanation, Experiment 1 resulted in a temporal flash-lead effect and a spatial flash-lag effect because the flash served as a temporal marker to start encoding the positions. This encouraged participants first to allocate attention to the flash and encode its position. As a result, encoding of the position of the moving object was delayed, so that it had traveled farther along the trajectory at the time that attention was finally allocated to it, leading to the spatial misperception that the flash was lagging behind the moving object. Both the temporal and spatial illusions were eliminated in Experiment 2 because both the stopping of the motion and the offset (or onset) of the flash could serve equally well as temporal markers to start encoding the positions of flash and moving object. Since there was no systematic preference for first encoding the position of one object over the other, both the temporal and spatial misperceptions were eliminated.

The sequential-encoding explanation certainly constitutes the most parsimonious explanation of the findings of Experiments 1 and 2. However, the findings so far do not necessitate an explanation in terms of preferential encoding: Since the main finding of Experiment 2 was a null effect, it is, for instance, still possible that the differential outcomes were driven by differences in low-level features that were present in Experiment 1 but were eliminated in Experiment 2. Experiment 3 critically tested a low-level explanation

against the attentional explanation proposed in the sequential-coding account.

Experiment 3

Experiment 3 provided a critical test of the sequential-coding account, by varying only the incentive to attend first to the flash versus the continuously rotating object, while keeping the low-level visual features identical across all conditions. Hence, if the previous findings of a temporal flash-lead effect and a spatial flash-lag effect were due to differences in the to-be-judged low-level visual features, then we would expect no differences between the temporal and spatial (mis)judgments in Experiment 3. If, on the other hand, the findings of Experiments 1 and 2 were due to sequential coding—here, the fact that the flash was processed with priority versus no priority—and this accounted for the spatial flash-lag effect and the absence thereof, respectively, in the two experiments, then Experiment 3 should show a markedly different result pattern: Specifically, when the stimulus conditions encouraged coding the position of the rotating object first, the flash should be perceived later in time, leading to a reversal of the spatial misperception of a flash-lag effect into a spatial flash-lead effect. If, on the other hand, participants were encouraged to first attend to the flash as the starting signal to begin encoding stimulus positions, the flash should then be perceived first, leading to a delay in the encoding of the rotating object and a spatial flash-lag effect.

This prediction was tested using a jumping (stroboscopically moving) bar as a substitute for the flash. Both the jumping bar and the moving bar travelled on aligned trajectories like the hands of a clock around a virtual hub at the screen center (see Fig. 3, lower right panel). To counterbalance the eccentricities of the stimuli, in Experiment 3a, the rotating bar travelled on the more eccentric trajectory and the flashed or jumping bar on the less eccentric trajectory, while in Experiment 3b, the trajectories were reversed. The rotating bar continuously travelled smoothly with 20 revolutions per minute (1 cycle/3 s). The flashed or jumping bar also revolved 20 times per minute. However, it did so in strobe motion, with an interval of 750 ms between its flashed static presentations at each of the four orthogonal cross-hair positions corresponding to 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock along the trajectories. These will be called the "comparison positions," because they were the only positions where the moving and jumping bars were spatially near enough to be compared to one another.

At the beginning, the jumping and continuously moving bars were shown with a spatial offset, and the participants' task was to adjust the interval between the flashed/jumping

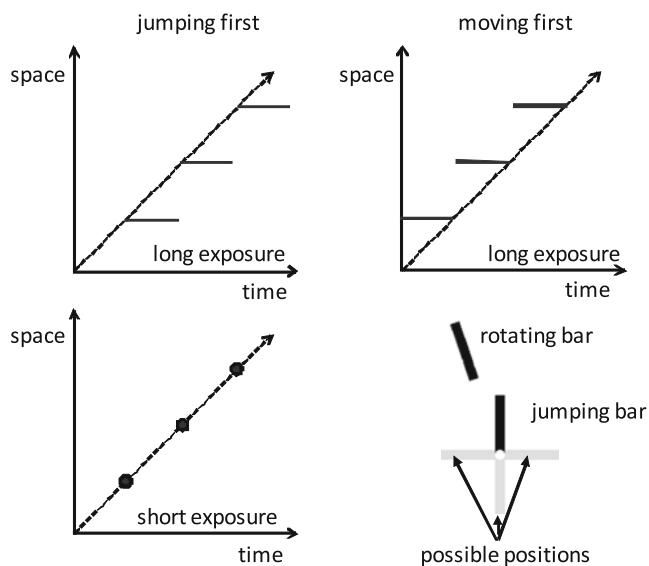


Fig. 3 Space-time plots (upper row and lower left panel) and schematic illustration (lower right panel) of the sequence of events in Experiment 3a. In the “code the jumping bar first” conditions, the jumping bar is only visible at a comparison position when the rotating bar has reached this position (upper left and lower left panels). In the “code the rotating bar first” condition, the order is the other way round (upper right panel): The jumping bar is visible at the comparison positions before the rotating bar has reached these positions. The lower right panel gives a schematic illustration of the stimuli and their sequence. The inner bar (black “jumping bar”) jumps from one cross hair to the next (referred to as “possible positions,” in gray, in the figure). The outer bar rotates smoothly with 20 rpm on a slightly larger circular trajectory. The task of the participants was to alter the timing between the two stimuli so that both bars would be perceived as exactly aligned at each cross hair (or comparison position) at the moment the inner bar jumped to this position or the outer bar passed this position. In this manner, we manipulated whether our participants would first code the jumping bar or the rotating bar. Participants pressed keys to vary the exact relative timing of the jumping and rotating bars. For further details, refer to the Method section. Experiment 3b was the same, but the eccentricities of the jumping bar and the rotating bar were reversed; that is, the jumping bar was presented in a slightly larger circular trajectory than the rotating bar. The stimuli are not drawn to scale

bar and the rotating bar until the flashed/jumping bar was perceived as being exactly aligned with the rotating bar.

Importantly, in both Experiments 3a and 3b, we manipulated the sequences of coding the two bars. In one blocked condition, the “code the rotating bar first” condition, the jumping bar was presented first at each comparison position and remained there for 750 ms, so that the rotating bar had to “catch up” with the flashed bar. The bars were objectively correctly aligned when their positions matched at the last refresh that the flashed bar was (still) at the comparison position, before it jumped to the next position. Accordingly, participants were instructed to align the interval of the rotating bar so that its position matched the position of the flashed bar directly prior to its offset.

In this condition, attention had to be deployed first to the moving bar, because its arrival was critical for making the required comparison. If, at a comparison position, attention was first deployed to the rotating bar and subsequently to the jumping bar, then perception of the jumping bar would be delayed, so that it would often have arrived at the next position by the time it was perceived. Hence, we would expect a reversal of the spatial misperception—that is, a spatial flash-lead effect—in this condition: Participants should create objectively positive intervals giving the rotating bar a head start over the flashed bar for the two bars to be perceived as aligned.

In the other two, “code the jumping bar first” conditions, the contingencies of the flashed and moving bars were reversed; now, the continuously moving bar preceded the onset of the flashed/jumping bar by almost 1/4th of the trajectory, so that the continuously moving bar arrived first at each comparison position and had almost reached the next comparison position before the offset of the flashed bar. Participants had to adjust the interval of the rotating bar until its position appeared aligned with the onset of the flashed bar at the comparison position: The stimuli were objectively correctly aligned when the position of the rotating stimulus matched the position of the flashed bar at the first refresh that it appeared at the comparison position. In this condition, attention should be deployed to the flashed/jumping bar, because it signals the possibility of making the required comparison, and speeded processing of the position of the flashed bar at its arrival was now critical for the decision.

If the flashed (or jumping) bar was attended first in the “code the jumping bar first” condition, perception of the rotating object should be delayed so that it would be perceived at a position farther along the trajectory. This in turn should result in the typical illusion of a flash-lag effect: To align the perceived locations of flashed and rotating bars at the comparison positions, participants should give the flashed bar a small objective head start over the rotating bar.

In one of the blocked “code the jumping bar first” conditions, we used jumping bars with a flash duration of 750 ms, to render the results compatible with the results of the “code the rotating bar first” condition, and in a second block, we used jumping bars with a flash duration of one frame or 16.6 ms. The latter condition was included as a control, to test whether judgments were biased toward the offset of the 750-ms flashed bar. Such a bias could easily account for the flash-lag effect in the condition in which the flashed bar was visible for an extended duration (e.g., the 750-ms condition) and only its onset position matched the position of the rotating bar. To ensure that the effect observed in the 750-ms condition reflected the classical flash-lag effect and not a bias to skew judgments toward the

offset of the flash, the results obtained in the long-presentation condition (750 ms) were compared to the results in the short-presentation condition, in which the bar was flashed only for a single frame. If the results did not differ between the conditions, we could be relatively certain that the judgments were based on the same features, the onsets of the flashed bars, in both presentation conditions of the “code the jumping bar first” condition.

Our manipulation proved to be so strong that it could easily be seen by virtually everyone (see <http://ppcms.univie.ac.at/fileadmin/usermounts/priessh9/jumpingDemo.html>).

Method

Participants of Experiments 3a and 3b Because everybody could see the illusion in our Web demo, only 5 voluntary observers, including the first author (H.-W.P.), were tested for an illustration of the effect. All had normal or corrected-to-normal vision, based on prior testing. Again, all gave informed consent.

Apparatus of Experiments 3a and 3b A PC with a 21-in. color monitor (Eizo Flexscan T 962) and a resolution of $1,024 \times 768$ pixels controlled the timing of the events and generated the stimuli. Event scheduling and response measurement were controlled by MATLAB and the Psychophysics Toolbox (Brainard, 1997). Control of gaze direction at the center of the screen was secured with an SMI RED-II eyetracker.

Stimuli of Experiment 3a See also Fig. 3. The stimuli were white bars (94 cd/m^2) on a dark gray (4 cd/m^2) background. The viewing distance was 83 cm. Both bars had a length of 1.62° and a width of 0.27° circling around (and pointing toward) screen center. The jumping bar was presented on a less eccentric trajectory and the rotating bar was shown on a more eccentric trajectory: The jumping bar’s less eccentrically presented end was centered on the screen, whereas the rotating bar’s less eccentrically presented end was shown with a 2.16° distance from the screen center. Thus, there was a 0.54° -wide gap between the more eccentric end of the aligned jumping bar and the less eccentric end of the rotating bar. Both bars travelled clockwise around the screen center with a speed of 20 cycles per minute. The rotating bar moved smoothly across the screen: It was shown at adjacent positions on its motion trajectory, with an SOA of 16.6 ms and an interstimulus interval (ISI) of 0 ms between its successive presentations. In different blocks of the “code the jumping bar first” condition, the jumping bar was presented for either 750 ms (with an ISI of 0 ms) or flashed for 16.6 ms (i.e., one

refresh of the computer screen) and an SOA of 750 ms at the four comparison positions on its motion trajectory—at the 12 o’clock, 3 o’clock, 6 o’clock, and 9 o’clock positions. In the “code the jumping bar first” conditions, the rotating bar was almost at a comparison position when the jumping bar caught up with the rotating bar to complete the pair of bars at a comparison position. In a final, blocked “code the rotating bar first” condition, the jumping bar was always presented first at a comparison position (for a duration of 750 ms in total), and the rotating bar completed the pair of bars at this position.

Stimuli of Experiment 3b Everything was exactly the same as in Experiment 3a, but the rotating bar was shown on the less eccentric trajectory and the jumping bar was shown on the more eccentric trajectory. (Our expectations were the same as in Exp. 3a. If the same results were observed in Exps. 3a and 3b, we could rule out that eccentricity differences accounted for the expected results.)

Procedure of Experiments 3a and 3b A block started with a nine-point eyetracker calibration. If a participant failed to fixate on the center of the screen during a trial, the trial was discarded and repeated at a later point of the experiment. Each of the two “code the jumping bar first” conditions (with 750-ms and with 16.6-ms durations of the jumping bar, respectively) and the “code the rotating bar first” condition were presented in separate blocks. Block order varied randomly between participants. In the “code the jumping bar first” conditions, participants had to wait for the jumping bar to complete a pair of bars for a judgment of the bars’ alignment, and in the “code the rotating bar first” condition, participants had to wait for the rotating bar until they could judge the bars’ relative positions.

Each block started with an instruction for the following task and three warm-up trials, during which fixation was successfully held at screen center and the temporal interval was adjusted. After the warm-up, the answers from 16 trials per condition were recorded for analysis. At the outset of each trial, the two bars were presented with a temporal asynchrony of $1/4$ revolution at the comparison positions, and the participant’s task was to adjust the interval between the two bars so that the rotating and jumping bars were perceived as aligned at the comparison positions. In all conditions, participants pressed a right key to increase the temporal interval between the two moving bars and the left key to reduce the temporal interval. After perceiving both bars aligned at the comparison positions, the participant pressed the space bar to confirm that he or she saw the bars as aligned, and the next trial began with the rotating bar either temporally leading or lagging the jumping bar.

Participants were not instructed to explicitly code either the jumping/flashed bar or the rotating bar first. Instead, the different orders of sequential coding were suggested by the way that the stimuli were presented to the participants, with either the jumping bar or the rotating bar completing the pair of stimuli at a comparison position.

Eye movement control in Experiments 3a and 3b Sometimes spatial illusions, such as the flash-lag effect, can be altered by and confounded with eye movements. This does not seem to be the case with the present procedure (compare with the Web demo), but as a security measure, we recorded eye movements. Trials on which the measured gaze position deviated by more than 0.81° from the center of the fixation point were discarded and later repeated.

Results

Results of Experiment 3a Spatial misperception was inferred from the participants' created (or selected) objective temporal intervals between the two bars (the rotating and jumping bars) for their perception of spatial alignment of the two bars. For the results, see also Fig. 4.

As expected, in the “code the jumping bar first” conditions, a spatial flash-lag effect was found, and participants had to compensate for the delayed perception of the rotating bar, so that the mean intervals were negative. With the long presentation of the flashed bar (750 ms), participants created a mean interval of -85.93 ms ($SD = 33.75$ ms; within-participants $SD [SD_{\text{within}}] = 33.48$ ms), and in the short-presentation condition (16.6 ms), they created an interval of -51.08 ms ($SD = 17.42$ ms; $SD_{\text{within}} = 22.56$ ms). This means that in the “code the jumping bar first” conditions, the rotating bar had to be presented at least 51 ms prior to the jumping or flashed bar at the comparison positions for the participants to perceive both bars as aligned at these positions.

By contrast, in the “code the rotating bar first” condition, the mean interval was 50.23 ms ($SD = 21.33$ ms; $SD_{\text{within}} = 31.43$ ms). This means that, as expected, the jumping bar had to be presented 50 ms before the moving bar at the comparison positions for the participants to perceive the two moving bars as spatially aligned at these positions.

Results of Experiment 3b Experiment 3b replicated these results. In the long-presentation condition (750 ms) of the “code the jumping bar first” condition, the rotating bar had to precede the jumping bar by an interval of -66 ms ($SD = 19.33$ ms; $SD_{\text{within}} = 22.65$ ms), and with the short presentation duration (16.6 ms), the rotating bar had to precede the jumping or flashed bar by -54.33 ms ($SD =$

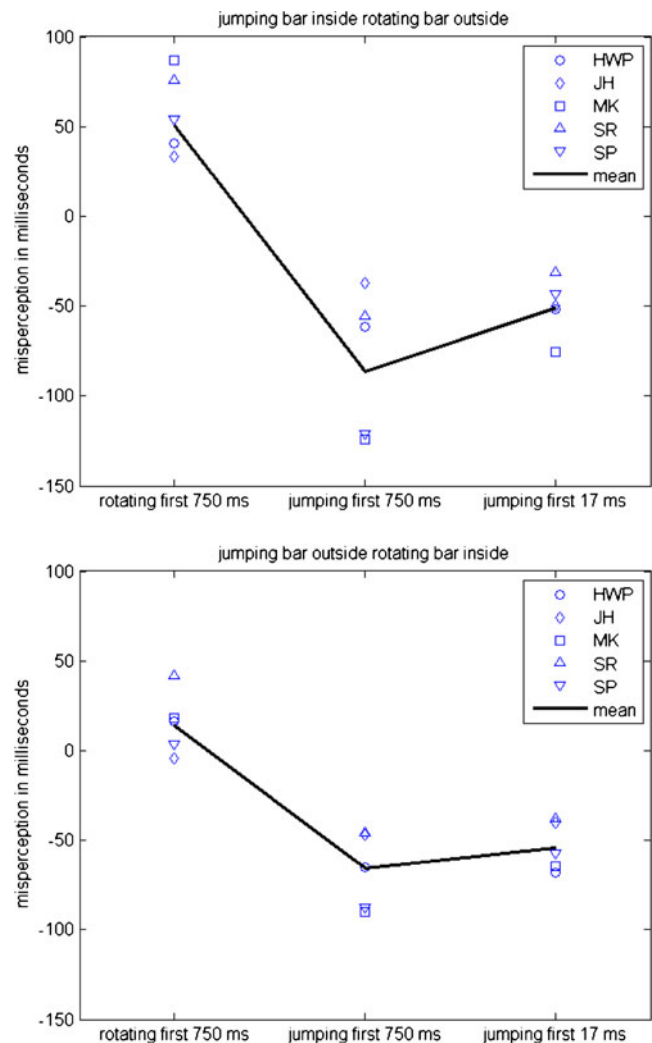


Fig. 4 Participants' average created intervals between the jumping bar and the rotating bar for their perception of both bars as aligned. Individual values represent the mean values of 16 measurements. The black line shows the mean values of all 5 observers. (Upper panel) Results of Experiment 3a. In the “code the jumping bar (750 ms) first” condition, the rotating bar had to precede the jumping bar by an average of 86 ms to be perceived as aligned with the jumping bar. This means that the rotating bar was perceived with a delay of 86 ms. Correspondingly, in the “code the jumping bar (16.6 ms) first” condition, the rotating bar was perceived with a delay of 51 ms. By contrast, in the “code the rotating bar first” condition, the jumping bar rather than the rotating bar was perceived with a delay of 50 ms. (Lower panel) Results of Experiment 3b. In the “code the jumping bar (750 ms) first” condition, the rotating bar was perceived with a delay of 66 ms. In the “code the jumping bar (16.6 ms) first” condition, the rotating bar was perceived with a delay of 54 ms. By contrast, in the “code the rotating bar first” condition, the jumping bar was perceived with a delay of 14 ms

14.08 ms; $SD_{\text{within}} = 19.39$ ms) for the two bars to be perceived as spatially aligned at the comparison positions.

By contrast, in the “code the rotating bar first” condition, the jumping or flashed bar had to precede the rotating bar by 13.95 ms ($SD = 17.17$ ms; $SD_{\text{within}} = 40.18$ ms).

Discussion

Experiment 3 showed that sequentially coding two different bars, one rotating and one flashing, in turn can cause a spatial misperception of the relative location of the rotating bar. This was evident from the fact that we were able to manipulate the direction of the spatial misperception by forcing the participants to code first either the flashed/jumping bar or the rotating bar at a particular position. If the participants coded the rotating bar first and then the flashed/jumping bar, a reversed spatial misperception to the typical flash-lag effect, a spatial flash-lead effect, was observed. Only if the participants coded the flashed/jumping bar first and then the rotating bar was the rotating bar seen as shifted in the direction of its motion. These spatial misperceptions are almost certainly a consequence of differences in the orders in which the bars were sequentially attended.

The different judgment conditions were absolutely identical in terms of their low-level features. This rules out any alternative explanation of the spatial misperception in terms of other latency differences, such as in the processing of the bars' visual low-level features. In line with this conclusion, the few low-level features that discriminated between the two stimuli to be compared in the present experiment, such as their exact eccentricity, their continuity of motion, and their overall duration affected the size of the misperception, but not its direction. The direction of the misperception effect—that is, whether a negative or positive interval was created for the participants' perception of spatial alignment—was governed solely by the sequence of coding the two bars. By exclusion of the alternative explanations in terms of sensory differences as the responsible factors for the sequence of coding the bars, the results thus supported the assumption that the sequence of first attending to one stimulus and then the other must have created the spatial misperception.

This interpretation could be criticized on grounds that the task differed between the two conditions. Participants had to align the position of the rotating bar with the jumping bar just prior to its offset in the “code the rotating bar first” condition, whereas they had to align it with the jumping bar's first refresh (or onset) at a comparison position in the “code the jumping bar first” condition. It might thus seem that the different results could be due to the stronger or weaker potential of the jumping bar to capture attention, because past research has seemingly demonstrated a unique role of onsets for capturing attention in a stimulus-driven way (cf. Yantis & Jonides, 1984). This, however, is unlikely. First of all, subsequent studies have shown that offsets have a strong potential to capture attention, too: If the onsets are task-relevant, they capture attention, and if the offsets are task-relevant, they capture

attention instead (Atchley, Kramer, & Hillstrom, 2000). Secondly, in line with this flexibility of attentional control (and more to the point), Baldo, Kihara, Namba, and Klein (2002) tested the flash-lag effect in response to a flash of a duration of a single refresh and in response to a stationary object's onsets and offsets, and they found a flash-lag effect across all three conditions, with an even larger flash-lag effect in the offset condition. These results demonstrate that the effects were not due to the difference of aligning the onset versus offset with the position of the rotating bar.¹

However, one observation in Experiment 3 was not expected: The spatial misperception in the “code the rotating bar first” condition was stronger in the conditions in which the rotating bar was at a more eccentric position on the screen. If the rotating bar was presented less eccentrically, the necessary interval to compensate for the earlier coding of the rotating bar was significantly smaller (13 ms) than when the rotating bar was presented more eccentrically (50 ms), $t(4) = 4.06$, $p = .02$. Two possible explanations can conceivably account for this difference: First, it is possible that this effect was due to metacontrast masking, which has been reported to be weaker for less eccentric positions and increases with more eccentric stimulus positions (cf. Bridgeman & Leff, 1979). More effective masking of preceding stimulus positions by subsequent stimulus positions on the motion trajectory is known to contribute to the misperception of moving stimuli (cf. Kirschfeld & Kammer, 1999) and would have further delayed perception of the position of the moving object, increasing the illusion of a spatial offset. Second, it is possible that the flash-lag effect was reduced because the moving bar had a lower tangential velocity when it was presented nearer to the screen center, and correspondingly, may have appeared less displaced (Nijhawan, 1994).

General discussion

In the first experiment, we showed that a spatial misperception, such as the flash-lag effect, co-occurs with a temporal misperception. Experiment 1 revealed that, in the typical stimulus conditions of a flash-lag effect, our participants perceived a flash as temporally preceding a concomitant change of a continuously rotating bar when the

¹ The findings of Baldo et al. (2002) are also consistent with the present findings, since participants in the previous study were not instructed to attend to the moving object, but presumably attended first to the offset. Moreover, in Baldo et al.'s study, the offsetting bar did not reappear at a future position of the trajectory, as was the case in the present study, so there was no chance that delayed perception of the jumping bar would result in the perception of the flash leading the object. Hence, the present findings can be safely attributed to the differences in the orders in which objects were sequentially coded or attended.

rotating bar was perceived to be spatially shifted in the direction of its motion. These results are in line with the assumption that sequential coding of flash and moving stimuli, such as in an attentional account, could be responsible for the spatial misperception. According to an attentional account, for example, the flash is usually attended first because it is presented only very briefly and thus signals task onset. This leads to its coding before that of the moving stimulus at or near its position. As a consequence, perception of the moving stimulus is delayed so that it is seen shifted in its motion direction, either because the earlier flash serves as an onset signal for an integrated perception of the moving stimulus over a few successive frames (cf. Eagleman & Sejnowski, 2000b) or because deploying attention to the flash facilitates perception of the flash but delays perception of the moving stimulus (cf. Baldo & Klein, 1995).

In the second experiment, we demonstrated that the temporal and spatial misperceptions not only co-occur but can be jointly manipulated in a predictable manner. Both of the misperception effects vanished when the stimulus conditions did not favor only one particular sequence of coding the two stimuli. In this condition, the flash and the rotating bar were presumably coded either simultaneously or sequentially, where the order of coding randomly varied between trials. The fact that the flash lag disappeared alongside the temporal misperception suggests that the flash-lag effect could indeed be due to sequential coding of the flash and the rotating bar. The corresponding preference for one type of sequential coding disappears when there is no clear incentive to code the position of only one stimulus prior to the other.

In the third experiment, we showed that the position of a rotating stimulus can be perceived as lagging or leading a jumping (or flashed) bar when in fact the two stimuli are objectively spatially aligned. Experiment 3 revealed that the sequence of coding the flashing versus the rotating bar was critical for the direction of the misperception (i.e., spatial flash-lag effect or spatial flash-lead effect, respectively). When the jumping bar was presented first at each comparison position and the rotating bar had to catch up with it, the movement of the rotating bar towards the comparison position was critical for the task, and therefore attention was mainly allocated to the rotating bar. In this condition, coding the rotating bar first delayed perception of the jumping bar, resulting in a spatial flash-lead effect. When the rotating bar was presented first at the comparison positions and the jumping bar had to catch up with it, the jumping bar was the critical stimulus and, hence, was first and foremost attended. Sequential coding of the jumping bar first and of the rotating bar afterward delayed perception of the rotating bar, creating a spatial flash-lag effect.

The present study is therefore in line with the explanation of the spatial misperception in terms of a sequence of coding first the flash and then the rotating bar—for example, by prior entry of an attended flash and a concomitant delay of the perception of a rotating stimulus, or in the form of an onset signal provided by the first-attended-to flash for the integration of visual information from the rotating stimulus and just after the onset of the flash. However, we cannot tell whether attention caused the spatial misperception by serving as a point of reference for the start of the integration of visual information from the moving bar over a few successive displays, or by being a necessary precondition for the perception of the moving bar. The present experiments do not allow us to distinguish between these two alternative explanations.

For a long time, it has been claimed that the sequential coding of stimuli based on a sequence of attending first to one and then to another stimulus, position, or feature could be responsible for the participant's percept of visuospatial input (cf. Titchener, 1908; see also Neumann & Niepel, 2004; Scharlau, 2002; Scharlau & Ansorge, 2003; Scharlau, Ansorge, & Horstmann, 2006). However, it has proven difficult to show that the sequence of sequential coding by successive attentional focusing could be responsible for spatial (mis)perceptions. The results of the present study clearly demonstrate that spatial misperceptions can arise from differences in allocating attention alone, and thus confirm earlier attentional explanations of diverse visual illusions (cf. Baldo et al., 2002; Baldo & Klein, 1995; Chappell, Hine, Acworth, & Hardwick, 2006; Müsseler & Aschersleben, 1998).

Specifically, it could be argued that previous results can partly be explained by reference to processing latencies between confounded low-level visual features (cf. Kirschfeld & Kammer, 1999; Nijhawan, 1994; Nijhawan, Watanabe, Khurana, & Shimojo, 2004; Ögmen, Patel, Bedell, & Camuz, 2004; Purushothaman et al., 1998). The same could be said, for example, of the first two experiments of the present study. Although, together, Experiments 1 and 2 were also suggestive of a contribution of sequentially focusing attention to a spatial misperception, such as the flash-lag effect, we noted that there were also subtle sensory feature differences between the flash and the rotating stimulus (which are typical of flash-lag experiments), and these may have contributed to the observed effects. For example, the contrast signs of the flash (white) and of the rotating stimulus (black) were different, and the flash always consisted of temporally proximal on- and offsets, but the moving stimulus change consisted of only an on- or offset at a particular point in time. Previous studies have indicated that such differences can contribute to spatial misperceptions, such as the flash-lag effect (cf. Gauch & Kerzel, 2009; Sheth, Nijhawan, & Shimojo, 2000; Whitney, Murakami, & Cavanagh, 2000). In

fact, we accidentally confirmed one of these perceptual factors, eccentricity, as an additional contributor to the percept in the “code the rotating stimulus first” conditions of Experiment 3 (e.g., Baldo et al., 2002; Kirschfeld & Kammer, 1999).

Such confounding low-level feature differences, however, were absent in the present Experiment 3, because the experimental conditions differed only in the order in which the stimuli arrived at a particular comparison position, whereas all of the low-level features were either identical or balanced across Experiments 3a and 3b. Thus, the large spatial misperceptions in Experiment 3 were undoubtedly caused by the sequence of coding first the jumping or the rotating stimulus. These results indicate that differences in the deployment of attention may also play a more important role in visual illusions than is currently appreciated.

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Chapter 4: Saccadic Inhibition of Return After Attention Shifts to Relevant and Irrelevant Color Singletons.

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Saccadic Inhibition of Return After Attention Shifts to Relevant and Irrelevant Color
Singletons

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Abstract

We tested whether color singletons lead to saccadic and manual inhibition of return (SIOR and IOR) and whether SIOR and IOR depended on the relevance of the color singletons. In altogether four experiments (Experiments 1 to 4), we observed SIOR after color singletons, and in one additional experiment we also found IOR under very similar conditions (Experiment 5). Across experiments, SIOR and IOR increased with reaction time (RT) and tended to be stronger with long (Experiment 1) than short intervals (Experiment 2 to 5) between color singleton and saccade target. In addition, stronger SIOR after irrelevant than relevant singletons was only found when the interval between color singleton and saccade target was relatively short (Experiments 3 and 4). Together, the results shed light on some factors responsible for SIOR and help to understand some inconsistencies in the literature on top-down contingent capture of attention and its relation to SIOR.

Saccadic Inhibition of Return After Attention Shifts to Relevant and Irrelevant Color
Singletons

Visual foraging behavior benefits from a track record of recently inspected locations. One way how this could be achieved is inhibition of return (IOR; Wang & Klein, 2010). IOR was first described by Posner and Cohen (1984) as the inhibition of shifting attention back to a previously already inspected location. These authors observed that presenting a peripheral cue before and at the position of a relevant target facilitated discrimination of the target with a brief cue-target onset asynchrony (CTOA) but turned into inhibition of target discrimination with longer CTOAs. IOR for cues at the same position (SP) as the target was found relative to cues at a different position (DP) than the target. This result is typical of unpredictable cues that do not inform about the target’s most likely position.

Posner and Cohen speculated that the cue captured attention. This was held responsible for the faster discrimination in SP than DP conditions with a short CTOA. After sufficient time had passed, however, the participants withdraw their attention if no relevant target had been presented at the cued location. According to Posner and Cohen, the participants must have used some of the long CTOA to even inhibit returning of their attention to the previously inspected location (therefore the name IOR). Subsequent research revealed that components besides attention capture, such as motor inhibition and sensory habituation, can also contribute to IOR (for reviews, see Klein, 2000; Lupiáñez, 2010; Wang & Klein, 2010).

Importantly in the present context, IOR also figures prominently in one of the large debates in attention research – the question as to what extent attention capture is top-down contingent (cf. Folk, Remington, & Johnston, 1992) versus stimulus-driven (or bottom-up; cf. Theeuwes, 1992, 2010). According to Folk and colleagues, only cues (and distractors) with a relevant feature that matches the participants’ top-down controlled set of searched-for target

features, capture attention. Folk et al. based their conclusion on experiments with two sorts of unpredictable cues. They used either one colored (red) cue as a color-singleton together with three white cues, or a single abrupt-onset cue. Both of these types of cues were presented with the same CTOA before the relevant target and both types of cues were equally likely at the same position (SP condition) as the target as at any of three different positions (DP condition) than the target.

Critically, in one block, the participants searched only for abrupt-onset targets, whereas in the other block, they searched only for color-defined (red) target singletons. In line with Folk et al.'s conception of top-down contingent capture, only the cue with a top-down matching feature captured attention. If the participants searched for onset targets, only the onset cue captured attention. However in the same onset-target conditions, the color cue failed to capture attention. This pattern of results was reversed when the participants searched for a color-defined target: Here, the color-singleton cue captured attention but the abrupt-onset cue failed to capture attention. Later research showed that even the cue's color has to exactly match the set of searched-for target colors (cf. Anderson & Folk, 2010; Folk & Remington, 1998; Lamy, Leber, & Egeth, 2004). If the participants search for red targets, a red cue but not a green cue captures attention but if the participants search for green targets, a green cue but not a red cue captures attention (e.g., Ansorge, Kiss, Worschech, & Eimer, 2011; Eimer & Kiss, 2008; Worschech & Ansorge, in press; for a review see Burnham, 2007).

By contrast to the top-down contingent capture theory, according to Theeuwes (2010), any strong feature contrast (e.g., color contrast) as well as any strong feature singleton, be this contrast or singleton now task-relevant or irrelevant, captures attention as long as the feature contrast is salient enough (e.g., Itti, Koch, & Niebur, 1998; Schreij, Theeuwes, & Olivers, 2010). For example, Schreij et al. (2010a) adapted the experimental protocol of the color-search conditions of Folk et al. (1992): Together with the color-defined target or else during the CTOA, Schreij and colleagues presented one additional abrupt-onset singleton as an

irrelevant distractor at a position away of the target (Schreij, Owens, & Theeuwes, 2008; Schreij et al., 2010a). These authors observed that the abrupt-onset distractor delayed the discrimination of the color-defined target. This delay was observed relative to a condition without an additional onset distractor. Schreij et al. (2010a) argued that the abrupt onset must have captured attention away from the color-defined target (just as a DP cue) although the distractor was completely task-irrelevant (or non-matching in the terminology of Folk et al.). Moreover if the abrupt-onset distractor was presented during the CTOA but with an interval of 900 ms before the color-defined target, the DP distractor's interfering effect had dissipated, just as if attention had been deallocated from the abrupt-onset distractor during this longer interval (Schreij, Theeuwes, & Olivers 2010b).

This latter observation fits perfectly with Theeuwes, Atchley, and Kramer's (2000) more general argument that all the null capture-effects of non-matching cues that were typically found in contingent-capture experiments à la Folk et al. reflected swift deallocation of attention after initial capture of attention by irrelevant cues. To understand this, remember that the cues in the contingent-capture studies (e.g., Folk et al., 1992) were usually unpredictable of the target position. Therefore, there is no incentive for the participants to maintain attention at a cued location, whereas deallocation of attention away from the cues was generally encouraged. In addition, according to Theeuwes et al., the brief CTOA of 150 ms that is commonly used in contingent-capture experiments (cf. Folk et al., 1992) is assumed to be already long enough for (1) attention capture by matching *and* non-matching cues and (2) for *deallocation only after the non-matching cues*. With the matching cues, deallocation is delayed because a higher cue-target resemblance makes cue recognition more difficult. As a consequence, with a short enough CTOA traces of capture can still be seen in top-down matching conditions but no longer in the non-matching conditions.

When this deallocation hypothesis was tested, the results were not always in line with it (e.g., Ansorge et al., 2011; Gibson & Amelio, 2000; Remington, Folk, & McLean, 2001;

Worschech & Ansorge, in press). Of particular relevance with respect to IOR, Gibson and Amelio (2000) used longer CTOAs of 1 s in the experimental protocol of Folk et al. (1992). In this study, IOR was neither observed after matching nor after non-matching color-singleton cues (for the latter result, see also Pratt & McAuliffe, 2002). These researchers only found deallocation in the form of IOR after abrupt-onset cues. In addition, IOR was only found for task-relevant abrupt-onset cues that matched the top-down search set and that also captured attention with a short CTOA. By contrast, with the longer CTOA, there was no IOR after the non-matching abrupt-onset cues (and there was no initial capture by these cues either).

Jointly, these findings are in disagreement with Theeuwes et al. (2000; Theeuwes, 2010) because the deallocation explanation predicts IOR after non-matching cues, and in fact the deallocation explanation predicts an even earlier onset of IOR after non-matching than after matching cues. Remember that deallocation after matching cues was assumed to trail behind deallocation after the non-matching cues. Therefore, until today researchers doubt the truth of the disengagement hypothesis (cf. Lamy, 2010).

These conflicting results were the point of departure for the present study. We wanted to test two critical predictions of Theeuwes et al.'s (2000) deallocation explanation. We aimed at testing whether IOR is found after color singletons and we wanted to test the further question whether IOR is stronger after non-matching (or irrelevant) color-singleton cues than after matching (or relevant) color-singleton cues. Evidently, the failure to observe the predicted pattern in prior research (cf. Gibson & Amelio, 2000) necessitated some procedural changes. In comparison to previous studies, we therefore took three measures to more thoroughly investigate IOR after matching and non-matching color singletons. First, across our experiments we used different CTOAs because with a single CTOA (e.g., Gibson & Amelio, 2000) IOR could easily be missed altogether.

Second, we used saccadic IOR (or SIOR; Abrams & Dobkin, 1994; Dorris, Klein, Everling, & Munoz, 2002; Taylor & Klein, 1998) because manual responses are not as

sensitive for IOR as saccades. In general, SIOR can be found in conditions where manual IOR is still absent. For example, a small SIOR effect of -5 ms was found even after relevant color singletons by Godijn and Theeuwes (2004; Exp. 2). This compares to the overall lack of IOR with color singletons in Gibson and Amelio. Related, SIOR can also be found with shorter CTOAs than manual IOR (Briand, Larrison, & Sereno, 2000). In fact, with eye movements deallocation occurs so rapidly as to temporarily overlap with bottom-up capture (of the eyes) (Born, Kerzel, & Theeuwes, 2011). SIOR thus provides a more exhaustive measure of IOR than manual responses.

Third, with a single mean latency score of all responses, the more subtle dynamics of how capture and IOR unfold over time can be overlooked (cf. van Zoest, Donk, & Theeuwes, 2004). Therefore, we vincentized our response latencies. Vincentizing yields mean saccadic response times (SRTs) for different percentiles of the SRT distribution, from fast to slow responses. Because IOR increases over time, a more exhaustive picture of how deallocation develops is provided by looking at SIOR in different percentiles of the SRT distribution (cf. van Zoest et al., 2004).

Experiments 1 to 4

The basic manipulation in the following experiments concerned the relation between cue and target position. When the cue was presented at a different position than the subsequent saccade target (DP trials), SIOR predicts faster responses than when the cue was presented at the same position as the subsequent saccade target (SP trials). The cue position did not predict the target position which encouraged the deallocation of attention after the cue.

Further, we manipulated whether the cue was relevant or irrelevant. In half of the trials, the color of the cue told participants to keep its position in mind for later target discrimination. At the beginning of the remaining trials, our participants could ignore the cue. Relevant and irrelevant cues had different fixed, known colors so that the participants could

set their control settings to attend to the relevant cues and to ignore the irrelevant cues.

Relevant and irrelevant cues thus corresponded to top-down matching and non-matching color cues in past research in so far as the relevant cue matched the search settings for the relevant colors and the irrelevant cue did not match these search settings.

To investigate the dynamics of SIOR, we looked at different parts of the SRT distribution (van Zoest et al., 2004). We rank ordered the correct SRTs from fastest to slowest and divided the resulting distribution into equally sized quintiles. This was done separately for each individual's combination of SP and DP conditions and relevant and irrelevant cues. The mean SRT of each quintile was then calculated and submitted to an analysis of variance (ANOVA) with the variables cue type (relevant vs. irrelevant), cue position (SP: same position as target vs. DP: different position than target) and quintile (first to fifth).

If the participants deallocated their attention after the color-singleton cues, we expected SIOR (i.e., slower SRTs in SP than DP conditions). Also, if deallocation is faster in irrelevant-cue than relevant-cue conditions, SIOR was expected to be stronger with the irrelevant color cues than with the relevant color cues, and SIOR might take effect at an earlier point in time (among faster SRTs, here: in a lower quintile) with irrelevant than relevant cues. However, it may also be possible that relevant color singletons capture attention but do not lead to subsequent SIOR (cf. Gibson & Amelio, 2000).

Finally, the CTOA was varied between Experiments. The CTOA in Experiment 1 was 500 ms. Experiment 2 used a shorter CTOA of 300 ms, and Experiments 3 and 4 used a CTOA of 200 ms. In addition, Experiment 4 used the same color for the relevant cues as for the saccade target. This was done to keep the search set of relevant colors simpler than in the other experiments because prior research has shown that participants can encounter difficulties keeping their top-down search set for a particular color if they have to search for more than one color at the same time (cf. Folk & Anderson, 2010).

Method

Participants. Ten participants (5 female), 14 (10 female), 10 (5 female), and 13 (10 female), mostly students, with mean ages of 25, 23, 21, 25, and 23 years participated in Experiments 1 to 4, respectively, in exchange for course credit. All participants reported normal or corrected-to-normal visual acuity.

Apparatus of Experiments 1 to 4. Visual stimuli were presented on a 19-inch CRT color monitor (Sony Multiscan G400) with a screen resolution of 1,024 × 768 pixels. Its refresh rate was 100 Hz. The participants sat at a distance of 57 cm from the screen in a quiet, dimly lit room, with their head resting in a chin rest to ensure a constant viewing distance and a straight-ahead gaze direction. Manual responses for the discrimination of the discrimination targets were registered via a standard keyboard, placed directly in front of the observers. Participants' manual responses were given by the keys #F and #J (labeled “left” and “right”). Saccades were recorded with an EyeLink 1000 Desktop Mount system (SR Research, Mississauga, Ontario, Canada) with a 35mm lens, and EyeLink Software version 4.52, sampling at maximal resolution. Eyetracking was monocular from the dominant eye. A 9-point calibration was used to adjust the eyetracker before the experiment and in advance of every single block.

Stimuli. See also Figure 1. All stimuli were lighter ($\sim 30 \text{ cd/m}^2$) than the dark background ($\sim 0.2 \text{ cd/m}^2$). The stimuli in the cue and saccade-target displays consisted of six digital figure-8s of a size of $1.7^\circ \times 1.0^\circ$ with a stroke width of 0.3° . The figure-8s were positioned at 0° , 60° , 120° , 180° , 240° , and 300° from the vertical meridian on a virtual circle around the center with an eccentricity of 7.0° . The top-most and lowest position were only used as filler positions and never contained the cue or the target. The color singleton in the cue display was either green (CIE color coordinates: -30.2, 24.9) or blue (CIE: 46.9, -89.0). During the entire experimental session, one of these colors indicated that the cue was relevant while the other color indicated that it was irrelevant. With the exception of Experiment 4, the

color singleton in the target display was red (CIE: 47.6, 41.1). Note that the color of the cue singleton (green or blue) was always different from the target singleton (red) in Experiments 1 to 3, but that it was of the same color as the relevant singleton cue in Experiment 4. All other stimuli were grey (CIE: 6.9, 16.8). A third, target-discrimination display was only shown in trials with relevant cues (50% of all trials). To create distinct forms, one vertical line of each of the six figure-8s was deleted so that three digital letter-Es and three digital figure-3s replaced the six figure-8s. In the discrimination-target display, all stimuli were grey.

Procedure. At the very beginning of every trial, a fixation cross ($0.7^\circ \times 0.7^\circ$) was shown in the center of the screen. Participants started a trial by looking at the fixation cross and pressing the space bar. At this point in time, a drift correction of the eye-tracking signal was conducted if the currently measured eye position deviated by more than 1.5° of the previous trial's measured eye fixation at screen center. In addition, eye position was visually monitored by the experimenter. After this, the fixation display persisted for another 500 ms. Next, the cueing display was shown for 50 ms. After the CTOA, the target display was shown and observers made a saccade to the red color singleton. The CTOA varied between experiments from 500 to 200 ms. The saccade target display was shown until saccade onset was measured or until 1 s had elapsed.

----- Insert Figure 1 about here -----

In the **same-position (SP) trials**, the saccade target was shown at the cued position. In the **different-position (DP) trials**, the saccade target was shown at an uncued position. Because saccade-target positions and cue positions were uncorrelated, SP trials made up for 25% and DP trials for 75% of all trials.

In the **relevant-cue trials**, the color cue indicated the position of the discrimination target in the final discrimination-target display. Participants therefore had to attend to the cue's position and keep it in mind for later retrieval of the discrimination-target's position.

The participants signaled the identity of the discrimination target by key-press. In the **irrelevant-cue trials**, the color cue could be ignored. No discrimination-target display was shown and no manual discrimination response was required at the end of the trial. Relevant and irrelevant cues had different colors (green and blue, respectively) and participants were informed at the beginning of the experimental session which color belonged to the relevant cue and which belonged to the irrelevant cue.

The experiment consisted of one training block, and four data-acquisition blocks. Every block consisted of 64 trials. Every block thus corresponded to one repetition of each of the two cue types (relevant cues; irrelevant cues) $\times$ four cue positions $\times$ four saccade-target positions. Within blocks, different conditions were realized in a pseudo-random order. Between blocks, participants were encouraged to take short breaks.

Written feedback was given after early saccades ($SRT < 100$ ms) and late saccades ($SRT > 1$ s). Thus, a relatively broad window of allowed SRTs was chosen. This was done for the sake of a broader distribution of SRTs and more information on the development of SIOR over time. In addition, written feedback indicated whether the actual target-discrimination response was correct in relevant-cue trials of the training block. In the experimental trials, no feedback about the discrimination response was given.

Stimuli and procedure of Experiments 1 to 4. The CTOA was 500, 300, and 200 ms in Experiments 1, 2, and 3. In Experiments 1-3, the two cue colors (green and blue) were always different from the color of the saccade target (red). In Experiment 4, the CTOA was 200 ms and the relevant cue had the same color as the saccade target.

Results and Discussion

Erroneous saccades in Experiments 1 to 4. Saccade landing position was calculated as the x-y coordinates of the eyetracker signal at the time at which eye velocity returned to a pre-saccadic baseline level. A saccade counted as correct if it landed in an area of 1.5° around the

center of the saccade target. A saccade counted as erroneous if the eyes landed in an area of 1.5° around the center of a distractor.

Of all responses, 2.4%, 2.3%, 4.9%, and 4.1% were discarded because they were faster than 100 ms, and another 2.0%, 1.0%, 1.0%, and 1.6% erroneous saccades in the SP conditions were not further analyzed in Experiments 1 to 4, respectively. Across relevant and irrelevant DP conditions, 4.8%, 7.7%, 16.9%, and 11.6% of all remaining trials were erroneous saccades and landed on distractor positions in the respective experiments. Separately for each experiment, these were analyzed by calculating the arc-sine transformed rates of erroneous saccades as a function of the cue's relevance (relevant vs. irrelevant) and of the saccade's direction (to the cued position vs. away from the cued position). The corresponding repeated-measurements ANOVAs with these two variables led to no significant effects or interactions in Experiment 1, all $F_s < 3.20$, all $p_s > .10$. Erroneous saccades in the relevant-cue condition towards the cue amounted to 2.9% and away from the cue to 3.4%. In the irrelevant-cue conditions, erroneous saccades landed at the cued location in 0.7% of the trials and they were directed away from the cue in 2.5%.

However, this picture was different for the three experiments with a shorter CTOA. In Experiments 2 to 4, corresponding ANOVAs led to significant main effects of cue relevance, all $F_s > 10.00$, all $p_s < .01$, and of direction, all $F_s > 9.00$, all $p_s < .05$, as well as to significant interactions, all $F_s > 9.00$, $p < .01$. There were more erroneous saccades in the relevant (Exp. 2: 5.5%; Exp. 3: 12.3%; Exp. 4: 8.3%) than in the irrelevant-cue conditions (Exp. 2: 2.2%; Exp. 3: 4.6%; Exp. 4: 3.4%). There were also more erroneous saccades towards the cued location (Exp. 2: 6.7%; Exp. 3: 15.2%; Exp. 4: 9.0%) than away from it (Exp. 2: 1.0%; Exp. 3: 1.7%; Exp. 4: 2.7%). Critically, however, this capture effect of the cues on erroneous saccades (calculated as erroneous DP saccades towards the cues minus erroneous DP saccades away from the cues) was always higher for the relevant cues [Exp. 2: 9.0%; Exp. 3: 20.2%; Exp. 4: 10.9%; all $t_s > 3.30$, all $p_s < .01$] than for the irrelevant cues [Exp. 2: 2.5%; $t(13) =$

2.33, $p < .05$; Exp. 3: 6.7%; $t(9) = 3.42$, $p < .01$; Exp. 4: 1.8%; $t(12) = 1.16$, $p = .30$]. These findings suggest that with the shorter CTOAs of 300 or 200 ms the relevant cues captured more attention than the irrelevant cues.

SRTs in Experiments 1 to 4. Starting from the low eye-velocity baseline during fixation at screen center and measured from the beginning of a trial, SRT was calculated as the time between (1) the onset of the saccade-target stimulus and (2) the time of a local velocity minimum that immediately preceded the point in time at which eye velocity exceeded 80°/s.

Separately for each experiment, a repeated-measures three-way ANOVA of the correct SRTs was run, with the within-participant variables cue relevance (relevant cue; irrelevant cue), cue-target position relation (SP; DP), and quintile (or bin) of the RT distribution (1st to 5th, from fastest to slowest saccades). Complementary ANOVAs were also run for each experiment with all irrelevant-cue trials but restricted to the relevant-cue trials in which the discrimination target was also correctly discriminated. For these complementary ANOVAs, an additional 1.4%, 1.0%, 1.0%, and 1.6% of all remaining trials in which the discrimination target was not correctly discriminated was discarded in Experiments 1, 2, 3, and 4, respectively. The results of the second ANOVA were very similar to the first and are not reported separately. (Where this was necessary, a Greenhouse-Geisser correction was conducted.)

As can be seen in Figure 2, there was an SIOR effect in all experiments but in Experiment 3, with later saccade onset in SP (Exp. 1: 240 ms; Exp. 2: 303 ms; Exp. 4: 337 ms) than DP conditions (Exp. 1: 197 ms; Exp. 2: 263 ms; Exp. 4: 290 ms). This SIOR effect was reflected in a significant main effect of position in Experiments 1, 2, and 4, all significant $F_s > 8.00$, all significant $p_s < .05$, but not in Experiment 3, $F(1, 9) = 1.16$, $p = .31$.

As can also be seen in Figures 2, the SIOR effect developed over time. Formally, this was supported by the significant interactions of position and quintile in Experiments 1 to 4, all

$F_s > 5.00$, all $p_s < .05$. SIOR was smaller in the faster responses, and it was stronger in the slower responses.

With shorter CTOAs, the interaction of relevance and quintile reached significance in Experiments 2 and 3, $F_s > 4.18$, $p < .05$, and was very close to significance in Experiment 4, $F(1, 12) = 4.18$, $p = .051$. This interaction was additionally accompanied by a main effect of cue relevance in Experiment 2, $F(1,13) = 7.20$, $p < .05$. As was the case with SIOR, these interactions reflected an increasing SRT cost in the relevant, more demanding conditions (as compared to the irrelevant, less demanding conditions) with an increasing RT (i.e., across quintiles).

----- Insert Figure 2 about here -----

Importantly, the interaction between position and relevance did not reach significance with CTOAs of 500 and 300 ms which indicates that SIOR did not differ between relevant and irrelevant cues. The disengagement theory had predicted that SIOR should be stronger with irrelevant cues because of more rapid disengagement. Only with the shortest CTOA of 200 ms, did we observe evidence in favor of this hypothesis.

In Experiment 3, there was a two-way interaction of position and cue relevance, $F(1, 9) = 11.05$, $p < .01$, indicating that SIOR (calculated as SRT in SP conditions minus SRT in DP conditions) was stronger with irrelevant cues than relevant cues (4 ms vs. 20 ms). Because the three-way interaction was not significant, the time-course of the transition from capture with fast responses (first and second quintile) to SIOR with slower responses (third to fifth quintile) was the same for relevant and irrelevant cues. This is also evident in the almost parallel lines in Figure 2, third row.

In Experiment 4, there was a three-way interaction of position, relevance, and quintile, $F(1, 12) = 4.65$, $p < .05$. With fast responses (first and second quintile), there was capture (calculated as SIOR) with relevant cues (of -46 ms and -28 ms) but SIOR with irrelevant cues (15 ms and 46 ms). The strong difference between relevant and irrelevant cues with fast

responses was backed up by a significant interaction of relevance and position in the first and second bins, $F(1, 12) = 25.87, p < .01$. By contrast, among the slower SRTs, SIOR was found both with relevant cues and irrelevant cues. The lack of difference between relevant and irrelevant cues with slow responses was backed up by a second ANOVA confined to the last three quintiles which showed no interaction of relevance and position, $F < 1.00$. Another way of looking at the three-way interaction is by comparing the slopes of the SIOR functions. In the previous experiments, we observed that SIOR increased with increasing RTs. With relevant cues in Experiment 4, the increase across the RT bins was particularly rapid and started from a lower initial value (i.e., attentional capture) and finished at SIOR values comparable to irrelevant cues.

Finally, trivial main effects of quintile were found in all experiments, $F_s > 10.00, p_s < .01$, indicating that RT increased with RT quintile.

Discussion

Experiments 1 to 4 showed strong SIOR after color-singleton cues. This confirms that deallocation also takes place after color singletons (cf. Godijn & Theeuwes, 2004; Kim & Cave, 1999). In addition, Experiments 3 and 4 also showed more SIOR after irrelevant than relevant color-singleton cues. Both results are at variance with the studies that have shown no deallocation and no IOR after set-matching color-singleton cues (cf. Gibson & Amelio, 2000; Remington et al., 2001) and they are at variance with the studies showing only a reduction of the capture effect (that potentially corresponded to deallocation) but no IOR after color-singleton cues (Ansorge & Heumann, 2004; Pratt & McAuliffe, 2002).

One important difference between the present study and past research concerned our use of the saccadic task in comparison to the manual responses used in prior studies. Because saccades are very sensitive to IOR in comparison to manual responses (e.g., Zhang & Zhang, 2011), it is possible that less IOR was found in past studies after color singletons because these studies used manual responses, whereas we used saccadic responses (cf. Godijn &

Theeuwes, 2004). Therefore, a final experiment with manual responses was run before the concluding discussion.

Experiment 5

A manual instead of a saccadic response was required. Otherwise the conditions were very similar to the ones of Experiment 2, that is, a CTOA of 300 ms was used. This was used because a CTOA of 200 ms seemed possibly too short for manual responses to lead to IOR at all (Klein, 2000; Taylor & Klein, 1998).

Method

Participants. Twenty-one students (7 male) with a mean age of 21 years participated. They had normal or corrected-to-normal visual acuity. They received course credit in exchange for their participation.

Apparatus, stimuli, and procedure. For the manual responses, a 19" Iiyama ProLite T1931SR touchscreen was used. It was slanted (with the upper border away from the participants by $\sim 80^\circ$) so that the participants looked down on the screen and could conveniently move their fingers across the screen. A pointing-target display was used instead of the saccade-target display. In the pointing-target display, participants had to lift their right index finger from the cross in the middle of the screen and had to put it as quickly and accurately as possible on the pointing target. A response counted as correct if the right index finger landed in a target area of 90×120 pixels (corresponding to a rectangle with a 1.0° frame around the pointing target of 30×90 pixels). Between trials, the participants had to put their right index finger on the home area in the center of the screen.

In the relevant-cue conditions, the target-discriminating responses had to be given by pressing one of two "buttons" displayed on the touchscreen, one with a digital letter-E on it, the other one with a digital number-3 on it. One of the buttons was in the lower left corner, the

other one in the lower right corner of the touchscreen. No keyboard was used. No eyes were tracked. Otherwise the experiment was very similar to the preceding experiments.

Pointing Errors. Out of all responses, 5.9% were anticipations and discarded because the pointing movements started before 100 ms had elapsed since the pointing target’s onset. Another 3 responses were discarded because they were wrongly directed towards a distractor. The 3 erroneous pointing movements were all directed to the cued distractor in the pointing-target display, two of these erroneous pointing movements went to a relevantly cued distractor and one to an irrelevantly cued distractor.

Pointing RTs. For the results, see also Figure 3. Repeated measurements ANOVAs of the correct RTs were submitted to a three-way ANOVA, with the same within-participant variables as were used in the preceding experiments, cue type (relevant cue; irrelevant cue), cue position (SP; DP), and quintile (or bin). (For a supplementary ANOVA with the irrelevant trials but restricted to the relevant trials in which the participants also correctly discriminated the discrimination target, another 1.1% of the remaining trials had to be discarded. This ANOVA led to very similar results.)

The ANOVA revealed a significant main effect of position, $F(1,20) = 8.42, p < .01$, a significant interaction of position and quintile, $F(4,80) = 4.54, p < .05$, and an almost significant interaction of relevance and quintile, $F(4,80) = 3.23, p = .07$. The main effect of position reflected that if cue and saccade target shared their positions (RT = 246 ms), RTs were 16 ms delayed as compared to the DP conditions (RT = 230 ms). The interaction of position and quintile reflected an increase of this IOR effect over the RT distribution, with IORs amounting to 5 ms, 9 ms, 11 ms, 19 ms, and 40 ms, from first to fifth quintile, all $t_s(20) > 1.98$, all $p_s < .05$ (single-sided). A numerical increase of the dual-task costs (calculated as irrelevant RT minus relevant RT) with an increasing RT accounted for the tendency towards a significant interaction between relevance and quintile, first to fifth quintile: 6 ms, 2 ms, -3 ms, -7 ms, and -19 ms, where only the first and last quintile led to significant SP-DP differences,

both $t_s(20) > 1.80$, both $ps < .05$ (single-sided). The other main effects and interactions were not significant, all non-significant $F_s < 1.70$, all $ps > .20$.

----- Insert Figure 3 about here -----

Movement Times. The ANOVA of the movement times (from lifting until landing) led to a main effect of relevance, $F(1,20) = 45.41$, $p < .01$, and a significant interaction between relevance and quintile, $F(4,80) = 23.55$, $p < .01$. The relevance effect reflected the interference by the second task (relevant cueing RT = 663 ms) as compared to the single-task conditions (irrelevant cueing RT = 627 ms). The interaction was due to the increase of the relevance cost (irrelevant RT minus relevant RT) with RTs, first to fifth quintile: -16 ms, -24 ms, -30 ms, -46 ms, -69 ms, all $t_s(20) > 3.30$, all $ps < .01$. All other effects were not significant, all non-significant $F_s < 2.00$, all $ps > .10$.

Discussion

In Experiment 5, we observed IOR in the RTs and dual-task costs in the movement times. This difference in the time course with which the two effects develop has not been observed with the saccades in Experiment 2. Otherwise, however, the results were very similar to those obtained in the first two experiments. In particular, again we found IOR after color-singleton cues among the slower responses and failed to observe significant interactions between cue relevance and position as these were predicted by the contingent-capture theory (predicting capture and/or IOR only in the relevant conditions; cf. Gibson & Amelio, 2000).

Therefore, it seems whether one uses a saccadic response or a manual response is in itself not responsible for whether (contingent) attention capture impacts on IOR. The same conclusion – that attention capture is reflected in SIOR and not only in manual responses has been reached in past research (e.g., Souto & Kerzel, 2009), although some aspects of SIOR are of a different origin than manual IOR effects and might not be due to attention (cf. Hunt & Kingstone, 2003; Tian, Klein, Satel, Xu, & Yao, 2011).

In the present experiment, this conclusion is tempered, however, by the fact that one factor that has often been held responsible for the differences between SIOR in saccades and IOR in manual responses – the fact that only the saccade’s motor trajectory but not that of a manual discrimination response could be specified by the cue’s location – was eliminated in the present study (cf. Gabay, Chica, Charras, Funes, & Henik, 2012). In the present experiment, we used a manual pointing movement. Like a saccade such a pointing movement could be specified by the cue position. Hence, one might argue that our manual responses and saccadic responses were equally sensitive to non-attentional motor effects and insensitive to attentional capture and IOR effects.

General Discussion

The present study used saccadic reaction times (SRTs; Experiments 1 to 4) and manual reaction times (RTs; Experiment 5) to test (1) whether color singletons lead to SIOR and IOR, and (2) whether SIOR was different after relevant and irrelevant color singletons.

With respect to the first question (i.e., the presence of SIOR and IOR after color singletons) past research led to inconsistent results. While some authors found SIOR after color singletons (cf. Godijn & Theeuwes, 2004) a majority of studies failed to find IOR in manual responses after color singletons (cf. Gibson & Amelio, 2000; Remington et al., 2001). In the present study, we were able to demonstrate SIOR in SRTs (Experiments 1 to 4) and IOR in manual RTs (Experiment 5) after color singletons. The present study also provided a clue as to why SIOR and IOR effects of color singletons might have been overlooked in past studies: The SIOR and IOR effects were most prominent only among the slower responses. In Experiments 3 and 4, we even found capture effects (i.e., advantages for SP relative to DP conditions) in the faster responses, and SIOR (i.e., advantages for DP relative to SP conditions) was restricted to the slower response (see Figure 2). Thus, SIOR and IOR effects

can cancel one another out and might be overlooked if one averages across all, fast and slow responses. (For an example, consider Experiment 3).

With respect to the second question that we investigated, some researchers argued that more deallocation could be found after irrelevant cues than after relevant cues (Theeuwes, 2010). According to the deallocation explanation, the different speed with which attention can be withdrawn from irrelevant versus relevant cues leads to more measurable capture after relevant than irrelevant cues (cf. Theeuwes et al., 2000; Theeuwes, 2010). This prediction could not be confirmed in all studies. Gibson and Amelio (2000), for example, were unable to find any indices of deallocation after irrelevant color cues. This was in marked contrast to their observations in relevant onset-cueing conditions, in which these authors found deallocation in the form of IOR.

In the present research, we therefore set out to test this important prediction of the deallocation explanation. Here, we used SIOR as a hallmark of deallocation. In line with the deallocation explanation, we found more SIOR after irrelevant than after relevant cues in our present Experiments 3 and 4. In Experiment 4, the interaction of relevance, position and quintile also suggests that the increase of SIOR or conversely, the offset of capture, across the RT distribution is particularly rapid when the cue color is unequal to the target color.

As with regard to the first question, our study also provided a number of clues as to why past research might have overlooked this deallocation effect. First of all, the number of relevant colors proved to be influential. When more than one relevant color was used, the indications of top-down contingent capture and of differential SIOR were numerically weak. This was found in a comparison of Experiment 3, where we used two relevant colors (one for the relevant cue and one for the target), with Experiment 4 in which we used one relevant color. The different strengths of capture and subsequent SIOR in Experiments 3 and 4 resonate with the known reluctance of the participants to search for colors where singleton search offers an easier way to find the targets (cf. Folk & Anderson, 2010).

Another important variable for whether one finds differential deallocation was the CTOA. With a CTOA of 300 ms (a CTOA that is not uncommon in IOR research because at least manual IOR would only commence at about this CTOA; cf. Klein, 2000) in Experiments 2 and 5, and even less so with a CTOA of 500 ms (in Experiment 1), we were not able to find any traces of differential deallocation in the SRT data. Only when the CTOA was reduced to 200 ms (in Experiments 3 and 4) were we able to find more deallocation after irrelevant than relevant color-singleton cues. Because CTOAs were longer in some past studies (cf. Gibson & Amelio, 2000) our findings also provided an insight into why the (differential) IOR effect could have been missed in these studies.

Finally, again, the variable of the speed with which a saccade was executed (here: the quintile of the SRT distribution) was critical because more SIOR after irrelevant than after relevant cues was most clearly seen among the fastest SRTs (of Experiment 4). Among the slower saccades, by contrast, differential SIOR was washed out and no significant interaction of the variables cue relevance and cue position was found anymore (Experiment 4).

In addition, as might be expected, the more difficult dual-task condition, with the relevant cues and the discrimination task at the end of the trial, interfered with response execution in Experiments 2 to 5 (cf. Carbone & Schneider, 2010). Note that our relevance manipulation affected response latencies mostly during the slower responses. This also offers a clue as to why the same interference effect by the secondary (cue-memorization) task on SRT was not found in Experiment 1. In Experiment 1, the CTOA was probably too long to still show the detrimental overall effect of the more demanding task of first having to attend to the cue and then having to saccade to the target because in Experiment 1, at the time that the capacity-limited bottleneck was needed for an attention shift towards the saccade target this bottleneck was no longer needed for the shifting of attention to the relevant cue and for encoding it into working memory (cf. Pashler, Carrier, & Hoffman, 2003).

Deallocation explanation vs. contingent capture

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3 In the current study, we have confirmed one critical prediction of the deallocation
4 explanation. This does not mean, however, that the top-down contingent capture principle
5 would be falsified. The critical predictions of the top-down contingent capture hypothesis
6 only concern the onset of attention capture – that is, the initial capture of attention by a top-
7 down matching (or relevant) stimulus should outweigh the initial capture of attention by a
8 non-matching (or irrelevant) stimulus. Because our SRT and RT distribution analyses were
9 not suited to show the onset of attention capture in any of the distributions, we cannot be sure
10 whether in the present study during the initial phase after the cues, capture might not have
11 been stronger in top-down matching than non-matching cueing conditions.
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23 Moreover, past research that was devoted to study exactly this prediction of the
24 contingent-capture hypothesis has consistently supported the contingent-capture hypothesis.
25 For instance, to continuously track the direction of attention with a millisecond resolution and,
26 thus, to get insight into the degree of initial capture by relevant versus irrelevant cues, one can
27 use the contra-ipsilateral activity difference of the event-related potential (ERP) relative to the
28 side of an attended stimulus that is created at posterior electrodes of the human scalp. If this is
29 done, one can clearly see that in the majority of the studies, even the earliest attentional
30 capture effect is selectively present or larger with top-down matching than with non-matching
31 cues (cf. Eimer & Kiss, 2008, 2010; Kiss & Eimer, 2011; Lien, Ruthruff, & Cornett, 2010;
32 Lien, Ruthruff, Goodin, & Remington, 2008).
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45 The few studies that showed initial ERP capture effects after non-matching color
46 singletons (e.g., Hickey, McDonald, & Theeuwes, 2006) are not necessarily at variance with
47 this conclusion because these studies might have reflected *top-down singleton search* (Bacon
48 & Egeth, 1994; Leber & Egeth, 2006). In addition, top-down contingent capture is also
49 supported by research that used predictive singleton cues to discourage deallocation (cf.
50 Ansorge, Kiss, Worschech, & Eimer, 2011; Folk et al., 1992), and by detailed RT distribution
51 analyses (cf. Ansorge & Horstmann, 2007). Therefore, we think it is more likely that top-
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down contingent capture and differential deallocation could both be operating in different degrees depending on further side conditions, such as the kind of attention-capturing feature that is used (Liao & Yeh, 2011; Neo & Chua, 2006), the number of stimuli per display (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007), the amount of practice (Liao & Yeh, 2011), and the expectancies of the participants (cf. Horstmann, 2005).

For Review Only

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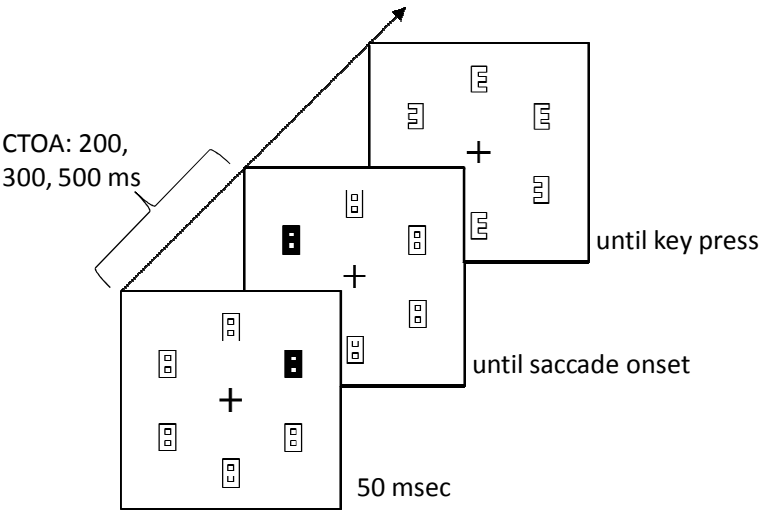


Figure 1: Depicted is an example of a different-position (DP) trial. The first (lower) display was a cueing display, in which a cue (illustrated as a black figure-8) was presented in green or blue with one color indicating the relevant and the other the irrelevant cue. The second (middle) display was a saccade-target display, in which a saccade target (illustrated as a black figure-8) was shown in red (in Experiments 1, 2, 3, 5) or in the color of the relevant cue (in Experiment 4). The third (upper) display was a discrimination-target display, in which a discrimination target was shown. The discrimination-target display was only shown after the relevant cue. The discrimination target was presented at the relevant cue’s position. The arrow depicts the direction of time. Stimuli are not drawn to scale. CTOA = Cue-Target Onset Asynchrony: 500 ms in Experiment 1; 300 ms in Experiments 2 and 5; 200 ms in Experiments 3 and 4.

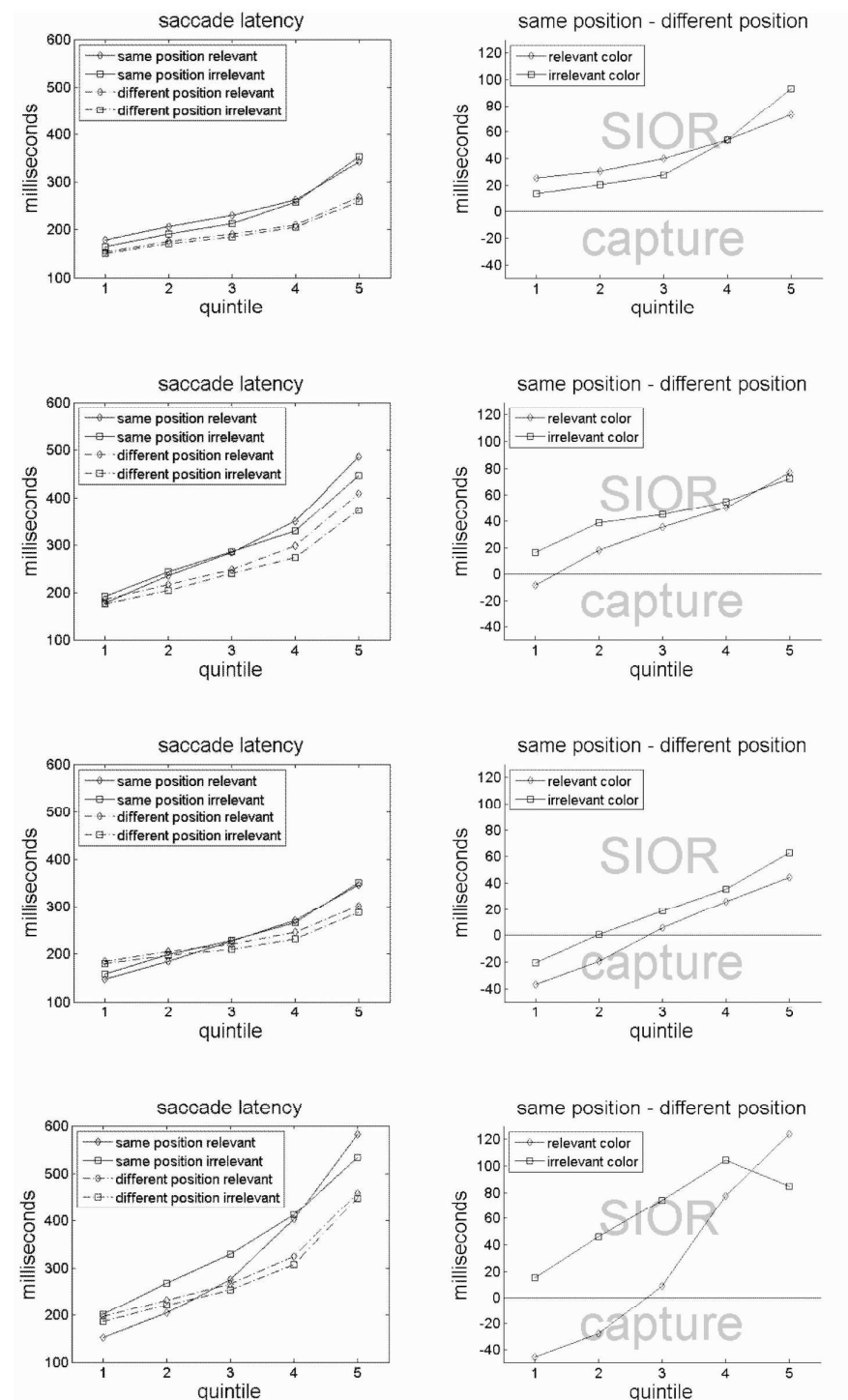


Figure 2: On the left, saccadic reaction times (SRTs; in milliseconds) as a function of the cue's relevance, the cue-target position relation, and the quintile of the SRT distribution. On the right, we plotted the SRT in same position conditions minus SRT in different position conditions. Inhibition of return (SIOR) results in positive values and attentional capture in negative values. Data from Experiments 1-4 are shown in rows 1-4, respectively.

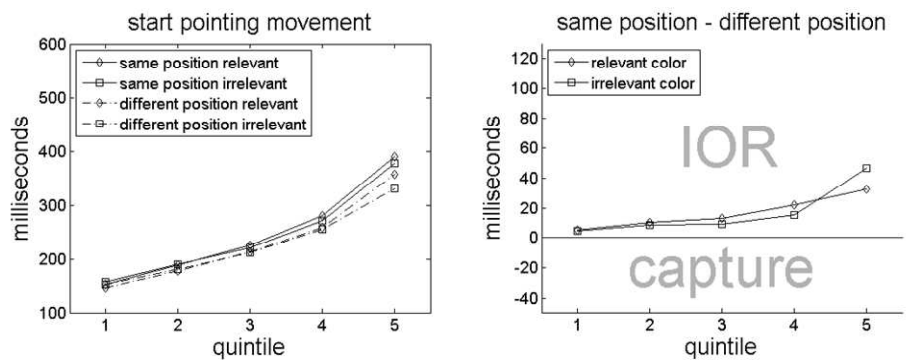


Figure 3: On the left, manual reaction times (RTs; in milliseconds) in Experiment 5 as a function of the cue's relevance, the cue-target position relation, and the quintile of the RT distribution. The RTs were measured under conditions with a cue-target onset asynchrony of 300 ms, and a different cue color than saccade-target color. On the right, inhibition of return (IOR; depicted above the x axis) and capture (below the x axis) (calculated as RT in DP conditions minus RT in SP conditions) of Experiment 5 as a function of the cue's relevance, and the quintile of the RT distribution.

Chapter 5: Inhibition of Return after Color Singletons

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Inhibition of Return after Color Singletons

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Abstract

Inhibition of return (IOR) is the faster selection of hitherto unattended than previously attended positions. Importantly, previous studies failed to find evidence for IOR after attention capture by color singletons. This has been attributed to a broad insensitivity of IOR mechanisms to color salience. However, by using a more sensitive method – saccadic IOR – we tested and found IOR after color singletons (Experiment 1). Also, an alternative explanation of our findings is ruled out in Experiment 2. We discuss our results in light of pertaining theories of IOR.

When we look around, we only register part of the information projected onto our retinæ at each moment in time. This form of selectivity is called visual attention. Visual attention has many different purposes. Selection can gate access of information to perception (cf. Scharlau, 2002), memory (cf. Duncan & Humphreys, 1989), or motor control (cf. Allport, 1989). Corresponding to its multiple purposes, visual attention is also influenced by many different factors, such as the properties of the stimulus (cf. Itti, Koch, & Niebur, 1998) and the goals of the human observer (cf. Folk, Remington, & Johnston, 1992). One important factor is the observer's memory trace of the visual information that has been selected in the recent past. One primitive form of such memory has been called inhibition of return (IOR): It has been demonstrated that shifting visual attention toward one position in space delays a second subsequent attention shift to the same position at a later point in time (Posner & Cohen, 1984; Taylor & Klein, 1998). This phenomenon is called IOR because originally it was believed that it reflected the human resistance to select information from positions that have recently already been inspected by a covert shift of attention (cf. Posner & Cohen, 1984). In this context, a covert shift of attention is a shift of attention without the eyes, whereas an overt shift would be accompanied by an eye movement (cf. Henderson, 2007).

Since IOR's original discovery, many factors were identified that influence the magnitude of IOR. Some authors believe that IOR mostly reflects selection-for-action because it is particularly strong with overt shifts – that is, with saccades, the fast jumping movements of the eyes, whereas IOR is weaker with a covert attention shift (e.g., starts later, Pratt & Neggers, 2008) and can even be absent with some forms of covert attention (cf. Klein & Pontefract, 1994; Rafal, Calabresi, Brennan, & Sciolto, 1989).

Understanding the principles governing IOR is mandatory for a broader understanding of attention for two reasons: First, in many everyday situations, human observers shift their attention several times toward and away from the same locations or objects. Think of having

breakfast: Any time that you pick up your cup to have a sip of coffee you would select information from one and the same location or object. Therefore, conditions under which IOR is demonstrated cover an important facet of everyday attention under ecological conditions outside the laboratory. Second, the conclusions that can be drawn from IOR research are not always the same as the conclusions which are reached in research on single attention shifts (e.g., Pratt, Sekuler, & McAuliffe, 2001). Accordingly, some neurophysiological studies suggest that attention capture and IOR arise at different stages of processing (e.g., Fecteau & Munoz, 2005). IOR research therefore complements the picture of the operation of attention under ecologically valid conditions.

The current study follows up on the observations by Pratt et al. (2001) of massive differences in the magnitude of IOR after attention shifts to abrupt onset stimuli versus color singletons. Both, abrupt onsets in the periphery and singleton stimuli popping out among a background of more homogenous color stimuli (such as a green apple among red apples) have a strong potential to capture human attention. Some researchers believe that this capture is truly automatic and stimulus-driven (see Theeuwes, 2010, for a review). Others are more reserved and regard it as being conditional on top-down search goals (Folk et al., 1992). Whichever of these two positions holds true: important in the present context is that Pratt et al. (2001) did not find IOR after color singletons. These authors used a classic cueing paradigm with peripheral cues presented either at the same position (SP) as the subsequent target or at a different position (DP) than the target. The participants had to report the identity of the target. They could ignore the cue because the cue was uninformative with respect to target position – that is, the cue and target positions were uncorrelated across trials. Pratt et al. (2001) used two kinds of cues, onset cues and color-singleton cues. The onset cue was a single onset stimulus (four white dots abruptly appearing around one of four placeholder squares). The color-singleton cue consisted of four red dots appearing around one of the four

placeholders, whereas white dots appeared around the remaining three placeholders.

Importantly, two cue-target intervals were used: one short and one long. With the long cue-target interval the authors only found IOR after onset cues. Reaction Times (RTs) were slower for SP than for DP targets. With the color-singleton cues, however, no IOR was found (see also Gibson & Amelio, 2000). These results seem to support the position that onsets are special in that they create stronger selection-for-action effects, maybe because onset-driven attention capture depend on color-insensitive processing in the midbrain's superior colliculi (SC) (cf. Fuchs & Ansorge, 2012). The SC are strongly involved in the programming and in the execution of eye movements (cf. Wurtz & Albano, 1980) and many results imply that onsets might have a higher ability than for example color to activate the eye-movement system (cf. Wu & Remington, 2003).

So far, however, little systematic research has been conducted to test whether color singletons could indeed lead to IOR when an eye movement is required (but see Godijn & Theeuwes, 2004). Most of the research has tested whether color singletons produce IOR with manual responses (Ansorge & Heumann, 2004; Gibson & Amelio, 2000; Pratt et al., 2001; Remington, Folk, & McLean, 2001). However, as we have reviewed above, IOR is much stronger with saccadic responses. To test whether color singletons lead to IOR with eye movements, we used color-singleton cues and investigated whether they impacted on saccades – that is on overt shifts to the targets, instead of covert attention shifts. To anticipate the results of our first experiment, we found saccadic IOR (SIOR) after the color singletons. We therefore also ran a control experiment to test whether attention was indeed responsible for SIOR – that is, whether SIOR could be successfully prevented if no attention shift to the first cue was required.

Experiment 1

On each trial, three successive displays were shown and participants had two different tasks, a target discrimination task and a saccade task (see Figure 1). The first display (cue display) contained a blue color-singleton cue presented among five gray distractors. The participants had to (covertly) select the cued position for subsequent discrimination of a target shape, presented 500 ms after the blue singleton cue (discrimination display). The target shape was either a digital figure-3 or a digital figure-E and the participants had to keep the identity of this discrimination target in memory (for a button press at the very end of the trial). Note that to successfully solve this task, the participants had to retrieve the cued position of the first display from memory because distractors were likewise figure-3s or figure-Es and the discrimination target was not highlighted in any way (see Figure 1). There was, however, one red shape among the gray elements in the discrimination display. This red color-singleton served as a cue for the saccade to be made on presentation of the third display (saccade display). Across trials, the position of the red saccade cue was uncorrelated to the position of the blue cue for the discrimination task. The saccade display consisted of six gray circles, and participants had to quickly saccade to the circle at the position cued previously by the red singleton. Finally, the participants had to press a button at the end of the trial for the discrimination of the target's shape.

We expected to find SIOR in saccadic reaction times (SRTs) and with respect to the position of the blue color-singleton cue in the first display. The reason is that (1) attention needed first to be shifted to the blue singleton cue to select its position as for the subsequent discrimination task; (2) with 1 s between the presentation of the blue singleton cue and the saccade target display, the interval was sufficiently long for IOR (cf. Klein, 2000); (3) saccades are very sensitive to IOR; and (4) there was no correlation between the positions of the blue singleton cue and the saccade target so that it was necessary for the participants to withdraw attention from the first cue in a vast majority (75%) of trials. The withdrawal is necessary because the programming of the saccade requires a shift of attention toward the

saccade target position (here; the red cue's position) (cf. Deubel & Schneider, 1996).

Importantly, we did not only compare mean SRTs, but analyzed SRT distributions. More precisely, we calculated and compared SRT quintiles to test how the SIOR effect developed over time. The reason is that attentional and SIOR effects sometimes develop across RT (cf. Theeuwes & Godijn, 2004; van Zoest, Donk, & Theeuwes, 2004), and we did not want to miss an SIOR effect in our data.

We also included 50% control trials, in which a green singleton cue was presented instead of the blue singleton cue. The green singleton cue signaled to the participants that no shape discrimination was required in the subsequent display and therefore the position of the green singleton cue was always irrelevant. Past research has shown that under very similar conditions, attention is often only shifted towards relevant (here: blue) cues but not (or less so) to irrelevant (here: green) cues (cf. Ansorge, Kiss, Worschech, & Eimer, 2011; Eimer & Kiss, 2008; Folk & Remington, 1998; Gibson & Amelio, 2000; for a review see Burnham, 2007). This pattern of results is attributed to feature-dependent top-down contingent capture, meaning that attention is only shifted toward a cue if it happens to match a top-down set of searched-for relevant features (cf. Folk et al., 1992). In the first display, only the blue singleton cue, but not the green singleton cue would have been relevant in this sense. If SIOR follows the rules of top-down contingent capture, we might expect SIOR after blue but not after green cues.

However, alternative principles might determine SIOR to the first color-singleton cues. For instance, one may argue that the blue and green cues are equally strong or equally salient, and according to some theories attention capture is purely stimulus-driven, that is, it is simply proportional to stimulus salience (cf. Itti & Koch, 2000; Theeuwes, 1992, 2010). If SIOR is governed by this stimulus-driven salience principle, one would expect equal amounts of SIOR after relevant and irrelevant singleton cues. Another possibility is that participants

might decide to actively search for all (color) singletons in a top-down way instead of only searching for the relevant colors (cf. Bacon & Egeth, 1994). This strategy is called singleton search and if SIOR follows the principles of singleton search, one would likewise expect equal magnitudes of SIOR for relevant and irrelevant cues because both are (color) singletons and would therefore match a top-down search set for (color) singletons. In fact, top-down singleton search might have been encouraged in the present experiment because it allows the participants to find all relevant, that is, blue and red cues, with the same top-down search template. Past research has shown that the selective top-down search for specific colors is sometimes discouraged under these conditions, probably because feature-based top-down search becomes more difficult (Folk & Anderson, 2010; but see Worschech & Ansorge, in press). In sum, the salience principle and the singleton-search theory lead to the same predictions: equal magnitudes of SIOR for blue and green singleton cues. Given such a pattern of results, we cannot distinguish between these two explanations.

Method

Participants. Ten volunteers (5 female) participated in Experiment 1. Their mean age was 31 years. Here and in Experiment 2, all observers reported normal or corrected-to-normal vision. Written and informed consent was obtained from each participant before the experiment.

Apparatus. Visual stimuli were presented on a 19-inch CRT color monitor (Sony Multiscan G400), with a screen resolution of $1,024 \times 768$ pixels. Its refresh rate was 100 Hz. The participants sat at a distance of 57 cm from the screen in a quiet, dimly lit room, with their head resting on a chin rest to ensure a constant viewing distance and a straight-ahead gaze direction. Manual responses for the discrimination task were registered via a standard

keyboard, placed directly in front of the observers. Participants' manual responses were collected by the keys #F and #J (labeled "left" and "right"). Saccades were recorded with an EyeLink 1000 Desktop Mount system (SR Research, Mississauga, Ontario, Canada) with a 35mm lens, and EyeLink Software version 4.52, sampling at maximal resolution. Eyetracking was monocular from the dominant eye. A 9-point calibration was used to adjust the eyetracker before the experiment and in advance of every single block.

Stimuli and Procedure. Three successive displays were shown on each trial (see Figure 1). A central fixation cross was visible throughout each trial. All objects on the screen were equi-luminant (~ 30 cd/m²). The first display (cue display) was presented for 50 ms. It consisted of six equidistant digital letter-8 placeholders (with size of $1.7^\circ \times 1.0^\circ$, stroke strength of 0.3°), presented on the circumference of a virtual circle with an eccentricity of 7.0° centered on the screen center. The figures were located at 0° , 60° , 120° , 180° , 240° , and 300° from the vertical meridian. Five digits were presented in gray (CIELAB color coordinates: 6.9, 16.8) and one was presented in a different color (color singleton cue), either in blue (46.9, -89.0) or in green (-30.2, 24.9). The color singleton cue was always shown at one of the four lateral positions. It was never presented on the vertical meridian, that is, above or below fixation.

--- insert Figure 1 about here ---

After an inter-stimulus interval of 450 ms (blank screen), the discrimination display was presented for 50 ms. At the positions of the figure-8 placeholders three letters "E" and three digits "3" were now presented in digital notation. Five of these shapes were presented in gray, one was presented in red (47.6, 41.1). Similar as for the color singleton in the cue display, the red singleton cue could likewise only appear at one of the four lateral positions (never above or below fixation). In this display, one figure served as a discrimination target if it had been cued by a blue singleton in the preceding display. In contrast, the red singleton

served as the cue for the saccade in the subsequent display. Positions of the first cue (blue or green) and the second (red) cue were uncorrelated across trials. As both cues were only presented at the four lateral positions, there were 25% trials with first and second cue at the same position (SP condition) and 75% trials with first and second cue at different positions (DP condition).

After another blank inter-stimulus interval of 450 ms the saccade display was presented, containing six empty circles surrounding the same stimulus positions as were used in the preceding displays. The saccade display was presented for 1 s.

The color of the singleton in the first screen indicated the task: A blue singleton signaled that the discrimination task had to be performed while the green singleton could be ignored. In the discrimination task, participants had to remember the shape of the digit presented in the second display at the position of the blue singleton in the first screen. The red singleton in the second display indicated the position of the subsequent saccade target. The onset of the third screen was the go signal for the saccade. After the saccade was executed, participants pressed the key corresponding to the identity of the discrimination target letter on a standard keyboard. If no discrimination was necessary, this part of the trial was skipped. Participants started the next trial in a self-paced manner by pressing the space bar. 500 ms elapsed before presentation of the next cue display.

Participants were informed that the color singletons could only appear at the four lateral positions and that the position of the second (red) singleton cue was independent of the position of the first (blue or green) singleton cue. Blocks consisted of 64 trials and feedback was given about whether the target discrimination was correct and about whether the saccade was registered during the third screen. Altogether ten blocks were run, the first block was considered as training. Within a block of trials, the different combinations of the discrimination target (E or 3), first cue position (above/left, above/right, below/left,

below/right), first cue color (blue, green), and second cue's position (above/left, above/right, below/left and below/right) were equally likely and presented in a pseudo-random order.

Results

The SRT was calculated as the local velocity minimum immediately preceding the point at which eye velocity exceeded $80^\circ/\text{s}$. Trials with saccades executed faster than 100 ms after the onset of the saccade screen or later than 1 s after onset of the saccade screen were rejected (4.9% of all trials). Of the remaining SP trials, 12.0% were discarded because they did not land on the target (i.e., outside an area of 1.5° around the center of the saccade target), and of the remaining DP trials, 6.6% had to be discarded for the same reason. This may already speak for an IOR-similar effect but a repeated-measures analysis of variance (ANOVA) on the arc-sine transformed error rates with the two variables position (same, SP, vs. different, DP) and first cue type (relevant/blue or irrelevant/green) only revealed a tendency towards a main effect of position, $F(1, 9) = 3.84, p = .08$. The main effect of first cue type, $F(1, 9) = 3.32, p = .10$, and the interaction, $F(1, 9) = 2.99, p = .12$, were also not significant.

Thereafter, the remaining correct SRTs were sorted from fastest to slowest and grouped into five percentiles or time-bins. A repeated-measures ANOVA with the variables position (same, SP, vs. different, DP), first cue type (relevant/blue or irrelevant/green) and percentile revealed a significant main effect of position, $F(1, 9) = 5.45, p < .05$. Average SRT for trials with both cues presented at the same position was slower than for trials with both cues on different positions (349 ms vs. 321 ms), indicating SIOR. With the exception of a trivial main effect of percentile, $F(1, 9) = 40.17, p < .01$ (SRTs increasing with percentile), no other significant effects or interactions were found, all F s < 1.80 , all p s $> .20$. See also Figure 2 for the results.

--- insert Figure 2 about here ---

Discussion

Experiment 1 showed clear SIOR after color singletons. This is different from prior studies with manual responses that have failed to find IOR after color singletons (cf. Gibson & Amelio, 2000; Pratt et al., 2001). However, our results are consistent with findings by Theeuwes and Godijn (2004), who found SIOR after a joint color change and luminance increment. Related to this, Godijn and Theeuwes (2004) found a small SIOR effect after a color singleton. Jointly, these results suggest that it is possible to find at least SIOR after color singletons.

Also of interest, the present SIOR effect was not affected by whether or not the color and position of the singleton cue in the first display had been relevant (i.e., signaling the position of the discrimination target) or irrelevant for the task in a given trial. As laid out above, this finding is in accordance with either stimulus-driven attention capture by all singleton cues (cf. Theeuwes, 2010) or it could reflect singleton capture according to a top-down singleton search set (cf. Bacon & Egeth, 1994). In any case, the results do not support the top-down feature search explanation (cf. Folk et al., 1992). If the participants had searched for only relevant blue cues, SIOR being conditional on a preceding attention shift should only have occurred with the blue but not with the green cues.

However, there is one caveat to this argument. One could argue that the SIOR effect was not due to an attention shift to the first cue. Instead, the color change from the first, blue (or green) cue to the red cue might have created (stronger) detection costs for the (color of) the red cue if this cue happened to be shown at the same position as the blue (or green) cue in the preceding display. A delayed detection of the red cue at the blue (or green) cue position

could also have created an SRT cost that would not reflect an attention shift to the first cue. This possibility was tested in Experiment 2.

Experiment 2

Experiment 2 served as a control experiment. Participants had to attend only to the red cue in the discrimination display, and could ignore the blue and the green cue in the first display. This was achieved by asking the participants to only search for the red cue, discriminate the target at its position and to subsequently saccade to that same position with onset of the saccade display.

Under these conditions, an SIOR effect that is conditional on a preceding attention shift to the first blue or green cue should be prevented. With only one relevant color, here: the color red, participants should be able to search for this red color in a top-down manner with a feature template (cf. Folk & Anderson, 2010). As a consequence, the irrelevant blue and green cue should no longer capture attention.

Our predictions are straightforward. If participants adopt a feature search template and only search for red cues, we expect no capture of attention by the non-matching blue and green cues and, hence, no subsequent SIOR conditional on such preceding attention shifts. In contrast, if the color change of the cues presented at the same positions created a sensory delay of the detection of the red cue in Experiment 1, we would predict likewise longer SRTs in SP conditions than DP conditions in Experiment 2 – that is, SIOR.

Two further accounts predict SIOR for Experiment 2. First, if the blue and green color singletons capture attention in a stimulus-driven way, we should find SIOR. Second, theoretically it is also still possible for the participants to search for the target with a singleton-search template, which should likewise produce SIOR.

To summarize the predictions: We can reject an explanation of Experiment 1's SIOR effect in terms of color switch costs if the SIOR effect was abolished in the present experiment. In turn, the conclusion that capture in the first display was critical for SIOR would be supported. If, however, SIOR persists in the present experiment, we cannot reject a color switch explanation of the SIOR effect, but an attentional explanation (stimulus-driven capture or top-down singleton search) of the SIOR effect might also be viable.

Method

Participants. Ten volunteers (3 female) with a mean age of 31 years participated in Experiment 2.

Apparatus, Stimuli and Procedure were the same as in Experiment 1 with the exception that the task changed. Participants had to discriminate the target at *and* subsequently saccade (in the saccade display) to the position that was indicated by the red cue. Thus, the participants were allowed if not encouraged to completely ignore all blue and green cues that were shown in the cue display, and no re-shifting of attention from these blue or green cues and to the red cues would have been necessary.

Results

As in Experiment 1, saccades faster than 100 ms or slower than 1 s were discarded (10.1%). Of the remaining SP saccades, 7.8% were not directed to the saccade target, while of the remaining DP saccades 6.8% landed at the wrong position. A repeated-measures ANOVA with the variables position (same vs. different position of the first and the second cue), and cue color of the first cue (blue or green), did not reveal any significant main effects or interactions, all F s < 1.00.

A repeated-measures ANOVA of the correct SRTs, with the variables position (same vs. different position of the first and the second cue), cue color of the first cue (blue or green),

and percentile (or time-bin), indicated no significant effect for cue position: Although SRTs were slower when both cues were presented at the same position than at different positions (278 ms vs. 271 ms), this effect failed to reach significance, $F(1,9) = 3.06$, $p = .11$. Besides percentile, no other main effect or two-way interaction was significant either. Only the three-way interaction of cue position, cue color, and percentile was significant, $F(4,36) = 2.88$, $p < .05$. This interaction was due to faster SRTs for different-position green-cue and same-position blue-cue conditions compared to same-position green-cue and different-position blue-cue conditions in the fifth percentile. In other words, the green cue produced an effect reminiscent of SIOR in the fifth percentile, whereas the blue cue produced an inversed SRT pattern. See also Figure 3 for the results.

--- insert Figure 3 about here ---

Discussion

Changing the task instructions led to the elimination of SIOR in all but one condition. This result falsifies the notion that multiple color changes at the same position could be responsible for worse cue detection. In turn, the absence of the SIOR effect is in line with an attentional explanation of SIOR in Experiment 1. We argued that the capture of attention to the blue and green cues in Experiment 1 was responsible for SIOR in the saccade display. By asking our participants to only search for the red cue in Experiment 2, we apparently prevented attention shifts to the green and blue cues and thus, also prevented SIOR.

We did find a residual SIOR effect in the slowest SRTs after the green cues. This residual cost might indeed reflect a contribution of sensory interference due to the color change from green to red, however, it seems, only on a small subset of trials. Importantly, for most trials, no SIOR effect was found.

General Discussion

In the current study, we found SIOR after color singletons (Experiment 1). This finding is in contrast to previous studies that have failed to find IOR with color singletons after manual responses (cf. Gibson & Amelio, 2000; Pratt et al., 2001). One decisive difference between the present study and previous studies concerned the use of saccades in the current investigation as compared to manual responses in the previous studies. The use of saccades is very likely a decisive difference assuming that IOR seems to reflect selection for action, at least to some extent (cf. Klein, 2000; Klein & Pontefract, 1994). Accordingly, IOR tends to be larger with overt shifts (or saccades) than with covert shifts of attention (cf. Pratt & Neggers, 2008). Also, in line with this explanation, the best evidence from previous research for (small) IOR effects after color singletons stems from a study that used saccades (cf. Godijn & Theeuwes, 2004).

Another potential prerequisite to obtain (S)IOR with color singletons is that the singleton cue provides task-relevant information. In the present Experiment 1, the color of the cue indicated whether the discrimination task had to be performed and, in case of a blue cue, on which position. In contrast, the cue in Experiment 2, similarly to previous studies on IOR after color singletons (cf. Gibson & Amelio, 2000; Pratt et al., 2001), was completely irrelevant for the subsequent discrimination and saccade tasks. In line with previous studies, IOR was abolished.

IOR (and SIOR) has sometimes been attributed to other factors than (overt) attention. Some authors argue that IOR reflects sensory adaptation (Dukewich, 2009; Hu, Samuel, & Chan, 2011). According to this account, inhibition is stronger whenever features are repeated. This inhibition can be observed for spatial position repetitions, as with the standard IOR effect, as well as for non-spatial feature repetitions, such as the repetition of a particular color (e.g., Hu et al., 2011). For two reasons, sensory adaptation effects did probably not play a

major role in the present study. First, we observed SIOR after color changes rather than after color repetitions. In Experiment 1, either a blue or a green cue was presented in the first display, whereas a red cue was shown in the second display. Also, the saccade target was yet of another color (gray). These color-change conditions would not be favorable for a feature-adaptation effect. Second, when we changed the task and asked our participants to only search for the red cues, SIOR was eliminated (Experiment 2). It would be difficult to understand how this change in task instruction should have abolished a task-independent automatic adaptation effect.

Other authors have emphasized that IOR could reflect motor activation (Hunt & Kingstone, 2003; Lupiàñez, 2010; Taylor & Klein, 2000). In line with this assumption, for example, SIOR is affected by variables that do not impact on covert attention effects (Hunt & Kingstone, 2003; but see Souto & Kerzel, 2009). This explanation of IOR in terms of motor activation is, however, not at variance with our view. In fact, we believe that much of the SIOR effects reflected selection for action. We propose that SIOR after color singletons may reflect the inhibition of overt attention (i.e., inhibition of executing an eye movement to prevent oculomotor capture) following a covert attention shift.

Finally, we want to address two remaining questions. First, which principles may account for the different results in Experiment 1 and 2? Second, how is SIOR by color singletons brought about if the SC is color-insensitive? Concerning the first question, we have argued that SIOR after relevant blue and irrelevant green cues in Experiment 1 could have reflected either stimulus-driven attention capture by any salient stimulus (cf. Theeuwes, 1992) or attention shifts contingent on a top-down search for a singleton (cf. Bacon & Egeth, 1994). Results of Experiment 2 seem to contradict the stimulus-driven account. In Experiment 2, our participants were asked to search for the red cue. This was evidently enough to overcome capture and SIOR by both color singleton cues in the first display. Accordingly, it seems

feasible that our participants were able to choose between one of two top-down search modes: top-down search with a feature template (as in Experiment 2) or top-down search for singletons (as in Experiment 1). However, it is still possible that the participants in Experiment 1 simply abandoned their top-down search settings: With two relevant colors, participants might have found it too difficult to search for two features in parallel and might simply not have used any kind of top-down control over their search. Thus, we cannot exclude that SIOR in Experiment 1 reflects stimulus-driven attention capture, whereas the lack of SIOR in Experiment 2 reflects top-down influences.

Concerning the second question, it is likely that the SC is not the only structure involved in IOR, but there may also be cortical areas, for example, the posterior parietal cortex (PPC) (cf. Tian, Klein, Satel, Xu, & Yao, 2011). The PPC is assumed to also contribute for instance to color salience effects (Arcizet, Mirpour, & Bisley, 2011). In addition, recent evidence suggests that some SC neurons are actually highly sensitive to information originating from chromatic pathways, albeit color information arrives with a certain delay compared to achromatic signals (White, Boehnke, Marino, Itti, & Munoz, 2009). Interestingly, Fecteau & Munoz (2005) report two distinct IOR-related modulations in SC neuron activity, one early, one late. They conclude that different components of IOR originate at early and late processing stages. We speculate that IOR after color singletons may originate at late processing stages. In sum, IOR seems to be mediated by more than one pathway or brain area, allowing for IOR effects to occur even after color singletons.

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Figure captions

Figure 1: Depicted is an example of a different-position (DP) trial. The first (lower) display was the cue display, in which a color singleton cue (illustrated as a black figure-8) was presented; a blue singleton indicated the position of the subsequent discrimination target (relevant cue); a green singleton indicated that no discrimination task followed (irrelevant cue). The second (middle) display was the discrimination display; following a blue singleton cue, participants had to memorize the identity (figure-E or figure 3) at the position previously occupied by the blue cue. Alongside the discrimination target, we presented a red color singleton as saccade cue (depicted as a black figure). The third (upper) display was the saccade display; participants had to saccade to the target ring at the position previously indicated by the red saccade cue. The arrow illustrates the temporal sequence. Stimuli are not drawn to scale. SOA = Stimulus Onset Asynchrony.

Figure 2: On the left, saccadic reaction times (SRTs; in milliseconds) in Experiment 1 as a function of the first cue's color, the relation between cue and target positions, and the SRT quintile. On the right, SRT difference between same position trials and different position trials as a function of the first cue's color, and the SRT quintile in Experiment 1; positive values denote saccadic inhibition of return (SIOR); negative values denote attention capture.

Figure 3: On the left, saccadic reaction times (SRTs; in milliseconds) in Experiment 2 as a function of the first cue's color, the relation between cue and target positions, and the SRT quintile. On the right, SRT difference between same position trials and different position trials as a function of the first cue's color, and the SRT quintile in Experiment 2; positive values denote saccadic inhibition of return (SIOR); negative values denote attention capture.

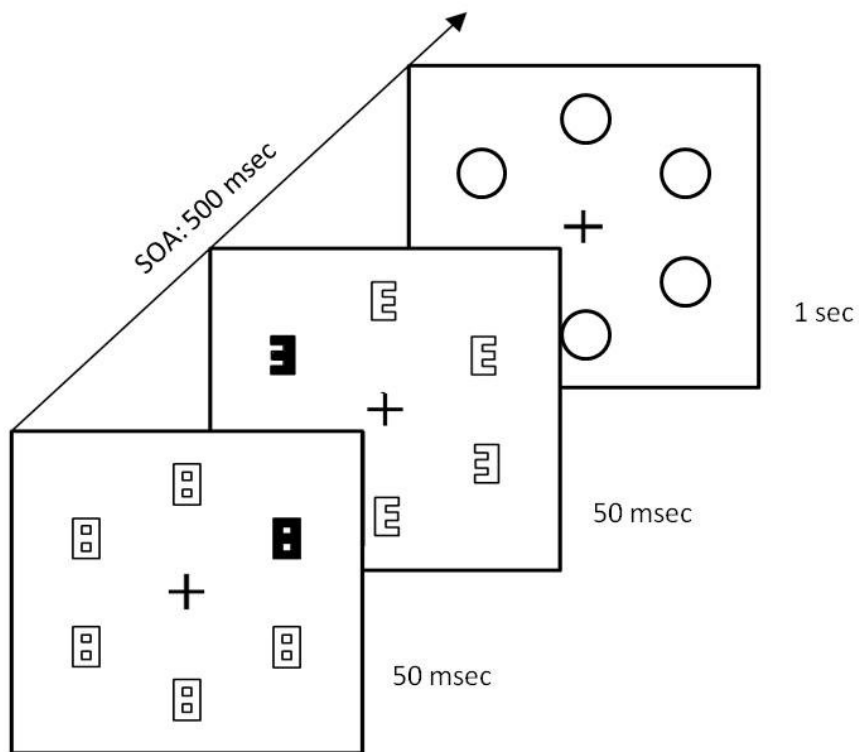


Figure 2

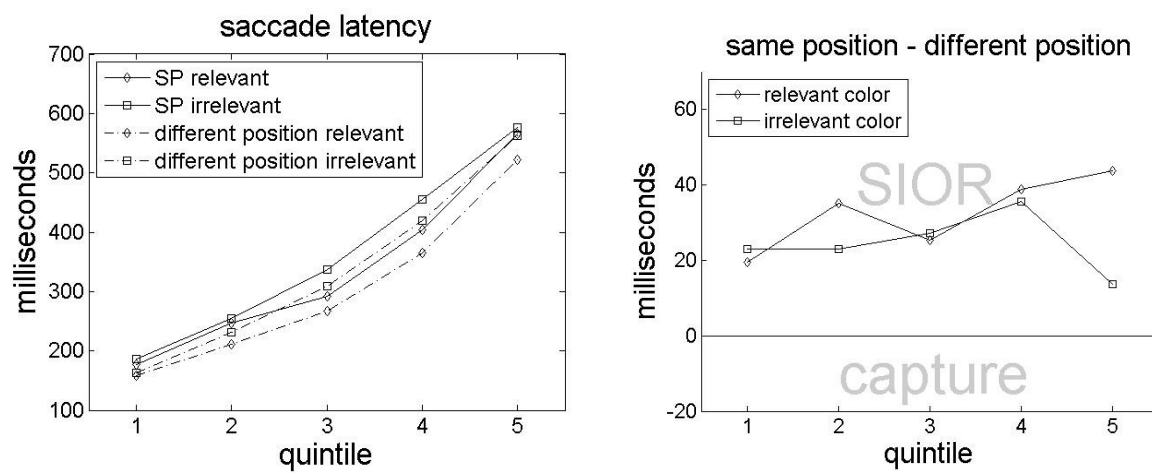
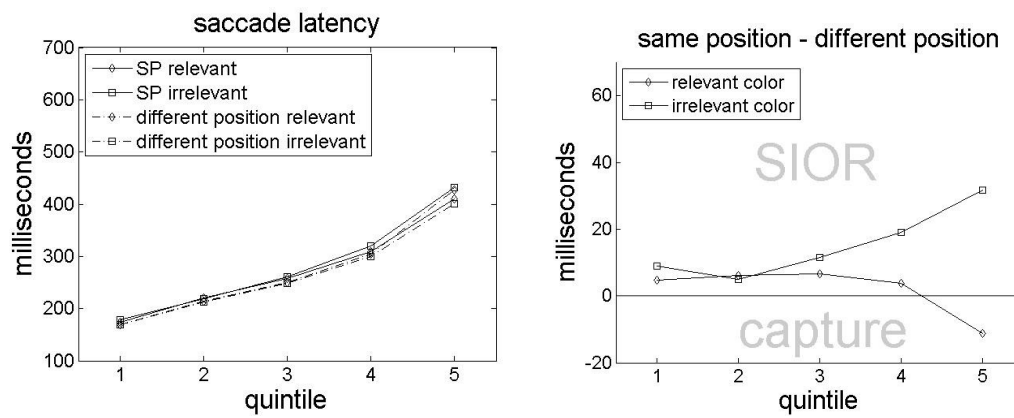


Figure 3



Chapter 6: Contingent Capture Preceding Similar Magnitudes of IOR

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Running head: CONTINGENT CAPTURE AND IOR

Contingent Capture Preceding Similar Magnitudes of IOR

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Abstract

Contingent capture is the stronger initial attraction of attention to task-relevant than irrelevant stimuli. Contingent capture has sometimes been doubted where task-relevant and irrelevant stimuli lead to equal magnitudes of inhibition of return (IOR). IOR is the faster selection of hitherto unattended than previously attended positions. Contingent capture is denied where IOR is the same for relevant and irrelevant stimuli because initial attention capture by relevant and irrelevant stimuli was then probably also the same. In the current study, we tested whether this conclusion is justified. We recorded saccadic IOR after relevant and irrelevant stimuli. At the same time, we recorded the N2pc, an event-related potential, reflecting initial capture of attention. At variance with the proposition that contingent capture must be denied where IOR is equal for relevant and irrelevant stimuli, we find stronger N2pc effects after relevant than irrelevant stimuli – that is, contingent capture –, although IOR to these two stimuli is the same. We conclude with a discussion of the mechanisms that are responsible for these effects.

Visual attention is the selection of visual information for purposes such as in-depth processing, perception or action control. Because we have to select information at all times, understanding attention is a key to an understanding of almost any form of cognition. To date, however, the mechanisms by which attention operates are not fully understood.

One very persistent debate in this area concerns the role of top-down control over attention versus stimulus-driven capture of attention. On the one hand, many researchers proposed that salient objects could be capturing attention in a bottom-up way (cf. Müller & Rabbitt, 1989; Theeuwes, 1992). According to the salience model of attention, for example, any visual stimulus that stands out among its surroundings by a strong feature contrast in color, orientation, or luminance, would be capturing attention in an exogenous stimulus-driven way and regardless of the current top-down search goals of the participant (cf. Itti, Koch, & Niebur, 1998; Parkhurst, Law, & Niebur, 2002). In line with this prediction, a color singleton – that is a stimulus with a color different from its surrounding stimuli and from the background, such as one green circle among several red circles –, interferes with finding a top-down searched-for shape-defined target stimulus (i.e., the one rectangle among several circles) (cf. Theeuwes, 1992). This is the case although the specific color of the singleton is neither necessary nor helpful to find the target. Results like this have been attributed to the bottom-up capture of attention by the irrelevant singleton. As a consequence, attention would first be distracted away from the relevant target and could only later be directed towards the target.

On the other hand, in many instances it seems that the participants can successfully ignore highly salient singletons. This is possible if a singleton does not match the set of searched-for relevant target features (Folk, Remington, & Johnston, 1992). For example, Folk and Remington (1998) had their participants search for a red target that was randomly presented at one out of four positions. Prior to the target, these authors presented either a top-

down matching (e.g., red) color-singleton cue at one of the potential target positions or they presented a non-matching (e.g., green) color-singleton cue. Both kinds of cues were equally salient. They were also both completely unpredictable of the most likely target position: Across the trials cue and target positions were uncorrelated. In line with top-down contingent attentional capture, these authors found a strong capture effect after the top-down matching cues. Responses were faster if the top-down matching cue was presented at the same position (SP) as the subsequent target than when it was presented at a different position (DP) than the target. This capture effect was absent if a non-matching singleton-color cue was used:

Reaction Times (RTs) for finding the target were about the same in conditions with SP non-matching and DP non-matching cues. These authors took their results as evidence for the fact that attention was top-down contingent. Attention was only attracted or captured by the singleton cue with a color matching to the mental template of searched-for target colors, whereas the attraction of attention was successfully prevented when the cue had a color different from the searched-for target color(s).

To explain the discrepant findings of researchers like Theeuwes (1992), a variety of possibilities were discussed. Folk and Remington, for example, argued that Theeuwes' (1992) results could have reflected unspecific color-filtering costs rather than a spatial attention-capture effect. This is possible because Theeuwes (1992) only used DP singletons and observed interference in the singleton-present as compared to the singleton-absent trials. Other researchers gave alternative explanations. Bacon and Egeth (1994) pointed out that Theeuwes' (1992) participants might have actively searched-for singletons. To note the shape-defined targets in the study of Theeuwes were also singletons, here: one angular target among circular distractors. A top-down search set to search for singletons might then have occasionally led to involuntary but top-down contingent capture by the color singletons, too. In line with this possibility, Bacon and Egeth (1994) were able to eliminate color-singleton interference if they forced their participants into a shape-feature search mode. They achieved

this by presenting a shape-defined diamond as a target together with irrelevant circles, triangles, and squares within the same displays. In this situation, the diamond target does no longer stand out as a shape-singleton. Instead, participants have to look for the diamond shape to find the target.

In their response to this criticism, Theeuwes, Atchley, and Kramer (2000) pointed out that especially the results of Folk et al. (1992) and Folk and Remington (1998) could have reflected initial stimulus-driven capture by all salient singleton cues plus quicker deallocation of attention after irrelevant than after relevant singleton cues. This is a plausible alternative explanation to reconcile the conflicting data with the bottom-up capture view because in the cueing paradigm of Folk et al. (1992) indeed a time of 150 ms elapsed between the cue and the target. During this cue-target onset asynchrony (CTOA) even the irrelevant singleton might have captured attention but if the participants were able to quickly withdraw their attention from the irrelevant or non-matching singleton-cue and back to a neutral position, then no trace of bottom-up capture would have been found at the time of the target's presentation (Theeuwes et al., 2000; Theeuwes, 2010; see also Kim & Cave, 1999). In addition, because it takes longer to tell the target-color-similar top-down matching cue from the target, the same CTOA would have been too short to successfully also identify the top-down matching cue as a cue and dellocate attention away from this cue before the target commences. As a consequence, when the target had its onset, attention would still have lingered at the top-down matching cue, hence, leading to advantages in SP as compared to DP conditions.

Basically, there is not much support for the deallocation explanation. Gibson and Amelio (2000), for example, used much longer CTOAs of 1000 ms to allow sufficient time to deallocate attention after the relevant singleton cues, too. This CTOA would have been long enough to already observe inhibition of return (IOR) – that is, deallocation of attention from

the cue plus active inhibition of the re-shifting of attention back to the cued position (Klein, 2000; Posner & Cohen, 1984; Taylor & Klein, 1998). Despite their long CTOA, however, Gibson and Amelio (2000) found no IOR after the relevant singleton-color cues and they neither found capture with a short CTOA nor IOR with a long CTOA after an irrelevant color-singleton cue.

Others, however, found small amounts of deallocation. This was reflected in reduced cueing effects for top-down matching cues with longer than shorter CTOAs (cf. Ansorge & Heumann, 2004; Pratt & McAuliffe, 2002) or in small amounts of IOR when the target required a saccadic rather than a manual response (cf. Godijn & Theeuwes, 2004). Importantly, however, the presence of deallocation or IOR after the matching (or non-matching) color singleton cues does not necessarily falsify the top-down contingent capture view. The contingent-capture view is concerned with the initial attraction of attention. According to the contingent-capture view, only the initial attraction of attention is determined by pre-existing top-down search sets for relevant targets. Therefore, to test whether quicker deallocation or IOR after irrelevant than relevant color singletons is a reflection of stimulus-driven attention capture or whether initially top-down contingent capture preceded IOR, one would also have to test whether the non-matching cue initially captures as much attention as the top-down matching cue (cf. Ansorge & Horstmann, 2007; Ansorge, Kiss, Worschech, & Eimer, 2011). This was the question that we wanted to put to a test in the present experiment.

Experiment

To test whether IOR could be found, our participants were asked to first shift their attention covertly (i.e., without the eyes) to a cue. This was necessary in the relevant conditions in which the singleton cue (e.g., a blue cue among grey distractors) indicated the

position of a discrimination target. After the covert shift, we asked our participants to conduct a saccade to a second position. The saccade target position was also indicated by a singleton cue but of a different color than the first cue. Whereas the relevant cue for the target discrimination was blue, for example, the relevant cue for the saccade was red. Importantly, however, the position of the saccade target and the position of the covert cue for the discrimination target were uncorrelated across trials. In addition, it is relatively certain that to conduct a saccade the participants have to allocate their attention to the position of a saccade target (cf. Deubel, 2008; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 2004). Therefore, the participants had to deallocate their attention away from the covert cue and towards the saccade target in a large majority of the trials. Also, the interval between covert cue and saccade target was 1 s long. This is sufficient to allow for both deallocation of attention and saccadic IOR (SIOR). We therefore expected SIOR with respect to the position of the relevant color-singleton cue (i.e., the cue that was used to covertly shift attention towards the discrimination target).

Importantly, however, at the same time we measured initial capture by the relevant singleton cue and compared this to the initial capture by an equally salient irrelevant singleton cue. The irrelevant singleton cue was of a different color than the relevant cues. For example, the irrelevant cue was green if the relevant cue was blue. This irrelevant cue was presented instead of the relevant cue in half of the trials. The participants knew that no target discrimination was required after the irrelevant singleton cue. Therefore, according to the contingent-capture theory, no initial capture by this irrelevant cue was to be expected. By contrast, according to a bottom-up capture perspective, we would expect attention capture after both, relevant and irrelevant singleton cues.

To test this prediction, we used the N2pc. The N2pc is an event-related potential (ERP) with a well-understood function and specific topography. The N2pc reflects the capture

of attention, either the selection of a relevant stimulus and/or the filtering-out of irrelevant distractors (cf. Eimer, 1996; Luck & Hillyard, 1994). It is a stronger contra- than ipsilateral negativity (with laterality defined relative to the left or right position of an attended stimulus). It occurs at about the time of the N2 – that is, at approximately 200-280 ms after stimulus onset. The N2pc has its maximum over posterior scalp areas, such as parietal, occipito-parietal, and occipital areas. These areas are concerned with visuo-attentional functions. The advantage of the N2pc is that it allows tracking attention in a continuous fashion with a high temporal resolution of 1 measurement per Millisecond. Related, the N2pc can be used to track the direction of attention even where the participants do not give an overt response. Therefore, the N2pc can be used for the current purpose of providing a clear picture of the initial attraction of attention, and in fact it has been used frequently for exactly this purpose. For example, Hickey, McDonald, and Theeuwes (2006) used the N2pc to confirm the existence of stimulus-driven capture after color singletons, whereas others recorded the N2pc and found evidence for the contingent-capture view (cf. Eimer & Kiss, 2008, 2010; Kiss & Eimer, 2011; Lien, Ruthruff, & Cornett, 2010; Lien, Ruthruff, Goodin, & Remington, 2008). Of particular interest for the current study, even when both relevant and irrelevant singletons capture attention, the N2pc can be used to determine the time of onset of initial capture in relevant (or matching) versus irrelevant (or non-matching) conditions (Ansorge et al., 2011; Ansorge, Kiss, & Eimer, 2009). Ansorge et al. (2011), for example, analyzed an early and a late window of the N2pc. In line with the contingent-capture theory, these authors found an earlier onset of the N2pc after matching than less or non-matching cues.

To summarize our rationale and predictions: We wanted to test whether evidence for deallocation in the form of SIOR can be found after relevant and irrelevant color-singleton cues. Several results are conceivable but most critically, if deallocation is quicker after irrelevant than after relevant cues (cf. Theeuwes et al., 2000), for example, it could be that SIOR in the irrelevant conditions exceeds SIOR in relevant conditions. Such a result would be

perfectly in line with bottom-up capture but according to our reasoning it could also be in agreement with contingent capture because one needs also an additional track of initial attentional capture. Therefore, alongside with the SIOR effects, we recorded the N2pc. This was done to test whether the initial capture of attention was stimulus-driven or whether it was governed by contingent capture.

Method

Participants. Twelve volunteers participated in this study (mean age = 25.25; 6 female). All observers reported normal or corrected-to-normal vision. Written and informed consent was obtained from each participant before the experiment.

Apparatus. Visual stimuli were presented on a 19-inch CRT color monitor (Sony Multiscan G400), with a screen resolution of $1,024 \times 768$ pixels. Its refresh rate was 100 Hz. The participants sat at a distance of 57 cm from the screen in a quiet, dimly lit room, with their head resting in a chin rest to ensure a constant viewing distance and a straight-ahead gaze direction. Manual responses for the discrimination of the discrimination targets were registered via a standard keyboard, placed directly in front of the observers. Participants' manual responses were given by the keys #F and #J (labeled "left" and "right"). Saccades were recorded with an EyeLink 1000 Desktop Mount system (SR Research, Mississauga, Ontario, Canada) with a 35mm lens, and EyeLink Software version 4.52, sampling at maximal resolution. Eyetracking was monocular from the dominant eye. A 9-point calibration was used to adjust the eyetracker before the experiment and in advance of every single block.

Stimuli and Procedure. Three successive displays were shown on each trial (see Figure 1). A central fixation cross was visible throughout each trial. All objects on the screen were equi-luminant (~ 30 cd/m²). The first display was presented for 50 ms. It consisted of six

equidistant placeholders, each of the shape of the digital letter 8 (with a size of $1.7^\circ \times 1.0^\circ$, and with a stroke strength of 0.3°). One of the placeholders was located at each of the positions 0° , 60° , 120° , 180° , 240° , and 300° from the vertical meridian – that is, the figure-8s were presented equally spaced on the circumference of a virtual circle centered on the screen, with an eccentricity of 7.0° . Five placeholders were presented in grey color (CIELAB color coordinates: 6.9, 16.8) and one was presented in a different color, either in green (CIELAB: -30.2, 24.9) or blue (CIELAB: 46.9, -89.0). This latter stimulus was the color-singleton cue. It was shown at the four lateral positions but it was never presented above and below the fixation.

--- insert Figure 1 about here ---

After an inter-stimulus interval of 450 ms, the discrimination display was presented for 50 ms. At the positions of the placeholders three letters “E” and three digits “3” were presented in digital notation. Five of these shapes were presented in grey color and one was presented in red color (CIELAB: 47.6, 41.1). The red cue could also appear at one of the four lateral positions. In this display, one figure served as a discrimination target if it had been cued by a blue cue (or green cue; cue color was fix across trials and balanced across participants) in the preceding display. By contrast, the red cue served as the cue for the saccade target in the subsequent display. Positions of discrimination target and red cue were uncorrelated across trials.

After another inter-stimulus interval of 450 ms the saccade display was presented with six circles surrounding the same stimulus positions as were used in the preceding displays. The saccade display was presented for 1000 ms and the other different shapes of the preceding display were not repeated.

The color of the singleton in the first screen indicated the task. A blue singleton was linked to the discrimination task while the green singleton could be ignored. (The roles of blue and green cues were reversed for half of the participants.) In the discrimination task, participants had to remember the shape of the digit presented in the second screen at the position of the blue (or green) singleton in the first screen. The red singleton in the second display indicated the position of the subsequent saccade target. The onset of the third screen was the go signal for the saccade. After the saccade was executed, participants typed the identity of the discrimination target letter on a standard keyboard. If no discrimination was necessary, this part of the trial was skipped. Participants started the next trial in a self-paced manner, by pressing the space bar. 500 ms elapsed after pressing the space bar and before the presentation of the next cue display.

Participants were informed that the color singletons could only appear at the four lateral positions on the screen and that the position of the second (red) singleton cue was independent of the position of the first (blue or green) singleton cue. Blocks consisted of 64 trials and feedback was given about whether the target discrimination was correct (if that feedback was appropriate) and about whether the saccade was registered during the third screen. Altogether ten blocks of trials were conducted, of which the first block counted as training and was not analyzed. Different possible combinations of the steps of the variables discrimination target (E or 3), first cue position (above/left, above/right, below/left, below/right), first cue color (blue, green), and second cue's position (above/left, above/right, below/left and below/right) were equally likely and presented in a pseudo-random order within each block.

EEG recording and analysis. EEG was DC-recorded from 23 scalp electrodes mounted in an elastic cap at standard positions of the extended 10/20 system at sites Fpz, F7, F3, Fz, F4, F8, Fc5, Fc6, T7, C3, Cz, C4, T8, Cp5, Cp6, P7, P3, Pz, P4, P8, O1, O2, Oz. The continuous EEG was sampled at a rate of 1000 Hz with a digital low-pass filter of 50 Hz.

Impedance was kept below 2 k Ω . No further filters were applied after EEG acquisition. All scalp electrodes were online referenced to a non-cephalic sterno-vertebral site, above the seventh vertebra and the right manilum sternum (Stephenson and Gibbs, 1951). The vertical EOG (electrodes below and above the left eye) and the horizontal EOG (electrodes at the outer canthi) were recorded bipolarly, so as to delete trials with eye movements after the recordings. Trials with saccades earlier than 100 ms after the saccade target (detected with the eye-tracker) or muscular artifacts (exceeding $\pm 80 \mu\text{V}$ at any electrode), as well as trials in which the target was not correctly discriminated, were excluded from analysis. ERPs were calculated for 400 ms after cue onset relative to a 50-msec precue baseline. N2pc amplitudes in response to the first color cue were calculated separately for left and right, and relevant and irrelevant cue, collapsed across all saccade target positions as mean ERP amplitudes at locations P3/4 in the 160-270-ms interval after cue onset.

Results

One participant had to be excluded because her saccade latencies were more than three standard deviations slower than that of the other participants. In total, 17.5% of all trials were excluded. Among the excluded trials, trials with saccades faster than 100 ms and slower than 1 s (8.1%), trials with saccades towards the wrong target or with EEG artifacts (6.4%), and trials with a false identification of the discrimination target (3%) were the most frequent incidences.

Saccade Task. To understand the dynamics of the saccadic response times (SRTs), SRTs were sorted for latency and grouped into five percentiles from fast to slow SRTs (cf. Theeuwes & Godijn, 2004). A repeated-measures ANOVA with the variables position (same vs. different position of covert cue and saccade target), cue type (relevant or irrelevant) and percentile (1st to 5th) indicated faster SRTs in trials with a relevant than an irrelevant cue in the first display (241 ms vs. 273 ms), resulting in a marginally significant main effect for cue

type, $F(1,10) = 4.72, p = .055$. SIOR was only found among the slowest responses in the form of slower SRTs in SP than DP conditions. From the 1st to the 5th quintile, SIOR (SRT in SP conditions minus SRT in DP conditions) was 0.05 ms, -0.84 ms, -4.12 ms, 3.27 ms, and 32 ms (1st to 4th quintile, all $t_s < 1.00$, 5th quintile, $t(9) = 2.29; p < .05$), resulting in a significant interaction of cue position and percentile, $F(4,40) = 2.79, p < .05$. Inhibition of return was selectively present in the slowest saccades and it was independent of the type of cue that was used in the first display. In addition, there was a numerically stronger SIOR effect after the irrelevant cue than after the relevant cue, as would be expected based on the deallocation explanation. However, the two-way interaction of relevance and position was not significant, $F(1,10) = 0.55, p = .48$, as was the three-way interaction, $F < 1.00$. Besides, there was also a trivial main effect of quintile, $F(4,10) = 94.56, p < .01$.

N2pc to the first cue. Figure 2 shows ERPs time-locked to cue onset at lateral posterior electrodes P3 and P4 contra- and ipsilateral to the first cue separately for cues with a relevant color and cues with an irrelevant color. The differences are depicted together with topographical ERP-difference maps for the time window of the N2pc (160 ms to 270 ms). All ERPs are relative to a baseline from -50 ms before the first cue to the onset of the first cue. As can be seen, there was an N2pc in the relevant and in the irrelevant cueing conditions. Also, the N2pc started later and it was weaker in the irrelevant than in the relevant cueing condition. These impressions were supported by formal analysis.

--- insert Figure 2 about here ---

A repeated-measures ANOVA with the variables cue type (relevant or irrelevant cue), laterality (electrode ipsi- or contralateral to the first cue), and hemisphere (right or left hemisphere) revealed a significant main effect for laterality, $F(1,10) = 7.3, p < .05$, and a significant interaction of laterality and cue type, $F(1,10) = 10.14, p < .01$. Both types of cues elicited an N2pc, regardless of whether the cue was relevant or irrelevant. However, if the cue

was relevant, the N2pc was stronger and started earlier. To demonstrate this, we split the N2pc window into an early phase (160 ms to 215 ms after the cue onset) and into a late phase (215 ms to 270 ms after the cue onset; cf. Ansorge et al., 2011). In the early window, an ANOVA revealed a significant two-way interaction of laterality and cue type, $F(1,10) = 30.17$, $p < .01$. Post-hoc t tests revealed that the contra-to-ipsilateral negativity difference ($-0.78\mu\text{V}$) was only significant in the relevant condition, $t(10) = 4.33$, $p < .01$, but not in the irrelevant condition ($0.02\mu\text{V}$), $t(10) = 0.08$, $p = .93$.

Discussion

In the present study, we tested whether SIOR after a relevant, top-down matching cue, and an irrelevant non-matching cue was equally strong and whether an initial attention shift to these cues was also of similar magnitude. Our results demonstrated about equal magnitudes of SIOR only among the slow saccades after both relevant and irrelevant singleton cues. If anything, the irrelevant singleton cue led to more SIOR. In line with previous results, this SIOR difference between relevant and irrelevant singleton cue was not quite significant, probably because the CTOA was already relatively long (cf. Ansorge, Priess, & Kerzel, under review). Importantly, qualitatively this observation of stronger SIOR after irrelevant singletons would be in line with the deallocation theory. According to the deallocation theory, attention is initially attracted by both relevant and irrelevant singletons, in a stimulus-driven way. Only after initial capture can attention be faster deallocated after the irrelevant than after the relevant cue, so as to falsely suggest different amounts of attention capture by these cues, at the time that the target was presented (cf. Theeuwes, 2010; Theeuwes et al., 2000).

However, when we looked into the N2pc as an index of the initial capture of attention, we found that the relevant cue initially captured more attention than the irrelevant cue. This observation is not in line with the deallocation explanation in its elaborated form. In other words, similar amounts of deallocation after relevant and irrelevant singletons do not

necessarily reflect similarly strong initial capture by relevant versus irrelevant singletons. The N2pc results of the present study are, by contrast, perfectly in line with the contingent-capture view (cf. Folk & Remington, 1998; Folk et al., 1992). They show that the earliest attentional effect of the singletons was driven by the cue's relevance. This result also aligns with many similar observations (cf. Eimer & Kiss, 2008; Lien et al., 2010). It shows that initial capture of attention and later deallocation are partly independent processes, meaning that both can contribute to the net cueing effect that is observed at the time an overt response to the target is recorded (cf. Ansorge & Heumann, 2004).

The present results are also interesting in that they show that IOR can be found after attention capture by color singletons. This is different from studies such as those of Gibson and Amelio (2000) who failed to find any evidence for IOR after color singletons, a result that was ascribed to the special role of abrupt onsets for the occurrence of IOR. Here, we show that even relevant color singletons lead to IOR when an eye movement instead of a manual response is used and when the SRT is taken into account. In line with this interpretation, Godijn and Theeuwes (2004) also demonstrated SIOR after color singletons in a saccade task. Also, the dynamics of attention and IOR can be easily overlooked when only one mean RT value is interpreted as has also been shown more than once before (cf. Theeuwes & Godijn, 2004; van Zoest, Donk, & Theeuwes, 2004).

Finally, we found some attention capture in the N2pc even in the irrelevant conditions. Several factors might account for this attention capture effect. First, it is possible that stimulus-driven capture took place but at a slightly later point in time than top-down contingent capture. According to this logic, top-down control settings could be working in a pre-emptive way so as to foster the top-down matching signals during first-pass processing. As a consequence, the top-down matching signal would attract attention due to the convergent operation of two factors, bottom-up salience and pre-sensitization of the neural mechanisms

responsible for the processing of the relevant features. By contrast, the irrelevant stimulus would only benefit from its salience and, thus, would at least on average attract attention slightly slower than the relevant cue. It is also possible that the participants sometimes searched for singletons instead of searching for only the relevant colors (cf. Bacon & Egeth, 1994; Leber & Egeth, 2006). The decisive difference is that singleton search is a form of top-down search, with the only difference that the corresponding search template would not be directed towards particular features but instead towards the singleton status of the relevant stimuli. In the current study, a singleton search mode would have allowed the participants to search for both relevant colors, that for the covert shift of attention in the first display and that for the overt shift of the eyes in the second display. Related, it has been shown that the participants can find it difficult to search for more than one color at a time (Folk & Anderson, 2010). If the participants used a singleton search mode at least in some of the trials, the irrelevant cue would have also captured attention to some degree. Interestingly, recent research by Ansorge et al. (2011) suggested that singleton search might be slightly slower than feature search, an observation nicely fitting the later onset of the N2pc in the irrelevant than the relevant conditions of the present study.

In conclusion, we have shown that SIOR after color singletons is not only a reflection of initial capture and that conclusions about initial capture that are only based on IOR should be accordingly drawn with great caution (cf. Pratt, Sekuler, & McAuliffe, 2001).

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Figure captions

Figure 1: Depicted is an example of a different-position (DP) trial. The first (lower) display was the cue display, in which a color singleton cue (illustrated as a black figure-8) was presented; a blue (or green) singleton indicated the position of the subsequent discrimination target (relevant cue); another singleton cue, green (or blue) indicated that no discrimination task followed (irrelevant cue). The second (middle) display was the discrimination display; for example, following a blue singleton cue, participants had to memorize the identity (figure-E or figure 3) at the position cued by a blue singleton. Alongside the discrimination target, we presented a red color singleton as saccade cue (depicted as a black figure). The third (upper) display was the saccade display; participants had to saccade to the target ring at the position cued by the red singleton. The arrow illustrates the temporal sequence. Stimuli are not drawn to scale. SOA = Stimulus Onset Asynchrony.

Figure 2: On the left: Depicted are ERPs (in μ Volts on the y axis) ipsilateral to the cue (black lines) and contralateral to the cue (broken lines) as a function of the time since cue onset (at zero) on the x axis. On the right: Depicted are scalp distribution plots of mean ERP activity in response to the cues in a time window of 160 to 270 ms after the cue, with negative values in blue and positive values in red. Top row: ERPs to relevant cues. Bottom row: ERPs to irrelevant cues.

Figure 1

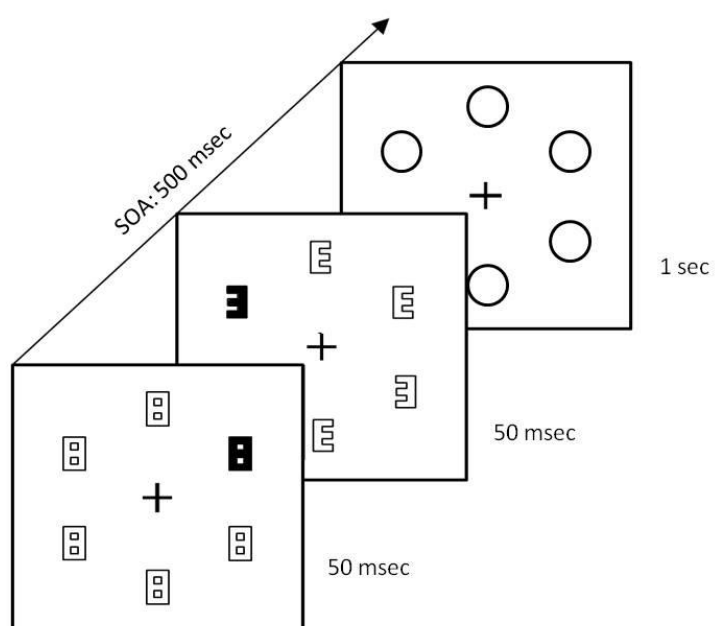
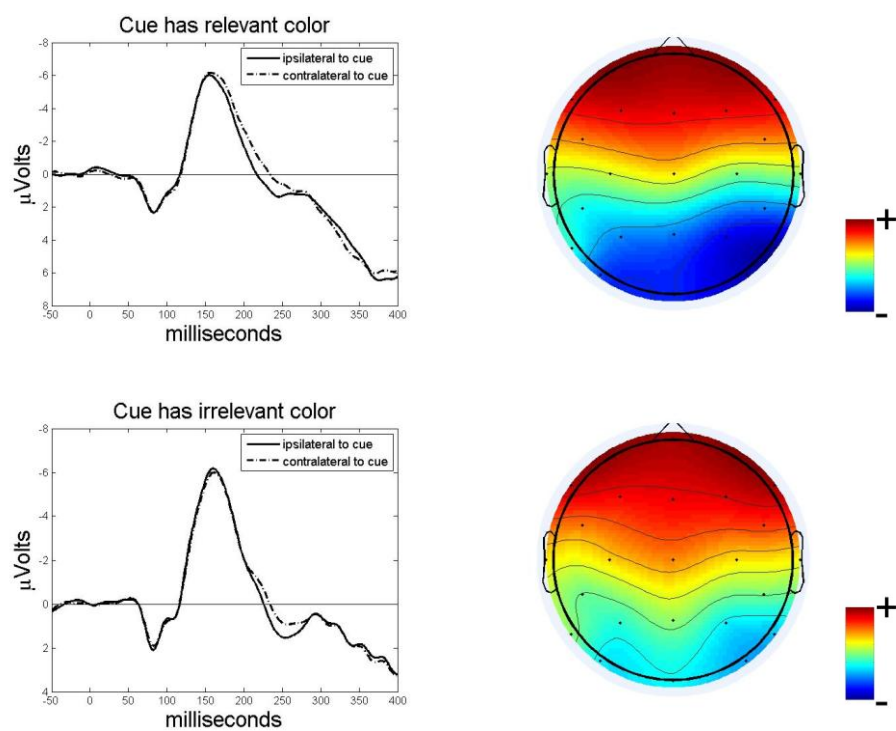


Figure 2



General Discussion and limitations of this thesis

Conclusion

Our goal was to shed light on the contribution of visual attention to two visual phenomena, the FLE and IOR. For the FLE the contribution of attention was unclear. In the majority of theories the FLE is discussed as a pre-attentive phenomenon. Thus, attention could be a candidate to modulate the effect but the origin of the FLE should be found elsewhere. However, the attentional account leads to new, never before tested predictions. 1) The spatial illusion is accompanied by a temporal illusion of the opposite direction, 2) conditions that are known to eliminate the visual illusion should eliminate the temporal illusion as well, and 3) the visual illusion should be reversed if the task demands another sequence for the deployment of attention. All three predictions could be confirmed (chapter 2 and chapter 3).

The contribution of visual attention to IOR remains somehow unclear. Previous research suggested exogenous attention capture as the root cause of IOR. IOR was reported to occur after exogenous attention capture regardless of the observers' task. Goal-driven attention shifts failed to produce IOR. In this thesis the contingent capture approach is used to elicit IOR. In chapter 4 we asked our participants to pick a location indicated by a cue (or do nothing if another cue was shown) and saccade towards another location, indicated by a second cue. We found similar IOR for relevant cues as well as for irrelevant cues. This outcome suggests exoge-

nous attention capture as root cause for IOR. However following experiments challenged the result. With a reduced stimulus onset asynchrony (SOA - 200 ms and 300 ms) and spreading of the reaction times according to their latency, the task became relevant for IOR. In all experiments, IOR was a function of response latency. The slower the response, the more IOR was present. However with short SOA irrelevant cues led to IOR for fast and slow reactions while relevant cues lead to capture for fast reactions and IOR for slow reactions. This result fits nicely with the assumption of singleton capture and differential disengagement for irrelevant and relevant cues (Theeuwes, 2010). However, if the task gets a bit more complicated, the results change. In chapter 5 and chapter 6 the observers' task was not only to pick a lateral position but to identify a stimulus on this position. Here the size of IOR was reduced and IOR was not a monotonically increasing function of response latency. Task relevant and task irrelevant singletons resulted in similar magnitudes of IOR. However, attention shifts towards color singletons, quantified with the N2pc component, were task sensitive. While every color singleton elicited an N2pc they differed for relevant and irrelevant singletons. In response to a relevant singleton the N2pc was starting early and well pronounced. In contrast an irrelevant color singleton produced a late and small but still significant N2pc. This is in stark contrast to the predictions of the differential disengagement account but fits with contingent capture (Ansorge, Horstmann, & Carbone, 2005; Folk & Remington, 1998; Folk et al., 1992). These results are in line with similar studies (Eimer & Kiss, 2008; Lien, Ruthruff, & Cornett, 2010). Together they suggest, ini-

tial capture and later disengagement are based on different processes.

Outlook and limitations of this thesis

Aside from the reported results some questions remain unanswered and some new questions have emerged.

Overt and covert attention

Usually covered attention is measured with reaction times. Reaction times could be due to manual or oculomotor (overt attention) responses. If reaction times vary in response to differential attentional work load, this could lead to the assumption of a tight coupling of both concepts. However, this might not be true, as we have seen in chapter 6. If the deployment of attention is measured with the N2pc component, attention can be quantified without overt visible reactions. And indeed, differential attentional capture as measured with the EEG did not vary necessarily with overt attention shifts. Following studies should investigate the relationship from the onset and size of the N2pc to overt reaction measures as reaction times or accuracy. If the dissociation of attention shifts to reaction times should be investigated for different tasks.

The flash-lag effect and attentional capture

Though all predictions of the attentional account of the FLE could be found in the data, it does not mean the attentional account is the right explanation. Perhaps observers use different cues to solve the temporal task and the spatial task. Thus the

spatial task could be initiated by the onset of the flash while the temporal task is initiated by the change of the tracked object. Thus our confirming results could be due to unrelated reasons. To test the attentional capture hypothesis of the FLE it would be nice to have an independent measure for attentional capture. The previously reported N2pc component would be a good candidate to measure attention. A possible test could use two conditions. In one condition two equiluminant objects with different colors start in the periphery, move horizontally towards the center and depart again. While in the center, a central flash occurs in one or the other color. The observers' task is to judge the spatial distance of the flash and the moving object sharing the same color. The dependent variable should be the appearance and possible onset of an N2pc towards the moving object of the same color. In a second task the flash occurs not in the center but in the periphery. The task remains the same. The flash has to be judged relative to the object in the same color. But now it is the N2pc towards the flash that is measured. In order to verify the attentional account, one would expect the following outcome: 1) there is an N2pc towards the flash. 2) There is an N2pc towards the moving object of relevant color. 3) The latency of the N2pc towards the flash is shorter than the latency towards the moving object.

Inhibition of return (IOR)

Our behavioral results are in line with the differential disengagement hypothesis (Theeuwes, 2010). However, the electrophysiological results are at odds. This could indicate different mechanisms for attention capture and motor preparation as

supposed by Van der Lubbe, Vogel, and Postma (2005). They reported a dissociation of attentional capture and motor preparation in response to automatic and voluntarily attention shifts. A limitation of our studies is the separation of behavioural and electrophysiological measures and a slightly different task for one of the three different chapters. EEG was recorded only with our maximum SOA of 500 ms. Thus the EEG signal in the first 500 ms after one cue is not biased by a following cue and can be taken as the result of the cue. However, for shorter SOAs and a more easy task, we found dissociating effects for cues of equal salience but different relevance. In addition the time bin analysis for shorter SOAs showed a strong relation from IOR to reaction times. Thus a following study should focus on shorter SOAs, the easy task and different time bins. Following this strategy one could measure differential reaction times and differential attentional captures within the same subjects. This facilitates the interpretation of the results. Strong electrophysiological results were obtained in a condition, in which participants had to identify an object at the location of the cue, 500 ms after the cue was presented. Strong behavioural results were found in response to location picking after relevant cues. Thus the mechanism responsible for differential IOR after different cues could be at odds with a mechanism responsible for IOR after shifting attention in order to read.

Another limitation is our use of the contingent capture paradigm. In the discussed experiments a double task was used. The first task was used to capture attention (remember a position or read a letter) and the second task was used to measure a

reaction (saccade towards the target). However, usually the effect of contingent capture is examined with single task operations. Thus, a more straight-forward contingent capture design should split the double task in two separate single task operations (e. g. first showing a cueing screen and afterwards identifying a letter or shifting the gaze).

The N2pc component as a marker of covert visual attention

The N2pc component is widely accepted as a marker for initial attention capture. However, this component is starting comparably late. Manual or oculomotor reactions can be observed up to 100 ms post target. However, the earliest onset for the N2pc as found in chapter 6 is 160 ms post cue. A latency of 160 ms for an attention shift could be a little late for reactions faster than 160 ms. So it is possible that the N2pc is not a direct measure for an attention shift but a correlate of a result of a previously accomplished attention shift. And indeed a study of Kiss, Van Velzen and Eimer (2008) revealed that the N2pc does not reflect an attention shift but is instead linked to spatially selective attentional mechanisms that occur after an attentional shift is completed. Thus the onset of the N2pc does not reflect the onset of an attention shift but rather the offset of an attention shift. However, referring to the experiment in chapter 6 this would not alter the interpretation of the results.

Zusammenfassung

Wenn wir uns in der Welt umsehen, dann wählen wir immer bestimmte visuelle Information aus, während wir andere Information ignorieren. Dieser Mechanismus nennt sich selektive visuelle Aufmerksamkeit. Selektive visuelle Aufmerksamkeit wird als Hauptursache verschiedener visueller Illusionen gesehen. Beispiele hierfür sind: „prior entry“, „cueing“, „inhibition of return (IOR)“, „Unaufmerksamkeitsblindheit“, „Wechselblindheit“ und der „Flash-Lag Effekt“. Während der Beitrag von Aufmerksamkeit zu einigen Phänomenen klar erscheint, ist er für den Flash-Lag Effekt und für IOR höchst umstritten. In dieser Dissertation wird die Frage gestellt, inwieweit visuelle Aufmerksamkeit die Ursache für beide Phänomene sein kann. Der Flash-Lag Effekt ist eine visuell-räumliche Illusion. Die meisten Theorien sehen seine Ursache in basalen, von der Aufmerksamkeit unabhängigen Prozessen. In Kapitel 2 und 3 zeige ich Experimente, die Aufmerksamkeit als Ursache der Fehlwahrnehmung untersuchen. Sollte Aufmerksamkeit den wesentlichen Beitrag leisten, dann leiten sich hieraus neue Vorhersagen ab: 1) der räumliche Effekt sollte von einem zeitlichen Effekt mit umgekehrtem Vorzeichen begleitet werden, 2) wenn man den räumlichen Effekt verschwinden lässt, dann verschwindet auch der zeitliche Effekt und 3) wenn die Aufgabe eine umgekehrte Reihenfolge der Beachtung vorsieht, dann wird auch der räumliche Effekt umgekehrt. Alle neuen Vorhersagen konnten bestätigt werden. Für IOR sehen meine Schlussfolgerungen dagegen weniger klar aus. Schon in den ersten Studien zu diesem Phänomen war den meisten Forschern klar, dass es sich um ein Aufmerksamkeitsphänomen han-

deln muss. Allerdings haben folgende Studien alternative Erklärungen vorgeschlagen. In dieser Dissertation nutze ich das aufgabenbezogene „contingent capture“ Paradigma, um den Beitrag von Aufmerksamkeit zu IOR zu untersuchen. Wenn Aufmerksamkeit die Hauptursache für IOR sein sollte, dann müssten aufgabenrelevante Objekte einen stärkeren Effekt nach sich ziehen. In Kapitel 4-6 wird gezeigt, dass diese Hypothese so nicht bestätigt werden kann. Die Aufmerksamkeitszuwendung ist für relevante Objekte tatsächlich stärker (Kapitel 6), allerdings ist IOR wenn überhaupt, dann bei irrelevanten Objekten stärker. Zusammen zeigen die Ergebnisse, dass die Zuwendung von Aufmerksamkeit nicht als alleinige Erklärung für IOR geeignet ist. Weitere Mechanismen müssen hier einen Beitrag leisten. Zusammengefasst zeigen die Ergebnisse, dass visuelle Aufmerksamkeit eine Ursache für den Flash-Lag Effekt sein kann. Dagegen ist visuelle Aufmerksamkeit als alleinige Ursache für IOR eine unzureichende Erklärung.

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