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„Attentional capture by abrupt onsets during visual-dynamic tracking"

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Introduction

Imagine driving through the countryside. While you drive along a narrow winding road, you approach a preceding car. As the narrow lane and the many curves make overtaking difficult, you have to be careful to keep your distance to the car before you. How do you manage to keep focused on the relevant information – that is the back of the preceding car? In this situation, this is a challenge given the potential for distraction: By driving, your whole visual environment is set in motion, resulting in a great amount of interesting and novel information entering your field of view through your shifting visual perspective all the time.

This short example illustrates the question I seek to answer with the present thesis. Before getting to the details of how I went about this, I will introduce the reader to the relevant theoretical background for the topic, beginning with a short section about driving and its potentially dangerous aspects. Then I will explain the functions of vision, highlighting the importance of selectivity in vision. Where would we be without our ability to focus on the relevant and ignore the irrelevant? I will thereby shortly introduce the reader to the attentional capture debate and its concurring representatives. Building up on this, I will show how attentional processes behave differently, depending on factors like task type, by summarizing the results of past studies coming to substantial conclusions. I will deal separately with the role of newly emergent objects in the visual scene, which have a special relevance for our experiment. In the following, I will introduce the reader to contingent capture theory to show the relevance of features matching the search intentions of the observer and then arrive at eye movements in smooth pursuit, as this is exactly what is required when we navigate through our environment, e.g., when driving a car through the streets. Outlining what we already know about human ability to focus under conditions of smooth pursuit, leading straight up to what I investigated in the current study. Let us start with a few words about driving.

Driving is a complex and dangerous activity with high requirements for human perception and attention (Johnson & Wilkinson, 2010): Every 24 seconds, a person is killed while driving, adding up to a total of 1.35 million deaths per year (World Health Organization, 2020). Despite numerous technological advantages, the rate of road traffic death has been remaining roughly the same in the last 20 years. Especially night driving results in an overproportioned amount of deaths compared with driving through daytime (Niemann et al., 2009). One potential source of danger is the production of new light dynamics created by the interaction of headlights and the environment, joining the vast amount of to-be-processed information while driving. These light dynamics have the potential to attract attention involuntarily and can lead to reduced perception of other, potentially more important information like traffic signs (Owens et al., 2007) and even other traffic participants (Owens & Sivak, 1996). Our study aimed to explore the underlying conditions under which attention and driving safety might be affected. We did this by investigating whether suddenly appearing stimuli that share the same color characteristics as a to-be-tracked moving object, similar to the task of driving while focusing on the road, attracted attention.

The attentional capture debate

This section gives a short overview about vision and the selectivity on it, leading to a rendition about the debate around the working mechanisms of this very selectivity. The visual world, in which we face a multitude of challenges every day, is diverse and complex. Vision allows humans to experience their environment, with object recognition being one of its main function (Yantis, 1998). Another primary function of visual perception is action control, embedded in the broader, evolutionary goal of species conservation (Gibson, 1966). According to Gibson’s theory, these two goals of visual perception are basically ident, humans perceiving *affordances* of objects, which are properties of the objects representing the actions the user can take with them. For example, a lever is perceived as something to be pulled, whereas a car is perceived as something to sit in and to drive with.

In order to be able to act in a goal-directed manner, we focus our resources on goal-relevant visual information. This can be either seen as a filtering process (Broadbent, 1958; Theeuwes, 2018). Here is where visual attention comes into play, making it possible to prioritize environmental information. Visual attention is considered to have two primary functions: Selection-for-perception (Posner, 1980), referring to information extraction from the environment, e.g., to understand the scene one is surrounded by, or to identify objects, and selection-for-action, referring to the extraction of relevant information for goal-directed action planning (Allport, 1987). When stimuli in the environment are prioritized in terms of their processing, this is called attentional capture (Theeuwes, 1992).

Over the last decades, a wide-ranging debate has risen regarding the extent to which attentional capture is automatically controlled by the properties of certain features of stimuli, voluntarily controlled by the observer, or a mixture of both (Theeuwes, 2010). The most relevant distinction in the field of visual attention is therefore the one between *goal-driven* (top-down, endogenous) and *stimulus-driven* (bottom-up) *attention*. Top-down attention is endogenous, controlled strategically and relies on volition to be directed to specific parts of the environment (Schoeberl & Ansorge, 2017). Goal-directed theories claim that only stimuli that match the current goals of the observer, called *attentional set*, are able to capture attention

(Folk et al., 1992). On the other hand, bottom-up attention is automatic and entirely driven by environmental properties, immediately directed to the stimulus after its occurrence (Posner, 1980; Theeuwes, 2010). Stimulus-driven attentional theories claim that stimuli that are salient enough capture attention in an automatic manner, independent from the observer's goals or intentions (Theeuwes, 1992; Yantis, 1993a). Physical salience of a stimulus is defined by local feature differences in orientation, color and luminance (Itti & Koch, 2001; Theeuwes, 1992) and it is crucial for attentional capture.

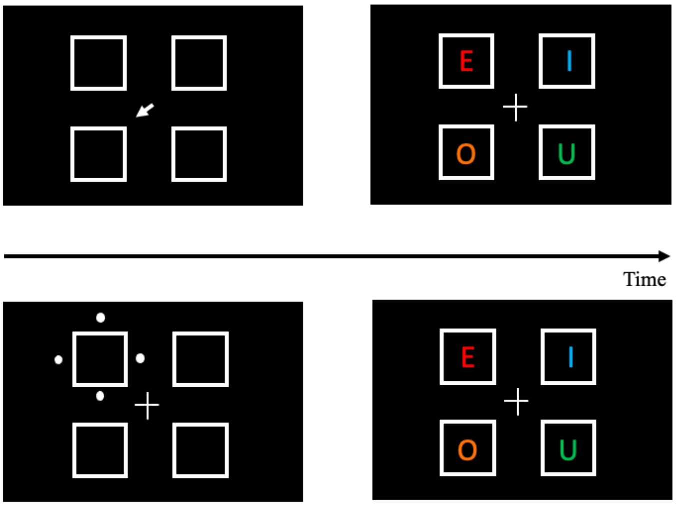
In the last 20 years, many theoretical and computational models came to the conclusion that the signals influencing attentional processes converge on a spatial priority map in the human brain (e.g., Bisley, 2011; Itti & Koch, 2001), integrating both top-down and bottom-up signals and leading to attentional capture toward the position with the highest activation on the map. But there is a third influencing factor on this priority map next to explicit (top-down) goals and sensory (bottom-up) information: Computations on the map can be adjusted by biases due to the history of former attentional capture processes by the observer, called selection history (Failing & Theeuwes, 2018). If one signal rises, others may get inhibited (Desimone & Duncan, 1995; Godijn & Theeuwes, 2002). Theeuwes and Failing (2018) claim that while salience and selection history influence selection at an early stage, top-down processes have an impact on the priority map in a later stage, although the nature of this interaction is not yet well researched.

Attentional capture by spatial cues

Here, I intend to cover some of the early experiments around attentional capture, many of which were designed using spatial cues, before leading to the discovery of distinct attentional mechanisms important for my research. A spatial cue is a stimulus which precedes a to-be-searched-for target (Posner, 1980) and can be valid, therefore correctly indicating target location, or invalid, by providing misleading spatial information about the potential target position. The difference between invalid and valid performances, defined as reaction time on invalid trials minus reaction time on valid trials, is called a *validity effect* (Ansorge, 2004; Lien et al., 2008). Cues can also be central or peripheral: A *peripheral cue* is a stimulus manipulation presented at or near one of the possible locations of the target stimulus, while a *central cue* is normally provided symbolically in the center of the visual field, providing information about a possible target location, e.g. an arrow (Ansorge & Heumann, 2003; Riggio & Kirsner, 1997). The difference between the two cue types are shown in Figure 1.

Figure 1

Central and Peripheral Cues



Note. On the top, a hypothetical search display with four items in the search array is depicted. An arrow in the center indicates a possible target position before the target display with the to-be-searched-for item is shown, thereby serving as a central cue. On the bottom, four white dots appear at a possible target position before the target display is shown. Please note that cues do not have to reliably indicate target position.

Eriksen and Hoffman (1973) were the first to show that voluntary direction of attention to spatial locations is possible by visual cues which are informative about the location of a given target, followed by Posner's (1980) experiment, in which he showed that valid cues lead to faster responses, whereas invalid cues slow down responses. Posner interpreted these effects as evidence for an attentional spotlight mechanism: Whenever participants see a cue, they orient their attention toward it, thereby enhancing visual processing at the cued location.

These findings also led researchers to the assumption that a peripheral display saliency change would capture attention in a bottom-up way. This was confirmed by Jonides (1981), showing that while peripheral cues captured attention even when participants intended to ignore them, central cues were only effective when participants adopted top-down strategies for cue usage.

Following up on this experiment, Müller and Rabbitt (1989) showed that attentional capture by peripheral cues could not be suppressed even if the cues were irrelevant (uninformative about the target location), while Remington et al. (1992) showed that peripheral display changes captured attention even when there was a substantial reward for ignoring the cue. Habituation also seems to play a role in attentional capture by spatial cues. First reported by Warner et al. (1990), after about 4,500 trials, participants were able to ignore peripheral cues, implying the existence of two different attentional mechanisms: a fast one responding to peripheral events, with rapid and automatic attentional capture and rapid disengagement, and a slower one, which is voluntary and is fueled by effort (Yantis, 1998).

Attentional capture by feature singletons

Let us cover some of the most important attentional experiments which used *feature singletons*, like I did in my current experiment. Feature singletons are visual stimuli that differ from their homogeneous immediate surroundings and fulfil the criterion of salience (Duncan & Humphreys, 1989). For example, a unique green circle on a uniform black background will appear as salient to the viewer. As singletons are rather easy detected in visual search experiments, one might assume that they capture attention automatically. Initial findings by Pashler (1988) and Theeuwes (1992), where participants could not ignore task-irrelevant color singletons, strengthened this impression. In the experiment by Pashler (1988), subjects had to search for a circle amongst tilted lines or a tilted line amongst circles and report the location of the form singleton. Two elements were colored red and served as the distractors, the rest of the elements were green. Although participants knew that the red color singletons were irrelevant and should have been ignored, they were not able to do so, indicated by decreasing localization accuracy. In the experiment by Theeuwes (1992), participants had to report the orientation of the line embedded into red and green diamonds and circles placed around a fixation point. The target differed from the other forms in shape, thereby indicating uniqueness. On some of the trials, one form had a unique color, thereby serving as a distractor, although participants knew that color variation was not relevant for the task. Distractors never served as a target and the targets had to the same color as the other diamonds except the distractor: When the distractor diamond was red, all the other diamonds including the target diamond were green. Response times of the participants were significantly higher when the color singleton was present, thereby indicating attentional capture. Conversely, multiple experiments came to the conclusion that task-irrelevant feature singletons, unlike task-irrelevant peripheral cues, do not capture attention (Hillstrom & Yantis, 1994; Jonides & Yantis, 1988).

To account for the inconsistency of findings regarding attentional capture by singletons and equipped with the findings of the contingent-capture paradigm, Bacon and Egeth (1994) replicated the findings by Theeuwes (1992) and then changed the design in a way that the target feature in the display was not a singleton anymore. Bacon and Egeth (1994) found that under these circumstances, singletons did not capture attention anymore, as the attentional strategy in place, named *singleton-detection mode,* was suspended. This led the authors to the conclusion that in the experiments by Theeuwes (1992) and Pashler (1988), participants adopted a certain search strategy they called *singleton-detection mode,* and that in case of the adoption of a different attentional strategy, irrelevant singletons do not capture attention. This limits the findings by Pashler (1988) and Theeuwes (1992), who both concluded that irrelevant singletons could not be ignored.

Capture by abrupt onsets

The distractor stimuli we used in our experiment were not only feature singletons, they also belonged to another category, namely that of *abrupt onsets,* which are newly emergent objects in the visual scene and said to attract attention in a bottom-up manner (Theeuwes, 1992; Yantis & Jonides, 1990). Abrupt onsets have a unique status in attentional research and should be considered here separately for full understanding of the reader, before diving deeper into methodical parts of our study. The unique status of abrupt onsets is an important evolutional mechanism, giving attentional priority to possible dangerous or even hazardous events in the environment (Turatto et al., 2018). According to this view, it is no surprise that attentional capture by abrupt onsets can happen even regardless of top-down settings (Gaspelin et al., 2016). Despite these findings, there is no definitive agreement between researchers when it comes to this question. Remington et al. (1992) examined the extent to which abrupt onsets capture attention in an involuntary way using a paradigm in which participants were incentivized to ignore abrupt onsets. According to the authors, this was the first study which really investigated if abrupt onset stimuli capture attention in an involuntary fashion, as previous studies did not meet this condition by either being the target itself (Yantis & Jonides, 1984), being at the same location as the target (Müller & Rabbitt, 1989) or showing task-relevance (Warner et al., 1990). Remington et al. (1992) presented a target letter which was preceded by a brief flashing abrupt onset stimulus at one of four target locations. In the distractor conditions, the abrupt onset always appeared at a different location as the target. Participants were informed about this relationship and were told to ignore the distractor. Compared with the other conditions in which the onset stimuli appeared at the target location, at the center, or did not appear, the authors found increases in choice reaction times in the different-location condition, indicating involuntary attentional capture by irrelevant abrupt onsets. The authors concluded that exertion of direct attentional control to prevent attentional capture by onsets is not possible under these circumstances; however, Yantis and Jonides (1990) found that if attention is focused on a specific location which also contains the target so that the target location is known for certain (cf. also Müller & Rabbitt, 1989), attentional capture can be prevented. This finding is also relevant for our experiment, although our target did not have a steady location but was moving in a predefined way, thereby establishing positional prediction up to a certain degree.

Researchers are divided if irrelevant onsets capture spatial attention, with study results split up between both possible answers. Gaspelin et al. (2016) hypothesized that this might be due to the difficulty of the underlying visual search task of the respective experiments. The authors argued that different research groups use different experimental tasks to investigate onset capture. Supporters of the goal-driven account mostly use the spatial cueing paradigm explained above (e.g., Anderson & Folk, 2012; Folk et al., 1992; Lien et al., 2008), whereas supporters of the stimulus-driven account often use the irrelevant feature paradigm (e.g., Franconeri & Simons, 2003; Yantis & Jonides, 1984). In these experiments, there is one stimulus missing in a circular search array of several eights, which serve as placeholder masks, before all masks are removed (by parts of the eights disappearing) so that they show a letter, and an additional letter – the abrupt onset – appears at the blank space in the array. Participants then have to report which of two predefined letters is present in the experiment at any location in the search array. Goal-driven researchers mostly use color search, while stimulus-driven researchers frequently use letter search.

Gaspelin et al. (2016) manipulated search type and search dimension in their experiments and indeed found differences in validity effects. They argued that these differences may explain the difference in previous results, through their differences in search difficulty. The authors hypothesized that onsets capture attention, but easy visual search used by goal-driven researchers containing irrelevant onset cues is not able to demonstrate this capture, as easy visual search does not result in observable costs indicated by higher reaction times (cf. also Theeuwes, 2010). Unlike the rapid disengagement hypothesis (Theeuwes et al., 2000), Gaspelin et al. (2016) attribute these missing effects to attentional dwelling. Rapid disengagement proposes initial attentional capture by the cue, followed by a quick rejection and an attentional shift to a neutral position. The attentional dwelling hypothesis by Gaspelin et al. (2016) states that there is no rapid disengagement of spatial attention from an onset cue but continuous lingering of attention on it after initial capture until the target is shown.

Contingent capture

An even more relevant question for our experiment is if distractor onsets, which are similar to the search template of an observer in a certain property like color or orientation, capture attention. On the contrary to purely stimulus-driven attentional theories, it is often argued that attentional capture relies on top-down attentional sets under certain conditions (Folk et al., 1992; Goller et al., 2016). According to this framework, also known as *contingent-capture theory*, only features that match the search intention of a subject attract attention, while features that are not coherent with their search intention do not lead to attentional capture. In contingent-capture experiments, participants have to search for a target immediately preceded by peripheral cues, which are nonpredictive regarding the target's location (invalid). If the validity effect, defined above as the reaction time on invalid trials minus reaction time on valid trials, is stronger when a cue has matching properties with participants' top-down settings than when it is a non-matching cue, the difference is called the contingent-capture effect. Folk et al. (1992) proposed that subjects adopt an attentional control setting (e.g., singleton search) that determines which features of a stimulus attract attention in a given task. This statement has been repeatedly challenged in the last three decades by different findings. Yantis (1993b) found that attentional capture by abrupt visual onsets happens even without a fitting search strategy for abrupt onsets, implying that a top-down attentional set is not per se needed for attentional capture. According to Yantis (1993b), one possible explanation for this uniqueness of abrupt onsets in capturing attention in a bottom-up fashion is that onsets accompany newly presented objects which is crucial for human survival, as new objects might bring unknown danger with them. In our experiment, we used distractors with the same color as the central part of the target, thereby establishing matching conditions.

In a recent meta-analysis of contingent capture effects, Büsel et al. (2020) additionally showed that non-matching and matching cues capture attention differently: Attentional capture by non-matching cues is never as good as by matching cues. The authors found a highly significant overall contingent-capture effect across the studies they have investigated. One might have expected that there might be more stimulus-driven and less contingent capture with using abrupt onsets as targets than with using static feature targets, but this was not the case. Büsel et al. (2020) also found that contingent-capture effects cannot be explained by rapid disengagement or intertrial priming alone and found less capture for singleton search than for feature search.

Goller et al. (2020) demonstrated top-down contingent capture by using color-matching and non-matching abrupt onset cues and providing electrophysiological evidence by examining their effects on an event-related potential called N2pc. N2pc is a specific visual event-related potential that has been linked to spatial attentional deployment (Woodman & Luck, 1999). It is observable 175-300 ms after stimulus presentation and is defined as a larger negative voltage contralateral than ipsilateral to the presented stimulus. According to Eimer and Kiss (2008), N2pc indicates attentional capture by cues even before target onset. In contrast to the assumptions of automatic attraction of attention by task-irrelevant, sudden-onset stimuli, Goller et al. (2020) found no evidence for this in the ERPs. According to Theeuwes (2010), however, this could only mean that attention did not linger long at the location of the cues, since the attention-induced ERPs could reflect processing following the attraction of attention rather than the attraction of attention itself.

Goller et al. (2020) argued that if abrupt-onset cues attract attention in a stimulus-driven way, N2pc activation should take place regardless of cue-to-target-similarity (Hickey et al., 2006). That means that also non-matching abrupt-onset cues should produce an N2pc. However, if contingent-capture theory is correct, only matching cues resembling top-down attentional control settings should trigger capture. They found that abrupt onset cues elicited an N2pc and resulted in a behavioral effect, while non-matching cues did not. Depending on the respective conditions, non-matching cues either elicited no N2pc or a PD, an event-related potential indicating active attentional suppression. They also discussed the possibility that the attraction of attention by irrelevant cues could benefit from the long duration that elapses under difficult search condition since cue onset, because of the slowness of the automatic attraction effect. Another possibility could be that the corresponding attraction effects only emerge in the target display (for a critical review on the attentional dwelling hypothesis, cf. also Lamy et al., 2018). These findings support contingent capture theory and contradict Gaspelin et al. (2016), who claimed that abrupt onsets capture attention regardless of their similarity to the target and that this stimulus-driven capture is masked because of quick attentional shifts.

To summarize, there are two main points in the attentional capture debate that all accounts agree upon: First, that certain kinds of stimuli, among which are abrupt onsets, automatically generate a priority signal that captures attention if there are no attentional control settings in place; second, that if such control settings are in place, attentional capture by salient singletons can be prevented (Luck et al., 2021). Nevertheless, it still remains unclear under which exact conditions abrupt onsets capture attention.

Smooth pursuit and anticipatory eye movements

One way to introduce complexity into the debate is the introduction of motion. Only a few studies tested onset capture under conditions where visual moving information had to be observed for task processing (Lovejoy et al., 2009; Van Donkelaar & Drew, 2002). Because the present work is based on such an experiment, a short overview of the literature should not be withheld from the interested reader. A combination of smooth pursuit eye movements and saccades make it possible to track moving objects (Barnes, 2008). If information moves, eye movements might not be able to follow smoothly, therefore making *saccades* necessary. Saccades are rapid ballistic eye movements that allow for quick positional reorienting of the eyes within 50 ms (Ross et al., 2001). They are also useful when eye movements cannot smoothly follow moving stimuli (catch-up saccades; Kerzel & Ziegler, 2005). Lovejoy et al. (2009) investigated the spatial allocation of attention using a dual-task paradigm while participants had to participate in a smooth pursuit task. Unlike saccadic eye movements, smooth pursuit eye movements follow a target object by moving the eye with a velocity similar to the target, thereby continuously keeping it in the fovea (Kerzel & Ziegler, 2005). Pursuit itself is essentially a feedback process, but given considerable delays in motion processing, anticipatory pursuit of expected eye movements is necessary in cases when object motion is expected based on past events (Barnes, 2008). These anticipatory pursuit mechanisms can thereby overcome considerable delays in motion processing. Both smooth pursuit and saccades are clearly relevant for driving: While saccades allow for quick positional reorienting, e.g. when newly appearing information like a child appearing at the side of the road has to be processed, smooth pursuit eye movements allow for continuously keeping track of moving objects, such as a moving car in front, to which a certain distance has to be maintained (Grüner & Ansorge, 2017).

One particular advantage of smooth pursuit is that visual sensitivity is not reduced during the eye movement, therefore making pursuit of the car in front of us easier. Lovejoy et al. (2009) found that during smooth pursuit the focus of attention is centered on the target, as attentional allocation is one of the factors by which the pursuit of the target is maintained. Another important finding by Schütz et al. (2007) is that if the target has to be attended selectively, there is reduced contrast sensitivity to background stimuli during smooth pursuit compared to fixation. This might lead to less attentional capture by irrelevant abrupt onset stimuli during the pursuit of a moving target.

Another type of such anticipatory movements are look-ahead fixations, which are used in real-world driving before and during curves as a method of acquiring foveal information in order to construct and update the trajectory plan (Lehtonen et al., 2014). During look-ahead fixations, drivers make an eccentric fixation towards another, further part of the road or an object on the road, thereby disengaging from active visual steering control, before quickly returning to current task guidance, looking at the steering point 1 to 2 seconds away from the driver.

Optic flow and its implications on onset capture

In our experimental condition, we simulated a continuous *optic flow* pattern to create the impression of three-dimensional movement. But how can optic flow be defined at all? Optic flow refers to the systematic pattern of changes in the magnitudes and positions of solid spatial angles in the optical array of solid angles surrounding humans in each viewing direction and was firstly introduced by Gibson (1950) to describe moving visual stimuli presented to animals. The relationship between optic flow and locomotion was also first described by Gibson (1979): In human locomotion through a static environment, for example, these changes occur in the direction of motion and their travelled distance and change in size per unit of time is inversely proportional to the distance from the observer moving within this environment. If the observer moves, this movement will always be guided by flow in his *optic array*, the spatial pattern of light resulting from variations in the intensity and spectral composition. The exact way of optic flow then depends on his particular way of movement. According to this description, flow always specifies movement, whereas nonflow specifies stasis. Approaching an object is specified by outflow, whereas movement away from an object is specified by inflow. The center of the outflow defines the direction of the movement within a given environment, whereas a shift of this center implies a change in the movement direction. Still, movement by the observer is only one way in which an optic flow can be induced. Another way is the motion or change of objects in the environment, leading to disturbances in the optic array (Gibson, 1966). As our target was also moving horizontally and vertically, following a predefined trajectory, the center of the optic flow was constantly changing, leading to perceived movement in all three dimensions.

There are a number of possible reasons why attentional capture by abrupt onsets may behave differently in an optic flow pattern from one under conditions without an optic flow when a moving target has to be followed with the eyes (visual tracking) and negatively modulate attentional capture by irrelevant onset distractors. First, a higher anticipation of future positions of visually tracked moving objects leads to the increase in spatial certainty about the target stimulus location compared to a typical visual search task. This increase in spatial certainty, paired with smooth pursuit eye movements also leads to decreased stimulus-driven attentional capture (Yantis & Jonides, 1990). Second, the optic flow pattern itself could reduce saliency of the irrelevant distractors and thereby suppress attentional capture, as the locational changes of the optic flow particles are similar to the offset and onset of other objects at a new location. Third, it is also possible that the use of visual-dynamic features diminishes the use of task-irrelevant abrupt onset stimuli. However, the opposite could also be true, as Folk et al. (1994) found that visual search for dynamic features during visual tracking might even favor stimulus-driven capture through irrelevant, but dynamic features. Another reason for diminished attentional capture by irrelevant onset distractors under these conditions may be the similarity of the task to serial search in contrast to parallel search (Belopolsky et al., 2007). In serial search, participants attend to items in a search display one by one to determine if it is the target. In parallel search, all items are examined at the same time regarding their target identity. Search mode has a strong influence on whether salient stimuli will capture attention in a stimulus-driven way by shrinking (serial search) or widening (parallel search) the attentional window (Gaspelin et al., 2012). Stimulus-driven allocation of attention is lower in serial search than it is in parallel search. Because gaze tracking of a moving target could correspond to serial search (the combination of target color and its position / positional changes), stimulus-driven attention under gaze-tracking conditions could in turn be reduced, as stimulus-driven allocation of attention is lower in serial search than it is in parallel search (Belopolsky et al., 2007). These reasons illustrate the introduction of additional complexity in the attentional capture debate by the application of optic flow.

In our experiment, we wanted to test if abrupt onset distractors with target-matching color properties capture attention in line with contingent capture theory. We determined this with the help of dependent variables, such as the accuracy with which the moving target can be tracked, under various conditions (with and without abrupt onset distractors). Participants had to track a visual moving target embedded in an optic flow pattern by cursor movements and their gaze, based on a vehicle control situation. We expected that the sudden onset of a color-matching distractor attracted attention under these conditions and therefore influenced the accuracy with which a dynamic target could be tracked. Regarding anticipatory smooth pursuit eye movements, we also expected that the spatial deviation between participants' gaze/mouse cursor and the target increases after directional changes until the direction of the target can be correctly anticipated again. Since distractor onsets defining the recorded time bins (see Method section) occurred significantly more often when the target was moving away from the center and accelerating rather than decelerating and/or moving towards it, an increase of the error is to be expected here until phases of correct anticipation of the target direction predominate again, visible in significant differences between the respective time windows aligned to distractor onset used in our experiment (see Method section). We did not analyze the distractor effect as a function of distractor position relative to target movement direction, though this could have a modulating effect: Higher distances between target and eyes where the distractor is presented opposite to the target's current movement trajectory, but lower distances where the distractor is presented in the target's current movement trajectory. Therefore, lower distances in distractor-present than in distractor-absent trials could still indicate attentional capture when more distractors were shown opposite to the direction of target movement.

Method

Participants

Thirty-five undergraduate and graduate psychology students (21 female, M = 23.7, SD = 3.5, range 19-37 years) of the University of Vienna participated in the experiment in exchange for partial course credit. Participants were recruited via the university's own study platform, Laboratory Administration for Behavioral Sciences (LABS). A sample size of 30 participants was aspired based on a power calculation (G*Power) for a repeated-measures Analysis of Variance (ANOVA) assuming a medium effect size of f = 0.20, an alpha level of .05, and a statistical power of .90. All participants had normal or corrected-to-normal visual acuity and normal color vision. Written informed consent was obtained from all participants before the start of the experiment. The experiment was conducted in accordance with the Declaration of Helsinki and the APA ethical standards in the conduct of research. All participants received an introduction to the experimental goals online and on-site immediately before the experiment, as well as written and verbal debriefing thereafter.

Apparatus

We conducted the experiment in a dimly lit room. Stimuli were presented on a 19'' Cathode Ray Tube (CRT) Monitor (Sony Multiscan, viewable size: 36.4 × 27.3 cm) with an aspect ratio of 4:3 and a resolution of 1,024 × 768 pixels at a vertical refresh rate of 85 Hz. The participants had a fixed viewing distance of 59 cm to the CRT monitor, supported by a chin rest. The experiment was programmed and controlled using MATLAB 8.4 (MathWorks Inc., Natick, MA, USA) and the Psychophysics Toolbox Version 3 (Brainard, 1997). The dominant eye of each participant was tracked with an SR Eyelink 1000 plus eye tracker, sampling data at 1,000 Hz.

Stimuli and procedure

All stimuli were presented against a black background (CIE L*a*b*, 7.8/22.7/−27.4). The target was a white (104.1/15.6/−52.9) fixation cross (1.04º × 1.04º) and a green (76.4/−76.7/54.6) fixation dot in its center with a radius of 0.10º, embedded in a black non-transparent disk with a radius of 1.57º and was present in all trials. A green ring with a radius of 0,12º served as a mouse cursor. Distractor dots had the same color and radius (0.12º) as the mouse cursor ring and the same color as the dot in the middle of the target. Figure 2 shows the task procedure with all the relevant stimuli.

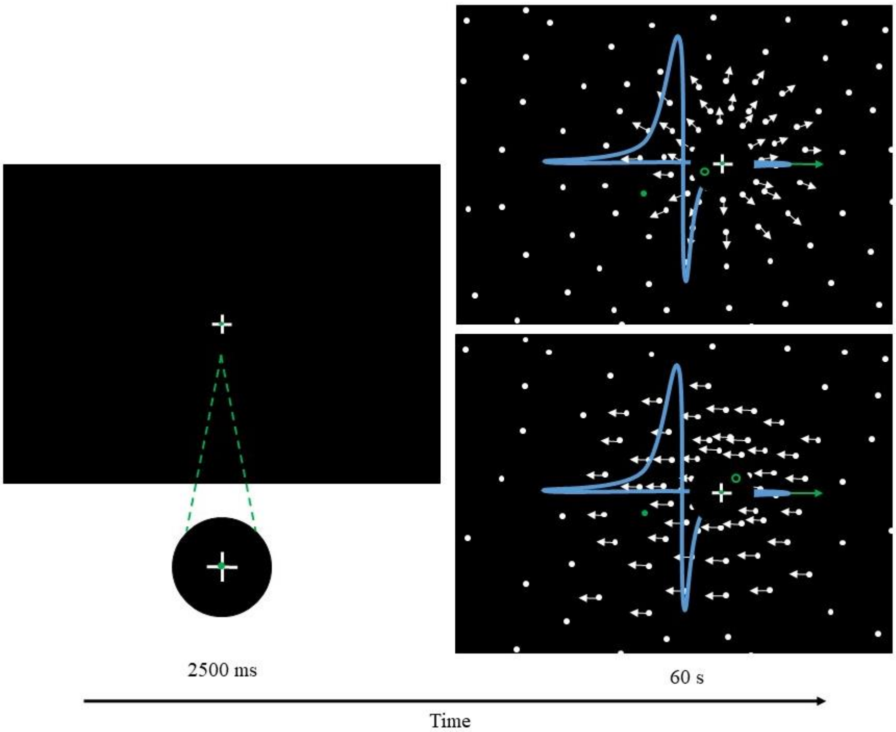
Preceding the first trial, the dominant eye of the participants was assessed by viewing an object located a few meters away from the participants through a funnel formed by both hands and then bringing the funnel onto one's face. As the dominant eye usually takes over control over the direction of this movement by setting a frame of reference, the funnel formed by the hands lands around the dominant eye (cf. Coren & Kaplan, 1973). Following this test and before the start of the trials, the eye-tracker was calibrated. Participants had to direct their gaze at ten dots appearing at the center and the corners of the screen. For the purpose of drift correction, a second block of the same ten dots appeared at the screen. If calibration quality was poor, the process was repeated. If the difference between the first gaze and the drift correction block at any single point was too big, the black dots were shown at this position.

Participants had to follow the moving target with their gaze and with a manually controlled mouse cursor. They had to complete 36 trials, each lasting 60 s, with self-paced breaks in between. Each trial began with the target serving as a fixation display shown for 2,500 ms before the aforementioned white dots appeared, and the target started moving. Participants had to maintain their gaze and the mouse cursor on the moving target throughout the trial. Instructions stressed both speed and accuracy. All relevant manipulations were within blocks, with the sequence of trials pseudo-randomized.

Green distractor dots appeared around the center for 258 ms on five out of 10 target journey sections per trial. Distractor onsets took place in a random interval between 0 and 1500 ms after a new journey section began (in the random half of the sections where a distractor appeared). Thereby, we could ensure that participants were unable to predict distractor onsets. Distractors maintained an equal distance to the target during this interval (thus, moving at the same speed as the target). Distractor to target distance was 2.10º in a random half of distractor onsets and 4.20° in the other half (exact positions were randomly selected from 720 positions placed on two imaginary circles surrounding the target with the described radii).

Figure 2

Task Procedure and Relevant Stimuli

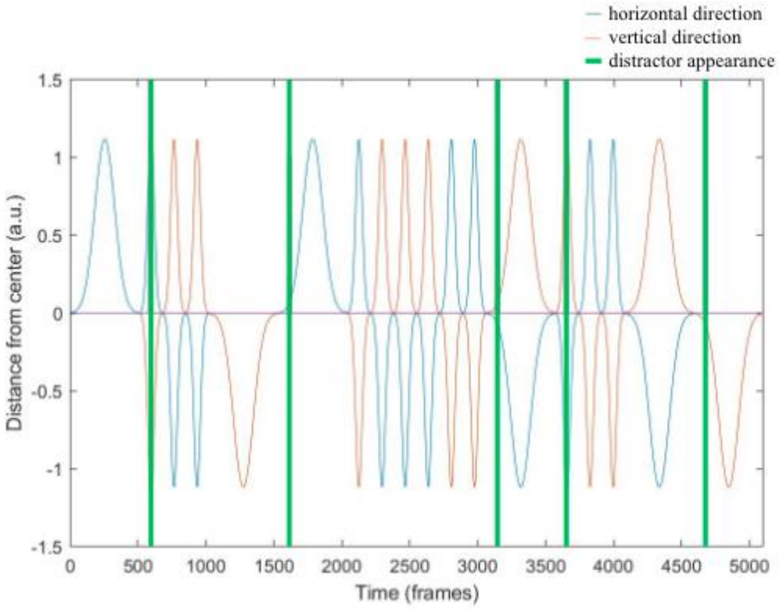


Note. On the left, the fixation display shown for 2,500 ms at the beginning of each trial is depicted. The target itself, a black circular disk with a white cross and a green dot in its middle, served as a fixation cross. On the top right, the experimental condition is shown. The white arrows indicate the movement of the dots, creating an expanding optic flow. On the bottom right, the control condition, the movement of the white dots imitate a curvilinear translational motion, simulating the rotation of the observer. A green ring serving as a mouse cursor and a green distractor dot are shown for both conditions. Possible trajectories of the target are indicated by the blue curvilinear figure.

During each trial, there were five target journey sections responsible for movement that were each repeated twice in randomized order, resulting in a total of 10 target journey sections per trial. In five of the 10 target journey sections, distractors were shown, in the other five, no distractor appeared. Each target journey section was 6 s long, and began and ended with the target at the center of the screen. Target velocity in each section followed a sinusoidal profile while the target moved away and returned to the center, sometimes several times per section. Target velocity ranged from 0 (at the center of the screen) to 11.56°/s at maximum acceleration. Thus, target velocities were well in a range comfortable for tracking by smooth pursuit eye movements (Lisberger et al., 1987). Figure 3 shows the target position relative to the center and distractor appearances over one trial. The maximum x and y coordinates of a movement were identical in every target journey section, but the exact combination of x and y coordinates was random.

Figure 3

Target Position across Time and Distractor Appearance



Note. The position of the target depicted as a function of time versus distance from center. Changes of the trajectory in the horizontal direction are depicted in blue, changes in the vertical direction are depicted in red. Negative distances from center indicate movements on the axes either to the left or down. Possible distractor onsets are marked by green vertical lines.

Out of the five different section types, in two section types the target only moved along one axis, either horizontally or vertically, whereas in the other three section types the target moved along both, horizontal and vertical, axes. If in a given target journey section distractors moved along two different axes (in the horizontal and vertical direction), one unit of movement in the vertical direction resulted in one unit of movement in the horizontal direction. For example, if the target moved away one visual degree upwards from the starting point and it also moved to the left side, the horizontal distance to the center was also one visual degree.

The different target journey section types can be categorized into *fast sections* and *slow sections.* Whereas during a slow section the target moved into one direction along the x- and/or the y-axis once and then returned to the center, during a fast section, this movement pattern was repeated three times. This implies that during a slow section, a curve and the return to the center took 6 s, whereas during a fast section, a curve and the return to the center only took 2 s.

Our experiment had two different conditions: An experimental condition and a control condition, which were randomized throughout the 36 trials. In the experimental condition, moving white (17.5/22.6/-29.1) particles (10,000 particles total per trial) with a lifetime of 20 ms and a radius of 0.16º emerging from the center of the target appeared on the screen to fill the screen with an expanding continuous optic flow pattern. This served as the simulation of movement following the moving target with an equal distance to the target, thereby, generating the sensation of driving behind a car ahead. Importantly, in order to be able to discriminate the target disk from the background, the optic flow pattern was not visible within the target disk.

In the control condition, the white dots persisted throughout the trial, unless the simulated directional change by the observer resulted in their cessation through the limits of the aperture and the appearance of other particles. These particles in the control condition also generated an optic flow sensation, but in a way that can be described best as a curvilinear translational motion along the x and y axes. The movement of the dot pattern in the control condition corresponded to what would result if the target was viewed in a fixed visual environment (here, consisting of a pattern of randomly dispersed dots) from different perspectives. In other words, the resulting impression should be as if the observer is standing at a certain point, without moving in any direction, and turning his head up and down, as well as left and right. The condition also still included the aforementioned 10 target journey sections.

Data analysis

After data from two participants was excluded because of insufficient eye-tracking data quality (as a significant amount of eye movements and eye positions were not recorded correctly, probably due to light reflections on the edges of participants' glasses), data of 33 participants was used for data analysis. Our dependent variables were Euclidean distance of participants' gaze from the target in visual degrees, the distance of the mouse cursor from the target in visual degrees, and eye movement velocity in visual degrees per second for both gaze and mouse cursor. We also analyzed the two conditions (the optic flow and the control condition) separately.

In order to be able to provide comparable data across conditions, trials and participants, we looked at the data 320 ms after each distractor onset and divided each timeframe into eight bins of 40 ms. For each bin, we calculated the average Euclidean distance and velocity from participants' gaze and mouse coordinates from the target using MATLAB 9.8 (MathWorks Inc., Natick, MA, USA). In the following, eight different repeated-measures ANOVAs (four for the optic flow condition, four for the control condition, two each for gaze and mouse tracking (with either Euclidean distance or velocity as a dependent variable) were carried out using JASP Version 0.14.1 (JASP Team, 2020).

Results

Eye movements: Euclidean Distance

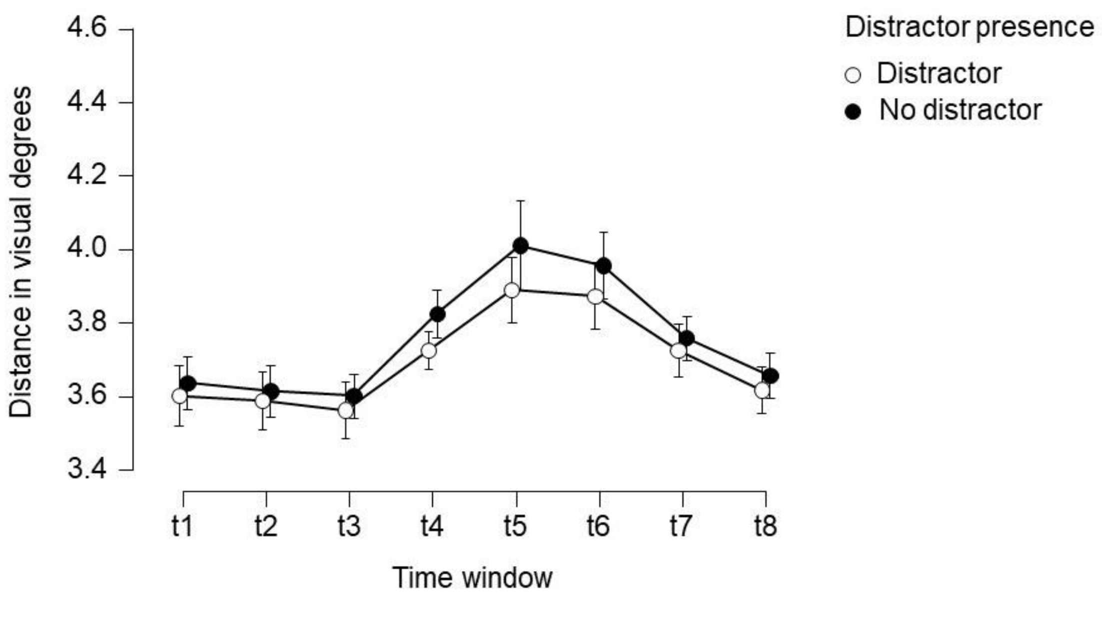
To compare participants' gaze behavior across different conditions, we first carried out an 8 (time window: t1 to t8) × 2 (distractor presence: distractor, no distractor) × 2 (optic flow: optic flow condition, control condition) repeated-measures Analysis of Variance (ANOVA) on the Euclidean distance of participants' gaze from the target. We found a significant three-way interaction of distractor presence, time window, and optic flow, $F(2.56, 32) = 5.10$, $p = .004$, $\eta^2 < .001$, after applying a Huynh-Feldt correction because the assumption of sphericity was violated ($W < .001$, $p < .001$). The interaction between distractor presence and time window was also significant, $F(3.87, 32) = 3.21$, $p = .02$, $\eta^2 < .001$, just like the interaction between time window and optic flow, $F(1.03, 32.944) = 10.09$, $p < .001$, $\eta^2 = .07$, after a Huynh-Feldt correction, $W < .001$, $p < .001$. However, the interaction between distractor presence and optic flow failed to reach significance, $F(1) < 0.001$, $p > .99$, $\eta^2 < .001$.

Holm-Bonferroni corrected post-hoc comparisons of Euclidean distances for all time windows and for distractor-present and distractor-absent trials averaged over the optic flow conditions are depicted in Appendix A, Table A1. A simple main effects analysis showed a significant main effect of distractor presence with time window and optic flow as moderator factors in the optic flow condition in t4, $F(1) = 5.05$, $p = .03$, and t5, $F(1) = 5.32$, $p = .03$, and in the control condition in t4, $F(1) = 16.41$, $p = .001$, whereas distractor presence in t5 just failed to reach significance, $F(1) = 3.31$, $p = .08$. These results indicate a difference in Euclidean distances 120-200 ms after distractor onset.

To account for the differences between the optic flow and the control condition, we analyzed both conditions separately by carrying out two 8 (time window: t1 to t8) × 2 (distractor presence: distractor, no distractor) repeated-measures ANOVA on the Euclidean distance of participants' gaze from the target for the optic flow and the control condition. For the optic flow condition, we found a significant effect of time window, $F(1.93, 61.63) = 22.05$, $p < .001$, $\eta^2 = .29$, after applying a Huynh-Feldt correction because of the violated assumption of sphericity ($W = .04$, $< .001$). Importantly, distractor presence as a factor was not significant, $F(1, 32) = 2.33$, $p = .14$, $\eta^2 = .01$), indicating no difference in distances between target journey sections where a distractor was present and those where a distractor was absent. The two-way interaction of time window and distractor presence was also not significant, $F(3.60, 115.04) = 2.09$, $p = .09$, $\eta^2 = .005$, after a Huynh-Feldt correction ($W = .01$, $< .001$. Post-hoc tests using the Holm-Bonferroni procedure as a correction method showed that the overall difference in distance between distractor and no-distractor condition was –0.06° ($t = –1.53$, $p = .14$). Figure 4 shows the distance of participants' gaze from the target in presence and absence of distractors for the optic flow condition.

Figure 4

Gaze Distance from Target in the Optic Flow Condition

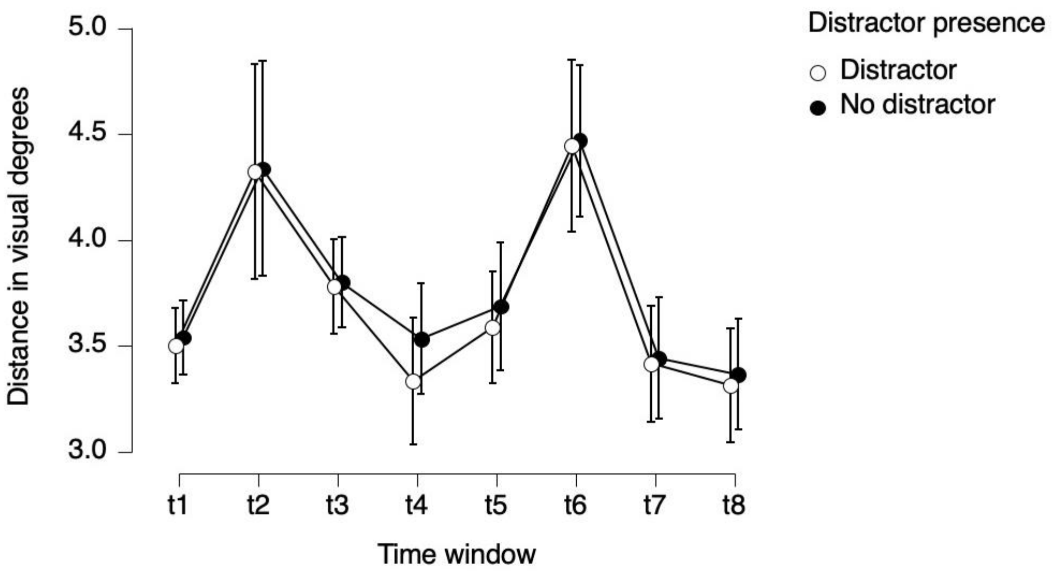


Note. Mean Euclidean distance of participants' gaze to the target in visual degrees over the course of the time windows in the optic flow condition. The beginning of t1 marks the distractor onset in the distractor condition and the same time windows are used for the no distractor condition. Each time window is 40 ms long, indicating a total time of 320 ms. Error bars represent 95% CI.

For the control condition, we found a significant effect of time window as well, $F(1.10, 35.34) = 9.50$, $p = .003$, $\eta^2 = .22$, after a Huynh-Feldt correction, as sphericity was violated in the control condition, too ($W < .001$, $p < .001$). The effect of distractor presence was not significant, $F(1, 32) = 2.50$, $p = .12$, $\eta^2 = .001$). A significant interaction of time window and distractor presence, however, modulated the main effect, $F(4.06, 130.06) = 4.42$, $p = .002$, $\eta^2 = .001$. A Huynh-Feldt correction was applied here as well ($W = .05$, $< .001$). An analysis of simple main effects showed a significant effect of distractor presence in time window t4, $F(1) = 16.407$, $p = .001$, just like in the optic flow condition. Distractor presence in t5 just failed to reach significance, $F(1) = 3.31$, $p = .08$. Post-hoc tests using Holm-Bonferroni correction revealed that the mean difference in gaze distance in the conditions where a distractor was shown versus where no distractor was shown was –.06° ($t = –1.58$, $p = .14$), resembling the results of the optic flow condition. Figure 5 shows the distance of participants' gaze from the target in presence and absence of distractors for the control condition.

Figure 5

Gaze Distance from Target in the Control Condition



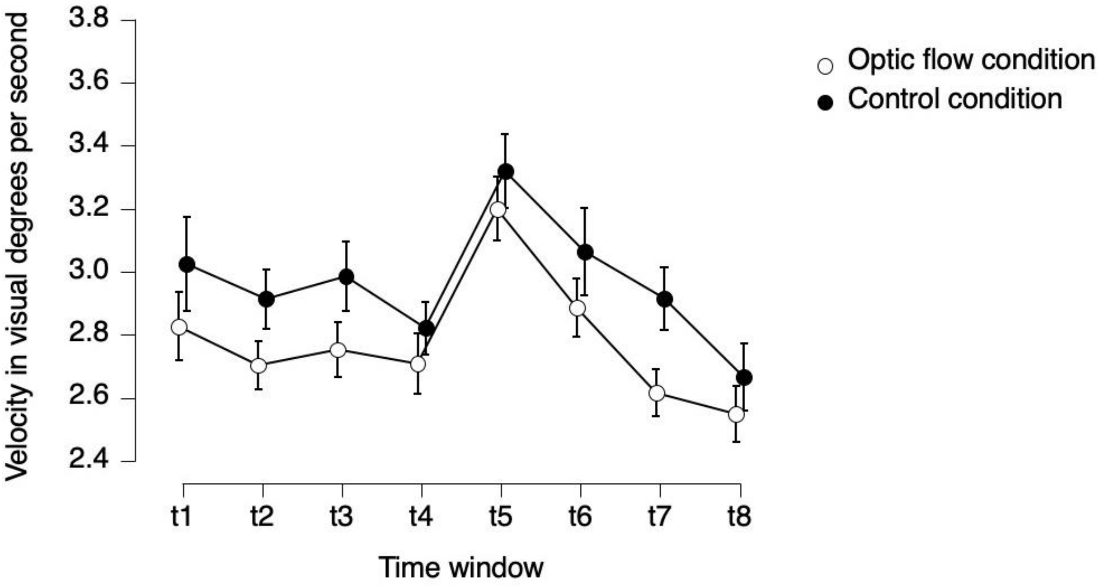
Note. Mean Euclidean distance of participants' gaze to the target in visual degrees over the course of the time windows in the control condition. The beginning of t1 marks the distractor onset in the distractor condition and the same time windows are used for the no distractor condition. Each time window is 40 ms long, indicating a total time of 320 ms. Error bars represent 95% CI.

Eye movements: Velocity

We also conducted an 8 (time window: t1 to t8) × 2 (distractor presence: distractor, no distractor) × 2 (optic flow: optic flow condition, control condition) repeated-measures ANOVA on the velocity of participants‘ gaze, revealing a significant main effect for time window, $F(2.97, 95.14) = 18.29$, $p < .001$, $\eta^2 = .16$, after a Huynh-Feldt correction ($W < .001$, $p < .001$). We also found a significant main effect of optic flow, $F(8.90, 32.22) = 8.84$, $p = .006$, $\eta^2 = .04$. Distractor presence as a main effect, however, was not significant, $F(1) = 1.09$, $p = .31$, $\eta^2 = .001$. All interactions failed to reach significance as well.

Figure 6

Mean Gaze Velocity per Time Window

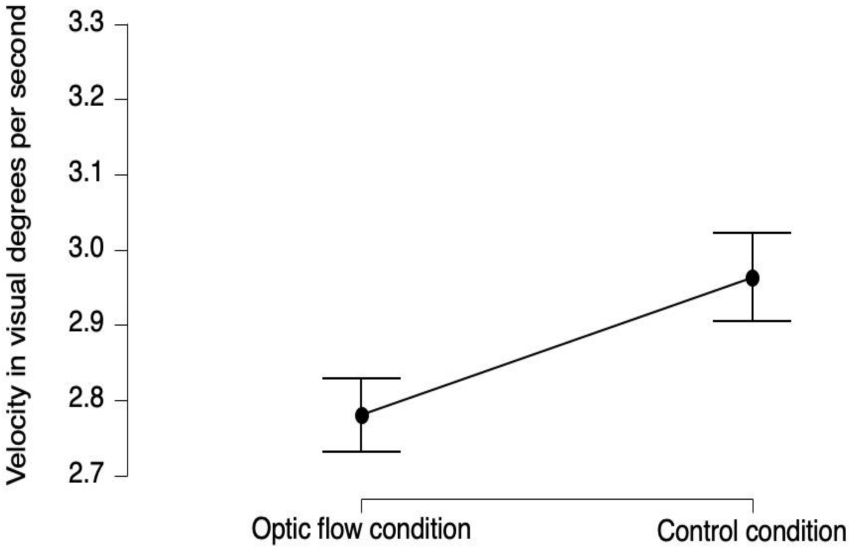


Note. Mean velocity of participants‘ gaze in visual degrees per second over the course of the time windows in the control condition. The white dots show the mean gaze velocity in the optic flow condition in the respective time window, while the black dots show the mean gaze velocity in the control condition. The beginning of t1 marks the distractor onset in the distractor condition and the same time windows are used for the no distractor condition. Each time window is 40 ms long, indicating a total time of 320 ms. Error bars represent 95% CI.

Holm-Bonferroni corrected post-hoc comparions of gaze velocities between all time windows can be found in Appendix A, Table A2. A post-hoc comparison of velocities between optic flow condition and control condition revealed that the velocity of participants’ gaze was .18° higher in the control condition than it was in the optic flow condition, depicted in Figure 7. A simple main effects analysis showed no significant differences in gaze velocity in any time window regarding distractor presence for both optic flow and control conditions. In contrast, the simple main effects analysis of optic flow revealed that the significant main effect of optic flow was driven by differences in velocity in time windows t2, $F(1) = 10.29$, $p = .003$, t3, $F(1) = 7.60$, $p = .01$ and t7, $F(1) = 13.30$, $p < .001$.

Figure 7

Mean Gaze Velocity Averaged over Time Windows



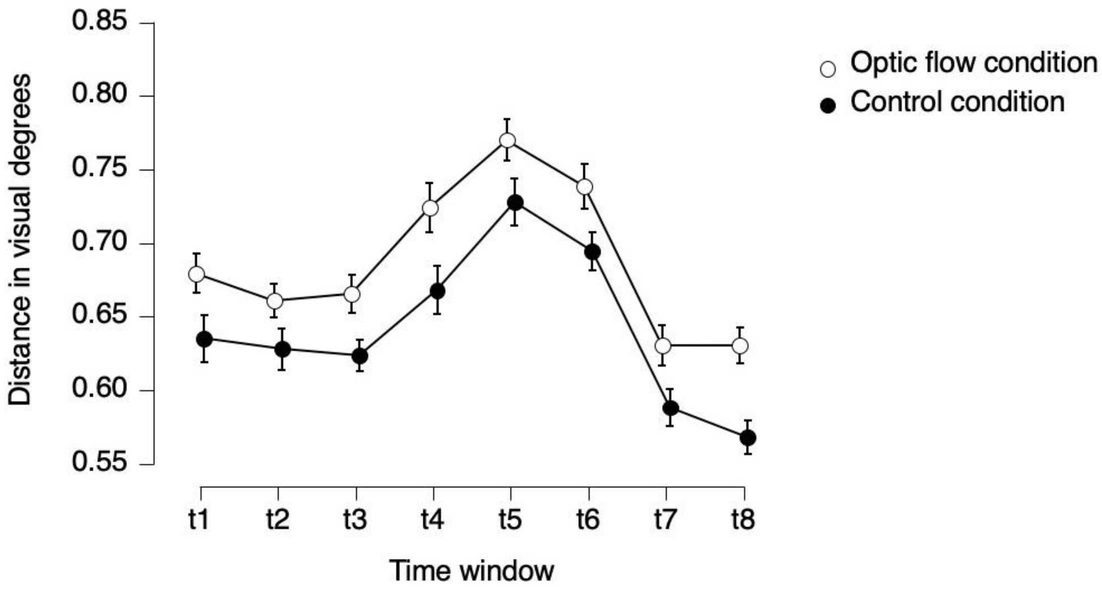
Note. Means of participants' gaze velocity in visual degrees per second averaged over time windows and distractor-present and absent target journey sections for the optic flow condition and the control condition. Vertical lines indicate 95% CI.

Mouse cursor movements

In accordance with our previous analyses on gaze behavior in optic flow and control conditions, we conducted an 8 (time window: t1 to t8) × 2 (distractor presence: distractor, no distractor) × 2 (optic flow: optic flow condition, control condition) repeated-measures ANO-VA with the Euclidean distance of the mouse cursor as the dependent variable. We found a significant main effect of time window, $F(3.26, 104.28) = 60.54$, $p < .001$, $\eta^2 = .41$, after ap-plying a Huynh-Feldt correction because of the violation of sphericity revealed by Mauchly's test of sphericity ($W = .09$, $p < .001$). Mean mouse cursor distances from the target in the respective conditions are shown in Figure 8. In addition, there was a significant main effect of optic flow, $F(1, 32) = 50.60$, $p < .001$, $\eta^2 = .09$. Importantly, distractor presence did not have a significant influence, $F(1, 32) = .59$, $p = .45$, $\eta^2 < .001$. All interactions failed to reach significance.

Figure 8

Mouse Cursor Distance from Target

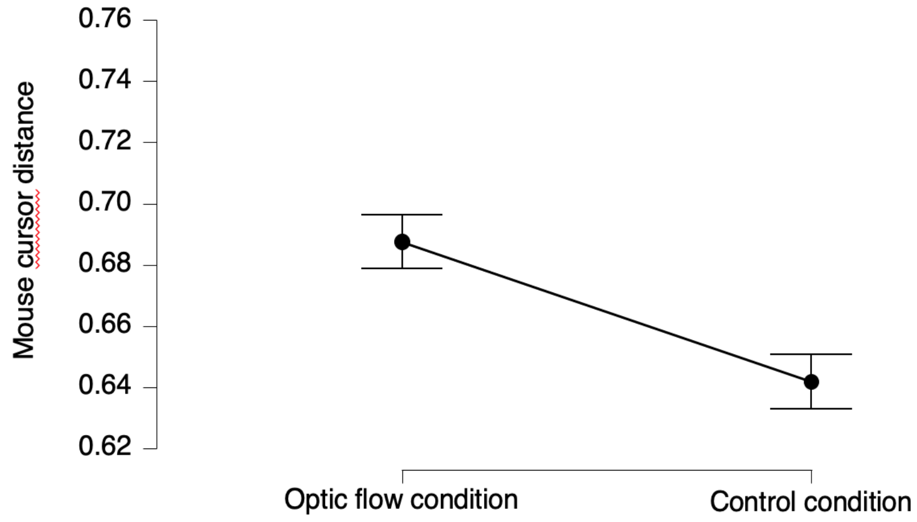


Note. Euclidean distance of participants‘ mouse cursor to the target in visual degrees over the course of the time windows in the optic flow and the control conditions (indicated by separate lines). The beginning of t1 marks the distractor onset in the distractor condition and the same time windows are used for the no distractor condition. Each time window is 40 ms long, indicating a total time for 320 ms. Error bars represent 95% *CI*.

Post-hoc comparisons of the optic flow condition and the control condition applying the Bonferroni-Holm method for correction revealed that the mean distance of participants' mouse cursor to the target across time bins and both distractor and no distractor conditions was .05° higher in the optic flow condition than in the control condition, $t(1) = 7.11$, $p < 0.001$. Figure 9 shows this difference between the optic flow condition. and the control condition. Holm-Bonferroni corrected post-hoc comparisons of mouse cursor distances between the time windows can be found in Appendix A, Table A3.

Figure 9

Mean Distance of Participants' Mouse Cursor with and without Optic Flow



Note. Mean distances of participants' mouse cursor to the target in visual degrees across all time windows and distractor-present and absent target journey sections for the optic flow condition and the control condition. Vertical lines indicate 95% CI.

Additionally, we computed mean Euclidean distances for all conditions to provide a comparison between mouse and gaze behavior, shown in Table 1. Differences between optic flow and mouse control conditions were not significant in any of the conditions, but we found a significant difference between gaze and mouse conditions, as the distance of participants' gaze from the target was more than five times larger on average than their mouse cursor error.

Table 1

Comparison of Means of Euclidean Distances in all Conditions

Condition	Distractor				No distractor			
		95% CI				95% CI		
	M	lower	upper	*SE*	*M*	lower	upper	*SE*
Gaze/flow	3.698	3.065	4.331	0.311	3.757	3.124	4.390	0.311
Gaze/ctrl	3.713	3.158	4.268	0.273	3.772	3.217	4.327	0.273
Mouse/flow	0.688	0.641	0.734	0.023	0.688	0.641	0.734	0.023
Mouse/ctrl	0.640	0.598	0.681	0.020	0.644	0.603	0.685	0.020

Note. Depicted are the means (in visual degrees) of Euclidean distances from participants' gaze and mouse cursor across all time windows for distractor-present and distractor-absent target journey sections in both optic flow and control conditions. Next to the means, the lower and upper limits of the 95% CIs and the *SE* are shown.

Discussion

The role of time windows

The present experiment aimed to demonstrate attentional capture by abrupt onsets with target-matching color properties. Contrary to our preliminary expectations, the general trend in the data showed larger distances in distractor-absent than in distractor-present target journey sections. Although these differences failed to reach significance, their direction was consistent in all analyses except in the mouse / optic flow / distance condition, where the difference was negligibly small ($t < .001$, $p = .98$). The significant three-way interaction between distractor presence, time window and optic flow in the gaze / distance condition showed that all three factors had an influence on participants' gaze behavior. As our follow-up analyses showed, this three-way interaction can be divided into further subcomponents: Whereas distractor presence did not have an influence on participants' gaze in the optic flow condition across all time windows, it interacted with time window in the control condition. This makes sense from the perspective that the higher perceptual noise caused by optic flow might have diminished the visibility of the distractors – I will cover this point in more detail in the general discussion. This interaction was, as shown by a post-hoc analysis (Appendix A, Table A1), mainly driven by time window t6, as it was significantly different from almost all other time windows except from time window t2, visible as peaks in Euclidean distance (particularly in Figure 5, as this trend is mainly driven by the control condition). This phenomenon and the significance of time window either as a main effect or a moderator in all our analyses could be the result of the fact that time windows were dependent on distractor onsets (t1 always started with distractor onset) and distractor onsets always happened within the first 1500 ms of a target journey section. This, combined with the limited amount of target journey sections used, resulted in certain statistical regularities of target velocity and position. As mentioned, the experiment had fast sections (1 s until curve apex) and slow sections (3 s until curve apex). Whereas during a slow section the target moved into one direction along the x- and/or the y-axis once and then returned to the center, during a fast section, this happened three times. Due to the temporal and spatial nature of the target journey sections as well as the jittering within the first 1500 ms after the start of target journey sections (a target journey section always began in the center of the screen) distractor onsets more often appeared during the period when the target was moving away from the center rather than moving towards the center. In summary, out of the 180 distractors shown during the experiment, 156 were shown when the target was moving away from the center and 24 when the target was moving towards the center. Therefore, regularities in participants' velocity might have been driven by these regularities, even though distractor onsets were jittered randomly within a timeframe of 1500 ms: With a higher chance of target velocity and/or distance from the center increasing in a certain time window, there is also a higher chance for gaze velocity and gaze distance to follow this trend.

Although distractor presence as the factor of our main interest was not significant in our analysis of the optic flow condition, thereby indicating the lack of attentional capture under optic flow conditions, a closer look at single time windows with Euclidean distance as dependent variable shows that distractor presence was significant in time windows t4 and t5. An interaction between time window and distractor presence was significant at first, but after applying a Huynh-Feldt-correction, it was not significant anymore. Nevertheless, with a sideways look at the significant interaction in the control condition and the similarity of the simple main effect analysis of the respective time window, this is an important finding to note. In the control condition, time window t4 showed a significantly higher distance when a distractor was absent compared to when a distractor was present, whereas time window t5, in which the same trend was present, scarcely failed to reach significance. As briefly mentioned before, there was a significant interaction between time window and distractor presence in the control condition, driven by distractor-induced facilitation in a single time window, t4.

These results show that the distance of participants gaze to the target was significantly higher in certain time windows when a distractor was absent than when a distractor was present. This is somewhat contrary to our initial expectations, as we believed that if there is attentional capture by top-down matching abrupt onsets, the distances should be higher in distractor-present than distractor-absent target journey sections. However, our results could still indicate the capture of attention: Through the random placement of distractors along two imaginary circles around the target, distractors could have either appeared in the direction of the eye movement or against it. If they appeared in the direction of the eye movement, a possible capture would be indicated by a smaller average Euclidean distance of the eye to the target compared with target journey sections where the distractor appeared against the direction of the eye movement – here, attentional capture by the abrupt onset distractor would result in a larger average Euclidean distance to the target, as the observer would look away from the target towards the distractor. A distractor in the direction of the eye movement would additionally result in a smaller average distance when a distractor is present compared to the same target journey section when a distractor is absent. This is due to the fact that distractors were shown in close temporal connection with directional changes in the respective trajectory, corresponding to simulated curves. These directional changes have the consequence that both possibilities, namely looking away and towards the target when looking towards the distractor at the same time are possible. Further studies therefore should indicate the direction of eye (and secondarily also mouse) movement: Is it anticipatory or lagging behind the target?

Differences between gaze and mouse tracking

In the mouse tracking conditions, the effects of time window and optic flow were significant. Interestingly, the differences in Euclidean distance between distractor-present and distractor-absent measures in both the optic flow and control conditions were smaller than they were in the gaze tracking conditions. Also, Euclidean distances on average were significantly smaller in the mouse tracking condition than they were in the optic flow condition.

The comparison of mean distances in the mouse tracking condition showed that there was a significant difference between optic flow and control conditions, as participants were able to maintain a smaller distance to the target during the control condition. This is, at the first look, plausible against the background of increased task complexity through optic flow reported by individual participants, as well as a higher distraction through the motion caused by optic flow (see General discussion below for the role of optic flow). However, the means for the gaze distances paint a different picture, with higher distances in the control condition compared to the optic flow condition.

The optic flow (or the pattern of the white dots) itself also could have significantly influenced participants' behavior in other ways that will be discussed further below, as indicated by its significant main effect. This analysis also brought up an intriguing distinction: Participants' gaze distance to the target was more than five times higher than the distance of their mouse cursor. One possible explanation for this trend could be an anticipatory movement of the eyes (Gowen & Miall, 2006) in the probable direction of the target stimulus along the predefined trajectories. The direction of the movement could be partly anticipated, as there was a limited amount (five) of different target journey sections along which the target moved continuously without changing directions for a fixed amount of time. Thereby, participants could partly anticipate the location of the target at a given time point. This anticipatory behavior might have increased viewing distance in the direction of the target movement.

Another possible explanation is that eye movements are more subject to distractions caused by the simulated 3D space and the optic flow, whereas with the mouse cursor (or hand movement) only the distance to the target itself has to be controlled. This makes sense from the perspective that eye movements are also more sensitive to attentional manipulations like distraction and inhibition of return than manual responses are (Briand et al., 2000). On a more general level, while our hands are more tuned to the execution of sensorimotor tasks, vision is primarily responsible to detect potentially dangerous or rewarding information in three-dimensional space, thereby being more sensitive to the distractions emerging from the simulated 3D space itself. One might argue that this is disproved by the nonsignificant difference of marginal means between optic flow and control condition, but we also have to take into the account that the curvilinear movement of the control condition also simulated motion in 3D space, thereby implying that it underlies the same rules as the optic flow condition.

Smooth pursuit eye movements and their role in hand-eye coordination could also play an important role in the discrepancy in the distances between mouse tracking and gaze tracking conditions. Koken and Erkelens (1990) showed that a greater degree of smooth pursuit eye movements is recorded during the combined tracking of eye and hand than it would be the case with eye tracking alone. The combination of eye and hand tracking also produces higher velocity smooth pursuit with an increased latency of eye movements and a decreased latency of hand movements (Vercher et al., 1993). Smooth pursuit thereby could indicate greater eye-hand coupling than the observation of saccades, with eye movements serving as an anticipatory mechanism while additionally providing continuous feedback in close cooperation with hand movement. Engel and Soechting (2003) found that hand and eye movement latencies influence each other when the other tracking modality is also present, additionally resulting in a changed velocity profile of the smooth pursuit part compared with only eye-tracking.

The anticipatory movements mentioned above and the less anticipatory movements of the mouse cursor, which might be indicated by the smaller distance, might be explained by the following mechanisms: The high demands of continuous comparison between the position of the to-be-traced target and the mouse cursor are met by the ongoing transfer of visual information to the part of the system responsible for the generation of the hand movement (Gowen & Miall, 2006). In our case, the eye then moves in a feedforward way anticipating the target location and arriving before the mouse cursor controlled by hand movements. Furthermore, anticipatory pursuit of eye movements relying on the expected motion of objects based on past events (Barnes, 2008) might be advantageous for the optimal execution of the task. Tabata et al. (2004) reported that target movements during fixation induced a larger eye movement if the target was followed by smooth pursuit eye movements than in the case of fixations or saccades. The authors attributed this increased ocular sensitivity to visual motion to the anticipation of the target movement direction based on past experiences. Interestingly, Tabata et al. (2005) could show that the higher the probability of required smooth pursuit eye movements was in relation to saccades during a task, the higher the mean velocity. This suggests that the pursuit system changes the gain of visuomotor transmission depending on this probability, thereby preparing for future movements. In our experiment, participants might have expected the target to move and have thereby used a strategy of anticipatory eye movements to overcome substantial delays in motion processing and optimize the accuracy of task completion. This anticipatory mechanism is not exclusively built on recent target motion history, but also relies on static visual cues (Eggert et al., 2008).

However, after looking at how the optic flow was constituted, one can say that it did not serve as a predictor of direction. The future trajectory could only be predicted, at a given point in time, through the information provided by the target. Target motion history and statistical learning of the five different target journey sections, as each of them were shown 72 times during the experiment, was the only possible basis for this anticipatory process and could have served as anticipatory cues in this sense. Looking at the eye-tracking data of individual participants, it also became clear that saccadic eye movements were by far outweighing smooth pursuit eye movements in the course of our experiment – less than 1 out of 10 eye movements were smooth pursuit eye movements. Therefore, these mechanisms can only partly explain the trends in the data and an explanation on saccadic eye movements is needed. Our follow-up experiments therefore should distinguish between these two mechanisms on the data analysis level by quantifying the different types of eye movements and including a factor in this regard.

The role of look-ahead fixations

Regarding saccades, look-ahead fixations, during which drivers fixate on a further part of the road to acquire relevant information for driving and then quickly return to the current task, might have played an important role. One could argue that such look-ahead fixations were not necessary during the current task, as active steering or another kind of directional control were not included in the task. However, Mars and Navarro (2012) demonstrated that when the need to steer was removed in a simulator, there was an increase in participants' look-ahead fixations, possibly by reducing visual demand of steering guidance (Horrey et al., 2006). Schnebelen et al. (2019) also found an increased proportion of look-ahead fixations with a concomitant decrease of guiding fixations (usually directed to a point 1-2 seconds ahead of the driver) in a driving simulator experiment. This increase started before entering the bend of a curve in case of active driving, but was much more visible when steering through the curve. In case of passive driving, which is more similar to our experiment, these look-ahead fixations represented more than 30% of the data collected by Schnebelen et al. (2019), compared to less than 5% in the case of active driving. Even if the optic flow did not include an actual road, the course of the trajectory still implied future movement, thereby enabling participants to probabilistically infer the future course of the trajectory, whereas the changes in this very trajectory served as curves. Also, existing driving habits and the innate human need for rapid information acquisition might have increased the tendency of these anticipatory movements in a rapidly changing artificial environment.

General discussion

Before our experiment, we expected to find a trend in the data showing higher distances in distractor-present compared with distractor-absent target journey sections, thereby indicating attentional capture. There are a couple of possible reasons why this was not the case. First, when observers direct attention to a spatial location, abrupt onsets that would normally capture attention, fail to do so (Theeuwes, 1995). In our experiment, attention was not placed at a single spatial location, however, future spatial locations could be partly anticipated by the continuous movement of the target on the trajectory, thereby making locations of the distractors (which were always 2.10º or 4.20º away from the target, no matter at which position) less suited for attentional capture. It could, therefore, be the case that the increased spatial certainty of the target, paired with the anticipation of possible future target positions and smooth pursuit eye movements leads to a decreased stimulus-driven capture of attention (cf. also Yantis & Jonides, 1990).

Second, the lack of robust evidence of attentional capture might also result out of the variety and number of moving stimuli present in the target display and the smooth pursuit nature of the task: The dot pattern and its movement could itself reduce attentional capture in both optic flow and control conditions, as the locational changes of the particles in both optic flow and translational motion conditions are similar to the offset and onset of other objects at new locations. This could have resulted in reduced detectability of the distractor, which was, although differently colored, slightly smaller than the white moving particles constituting the simulated three-dimensional space. This might go hand in hand with the reduced contrast sensitivity to background stimuli when attention is directed to a target in smooth pursuit tasks, like it was shown by Schütz et al. (2007).

Third, as briefly mentioned in my introduction on optic flow and its special position in attentional research, an additional reason for diminished attentional capture by irrelevant onsets may be the similarity of the task to serial search (Belopolsky et al., 2007), during which the attentional window is constricted in comparison to parallel search and stimulus-driven capture (Gaspelin et al., 2012). This constricted attentional window might have led to the peculiarity that receptive fields sensitive to distractor processing might have been too small to detect distractors while focusing the target. In contrast, one can argue that the task was not a visual search task after all: Participants successfully located the target to some extent throughout the entire trial. Otherwise it would have been impossible for the participants to track the target at all. Whether the same fundamental principles regarding the attentional window as in serial search tasks underlie tracking and smooth pursuit is not entirely clear and needs further clarification.

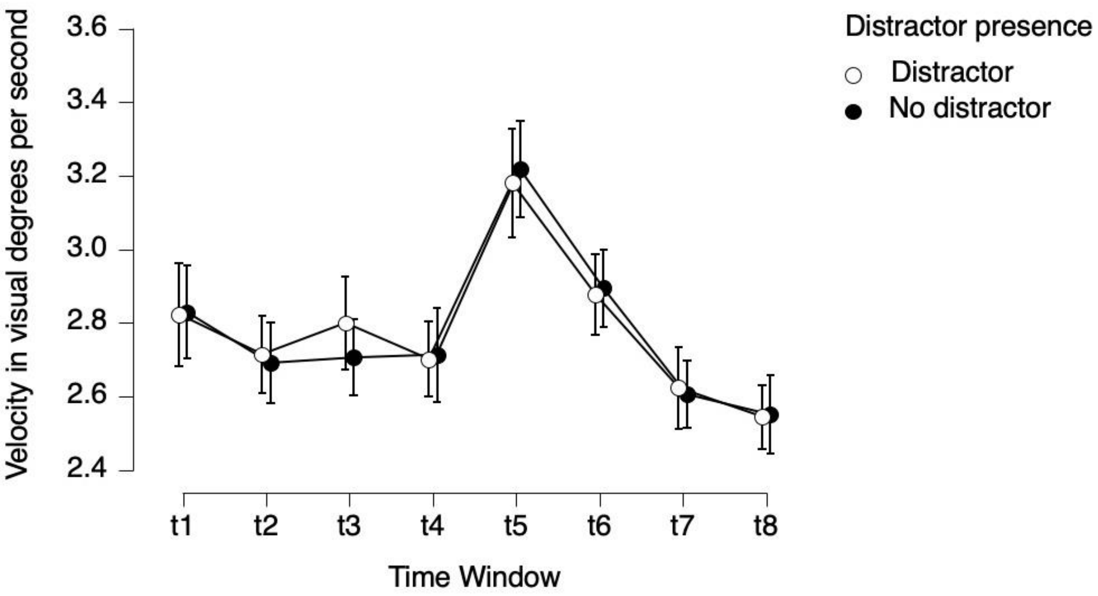
Lastly, also the mere frequency of the onset stimuli could result in diminished or missing attentional capture: This could be the result of habituation of the observer to the stimuli, which are the result of long-lasting memories of the information provided by the distractors (Turatto et al., 2017). This is not very surprising, given that the abrupt onsets appeared 180 times during the experiment. Therefore, there was no reason for the participants to assume that the information they represent is something new, rewarding or dangerous and therefore can be ignored during the task. This habituation mechanism thereby allowed the observers to filter stimuli which were not relevant for the task. One might argue that parts of the target, namely the green dot in the middle, was similar to the distractors and therefore irrelevance could not be properly assessed. However, as participants always kept their gaze on the target, they could conclude that the abrupt onset stimuli were not part of the target and had no relevance for their task, thereby making habituation possible. Geyer et al. (2008) also showed that the presence of an irrelevant color singleton can result in attentional capture, but only when the distractor occurs relatively infrequently within a block of trials. Folk and Remington (2015) also examined the effect of presentation frequency of color and onset distractors on attentional capture in a contingent capture spatial cueing paradigm and found that when the task requires a top-down set for color, presenting a single abrupt onset on every trial does not lead to attentional capture. However, when abrupt onsets appeared only in 20% of the trials, significant cueing effects were obtained. This was not the case for color singletons when searching for onset targets. Therefore, the lack of capture in our experiment might reflect an adaptive strategy to maximize efficiency.

The results with velocity as a dependent variable in the gaze tracking condition are partly consistent with the distance results, as in both optic flow and control conditions time window constitutes a significant main effect, but distractor presence did not significantly influence gaze velocity (this is also true for single time windows, unlike for Euclidean distance). This is not a surprise, as first, target velocity (which should correlate with gaze velocity) followed a sinusoidal profile, with velocities ranging from 0 to 11.56°/s. Additionally, through the random onset of distractors (between 0 and 1500 ms after the beginning of a target journey section) and the definition of the bins depending on distractor onset the compared bins consisted of entirely different target journey sections within participants. To make this clearer, the distractor might have appeared concomitant with a direction change of the target trajectory in one condition A, but a distractor might have appeared following the direction change of the target in a different condition B. By aligning time point definitions with distractor onsets, direction changes, thus, contributed to different degrees to the tracking precision and to the velocities measured for different time points t1 to t8. Assuming that, following a direction change, the visual system lagged behind the target movements for a while, in the optic flow conditions, direction changes would have necessitated an increasing number of catch-up eye movements for the first few time points, until a time point was reached where the majority of the direction changes had occurred, been registered by our participants, and the eyes had caught up with the target again. Thereby, differences in velocity were expected to increase and then to decrease across time bins. This is exactly the pattern that we observed (see Figure 10).

A clear limitation of the current study is the fact that due to the random onset of the distractors and the alignment of time windows to these random onsets, the comparison of distances within each time window and across time windows is difficult, as due to the random begin of time windows are composed of different timeframes within the same trajectory. This is a result of a trade-off between reducing expectancy effects and providing comparability of results: If distractors would appear at the same time or place on a given target journey section during the experiment, participants could expect that a distractor is going to appear and consciously suppress attentional capture. A way to bring out the best from both worlds might be to show distractors at the same time and place within each target journey section, but only show them in less than 20% of the target journey sections, thereby counteracting possible habituation effects and the disadvantage of bad comparability within and across time windows. However, this would imply a considerable increase in the duration of the experiment.

Figure 10

Gaze velocity in the optic flow condition



Note. Mean velocity of participants' eye movements in visual degrees per second over the course of the time windows. Despite the random distractor onset, there is a clear and concordant trend in velocity change across both distractor and no distractor conditions over the time windows. Error bars represent 95% CI.

To conclude, despite the fact that we did not find clear signs of attentional capture by abrupt onsets with target-matching color properties during the observation of a visual moving target, the significance of single time windows in the optic flow (t4 and t5) and in the control condition (t4) could still be a sign of capture. Although the results paint a clear picture with higher distances in distractor-absent than in distractor-present trials, these might have occurred due to the anticipatory eye movements during smooth pursuit and caused by look-ahead fixations. Also, the significant main effects of optic flow in the gaze condition with velocity as a dependent variable and in the mouse condition with gaze as a dependent variable shows a clear modulation of participants' behavior by optic flow and could have important implications for real-world driving. Looking into the future, it is therefore crucial to connect these findings with real-world experiments assessing attentional capture during driving and with further experiments in the laboratory with the observation of visual moving information and smooth pursuit as potential experimental paradigms.

On the short term, our results open the door for further follow-up experiments to be conducted after the adaptation of the current experimental paradigm. By doing this, we see the potential to contribute to the growing field of attentional research with regard to smooth pursuit, as there is still limited amount of research about attentional processes with moving targets. One such adaptation is the realignment of distractor positions at fixed locations so that the measurement of not only distance but also direction towards or away from the target becomes possible. By applying this method, we will potentially be able to distinguish anticipatory eye movements from eye movements following the target. An important distinction should also be made between different types of anticipatory eye movements, thereby clearly distinguishing smooth pursuit eye movements from look-ahead fixations. Also, reducing the amount of optic flow to increase the visibility of the target might have an effect on attentional capture and should be assessed in a follow-up experiment.

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List of abbreviations

3D:	Three-dimensional
ANOVA:	Analysis of Variance
CRT:	Cathode Ray Tube
ERP:	Event-related potential
N2pc:	N2-posterior contralateral

Appendix A

Table A1

Post-hoc Comparisons of Euclidean Distances (Time Windows and Distractor Presence)

			95% CI for Mean Difference				
		M	Lower	Upper	*SE*	*t*	p_{holm}
Distractor, t1	No.distractor, t1	-0.037	-0.204	0.129	0.045	-0.837	1.000
	Distractor, t2	-0.406	-0.789	-0.024	0.107	-3.800	0.017
	No.distractor, t2	-0.425	-0.828	-0.021	0.113	-3.761	0.019
	Distractor, t3	-0.121	-0.503	0.262	0.107	-1.131	1.000
	No.distractor, t3	-0.150	-0.553	0.254	0.113	-1.325	1.000
	Distractor, t4	0.021	-0.362	0.403	0.107	0.195	1.000
	No.distractor, t4	-0.129	-0.532	0.275	0.113	-1.141	1.000
	Distractor, t5	-0.188	-0.571	0.194	0.107	-1.764	1.000
	No.distractor, t5	-0.298	-0.702	0.105	0.113	-2.644	0.652
	Distractor, t6	-0.610	-0.992	-0.227	0.107	-5.705	< .001
	No.distractor, t6	-0.662	-1.066	-0.259	0.113	-5.868	< .001
	Distractor, t7	-0.021	-0.403	0.362	0.107	-0.196	1.000
	No.distractor, t7	-0.050	-0.454	0.353	0.113	-0.444	1.000
	Distractor, t8	0.085	-0.297	0.468	0.107	0.798	1.000
	No.distractor, t8	0.039	-0.364	0.443	0.113	0.349	1.000
No.distractor, t1	Distractor, t2	-0.369	-0.772	0.035	0.113	-3.266	0.104
	No.distractor, t2	-0.387	-0.770	-0.005	0.107	-3.624	0.032
	Distractor, t3	-0.084	-0.487	0.320	0.113	-0.740	1.000
	No.distractor, t3	-0.112	-0.495	0.270	0.107	-1.050	1.000
	Distractor, t4	0.058	-0.345	0.462	0.113	0.516	1.000
	No.distractor, t4	-0.091	-0.474	0.291	0.107	-0.856	1.000
	Distractor, t5	-0.151	-0.555	0.252	0.113	-1.339	1.000
	No.distractor, t5	-0.261	-0.644	0.121	0.107	-2.443	1.000
	Distractor, t6	-0.572	-0.976	-0.169	0.113	-5.069	< .001
	No.distractor, t6	-0.625	-1.007	-0.243	0.107	-5.850	< .001
	Distractor, t7	0.016	-0.387	0.420	0.113	0.146	1.000
	No.distractor, t7	-0.013	-0.395	0.370	0.107	-0.120	1.000
	Distractor, t8	0.123	-0.281	0.526	0.113	1.087	1.000
	No.distractor, t8	0.077	-0.306	0.459	0.107	0.719	1.000
Distractor, t2	No.distractor, t2	-0.019	-0.185	0.148	0.045	-0.415	1.000
	Distractor, t3	0.285	-0.097	0.668	0.107	2.669	0.619
	No.distractor, t3	0.256	-0.147	0.660	0.113	2.272	1.000
	Distractor, t4	0.427	0.044	0.809	0.107	3.995	0.008
	No.distractor, t4	0.277	-0.126	0.681	0.113	2.456	1.000
	Distractor, t5	0.218	-0.165	0.600	0.107	2.036	1.000
	No.distractor, t5	0.108	-0.296	0.511	0.113	0.953	1.000
	Distractor, t6	-0.204	-0.586	0.179	0.107	-1.905	1.000
	No.distractor, t6	-0.256	-0.660	0.147	0.113	-2.271	1.000
	Distractor, t7	0.385	0.003	0.768	0.107	3.605	0.034
	No.distractor, t7	0.356	-0.048	0.759	0.113	3.152	0.146
	Distractor, t8	0.491	0.109	0.874	0.107	4.599	< .001
	No.distractor, t8	0.445	0.042	0.849	0.113	3.946	0.010
No.distractor, t2	Distractor, t3	0.304	-0.100	0.707	0.113	2.690	0.585
	No.distractor, t3	0.275	-0.107	0.658	0.107	2.574	0.789
	Distractor, t4	0.445	0.042	0.849	0.113	3.946	0.010

			95% CI for Mean Difference				
		M	Lower	Upper	*SE*	*t*	p_{holm}
	No.distractor, t4	0.296	-0.087	0.678	0.107	2.768	0.481
	Distractor, t5	0.236	-0.167	0.640	0.113	2.091	1.000
	No.distractor, t5	0.126	-0.256	0.509	0.107	1.180	1.000
	Distractor, t6	-0.185	-0.589	0.218	0.113	-1.639	1.000
	No.distractor, t6	-0.238	-0.620	0.145	0.107	-2.226	1.000
	Distractor, t7	0.404	1.426e -4	0.807	0.113	3.576	0.036
	No.distractor, t7	0.374	-0.008	0.757	0.107	3.504	0.048
	Distractor, t8	0.510	0.106	0.913	0.113	4.517	< .001
	No.distractor, t8	0.464	0.081	0.846	0.107	4.343	0.002
Distractor, t3	No.distractor, t3	-0.029	-0.195	0.138	0.045	-0.642	1.000
	Distractor, t4	0.142	-0.241	0.524	0.107	1.327	1.000
	No.distractor, t4	-0.008	-0.411	0.396	0.113	-0.070	1.000
	Distractor, t5	-0.068	-0.450	0.315	0.107	-0.633	1.000
	No.distractor, t5	-0.178	-0.581	0.226	0.113	-1.573	1.000
	Distractor, t6	-0.489	-0.871	-0.106	0.107	-4.574	< .001
	No.distractor, t6	-0.541	-0.945	-0.138	0.113	-4.797	< .001
	Distractor, t7	0.100	-0.283	0.482	0.107	0.936	1.000
	No.distractor, t7	0.071	-0.333	0.474	0.113	0.627	1.000
	Distractor, t8	0.206	-0.176	0.589	0.107	1.930	1.000
	No.distractor, t8	0.160	-0.243	0.564	0.113	1.420	1.000
No.distractor, t3	Distractor, t4	0.170	-0.233	0.574	0.113	1.509	1.000
	No.distractor, t4	0.021	-0.362	0.403	0.107	0.194	1.000
	Distractor, t5	-0.039	-0.442	0.365	0.113	-0.345	1.000
	No.distractor, t5	-0.149	-0.531	0.234	0.107	-1.394	1.000
	Distractor, t6	-0.460	-0.864	-0.057	0.113	-4.075	0.006
	No.distractor, t6	-0.513	-0.895	-0.130	0.107	-4.800	< .001
	Distractor, t7	0.129	-0.275	0.532	0.113	1.140	1.000
	No.distractor, t7	0.099	-0.283	0.482	0.107	0.930	1.000
	Distractor, t8	0.235	-0.169	0.638	0.113	2.080	1.000
	No.distractor, t8	0.189	-0.194	0.571	0.107	1.769	1.000
Distractor, t4	No.distractor, t4	-0.150	-0.316	0.017	0.045	-3.353	0.113
	Distractor, t5	-0.209	-0.592	0.173	0.107	-1.959	1.000
	No.distractor, t5	-0.319	-0.723	0.084	0.113	-2.828	0.403
	Distractor, t6	-0.630	-1.013	-0.248	0.107	-5.900	< .001
	No.distractor, t6	-0.683	-1.087	-0.280	0.113	-6.052	< .001
	Distractor, t7	-0.042	-0.424	0.341	0.107	-0.391	1.000
	No.distractor, t7	-0.071	-0.475	0.333	0.113	-0.629	1.000
	Distractor, t8	0.064	-0.318	0.447	0.107	0.603	1.000
	No.distractor, t8	0.019	-0.385	0.422	0.113	0.165	1.000
No.distractor, t4	Distractor, t5	-0.060	-0.463	0.344	0.113	-0.529	1.000
	No.distractor, t5	-0.170	-0.552	0.213	0.107	-1.588	1.000
	Distractor, t6	-0.481	-0.884	-0.077	0.113	-4.259	0.003
	No.distractor, t6	-0.534	-0.916	-0.151	0.107	-4.994	< .001
	Distractor, t7	0.108	-0.296	0.511	0.113	0.956	1.000
	No.distractor, t7	0.079	-0.304	0.461	0.107	0.736	1.000
	Distractor, t8	0.214	-0.189	0.618	0.113	1.897	1.000
	No.distractor, t8	0.168	-0.214	0.551	0.107	1.575	1.000
Distractor, t5	No.distractor, t5	-0.110	-0.276	0.057	0.045	-2.464	1.000
	Distractor, t6	-0.421	-0.804	-0.039	0.107	-3.941	0.010
	No.distractor, t6	-0.474	-0.877	-0.070	0.113	-4.198	0.004
	Distractor, t7	0.168	-0.215	0.550	0.107	1.569	1.000

			95% CI for Mean Difference				
		M	Lower	Upper	*SE*	*t*	p_{holm}
	No.distractor, t7	0.138	-0.265	0.542	0.113	1.225	1.000
	Distractor, t8	0.274	-0.109	0.656	0.107	2.563	0.804
	No.distractor, t8	0.228	-0.176	0.631	0.113	2.019	1.000
No.distractor, t5	Distractor, t6	-0.311	-0.715	0.092	0.113	-2.756	0.488
	No.distractor, t6	-0.364	-0.746	0.019	0.107	-3.406	0.067
	Distractor, t7	0.278	-0.126	0.681	0.113	2.459	1.000
	No.distractor, t7	0.248	-0.134	0.631	0.107	2.324	1.000
	Distractor, t8	0.384	-0.020	0.787	0.113	3.399	0.067
	No.distractor, t8	0.338	-0.045	0.720	0.107	3.162	0.145
Distractor, t6	No.distractor, t6	-0.053	-0.219	0.114	0.045	-1.183	1.000
	Distractor, t7	0.589	0.206	0.971	0.107	5.510	< .001
	No.distractor, t7	0.559	0.156	0.963	0.113	4.956	< .001
	Distractor, t8	0.695	0.312	1.077	0.107	6.504	< .001
	No.distractor, t8	0.649	0.245	1.053	0.113	5.749	< .001
No.distractor, t6	Distractor, t7	0.641	0.238	1.045	0.113	5.682	< .001
	No.distractor, t7	0.612	0.230	0.995	0.107	5.730	< .001
	Distractor, t8	0.748	0.344	1.151	0.113	6.623	< .001
	No.distractor, t8	0.702	0.319	1.084	0.107	6.569	< .001
Distractor, t7	No.distractor, t7	-0.029	-0.196	0.137	0.045	-0.656	1.000
	Distractor, t8	0.106	-0.276	0.489	0.107	0.994	1.000
	No.distractor, t8	0.060	-0.343	0.464	0.113	0.534	1.000
No.distractor, t7	Distractor, t8	0.135	-0.268	0.539	0.113	1.200	1.000
	No.distractor, t8	0.090	-0.293	0.472	0.107	0.838	1.000
Distractor, t8	No.distractor, t8	-0.046	-0.212	0.121	0.045	-1.028	1.000

Note. Mean differences in the distance of participants' gaze to the target between the eight time windows in visual degrees, with *p*-values and CI adjusted for comparing a family of 28 estimates using the Bonferroni-Holm correction method). Distractor and no distractor conditions are depicted separately. Results are averaged over the level of optic flow.

Table A2

Post-hoc Comparisons of Gaze Velocity for all Time Windows

			95% CI for Mean Difference				
		M	Lower	Upper	*SE*	*t*	p_{holm}
t1	t2	0.117	-0.084	0.319	0.064	1.840	1.000
	t3	0.057	-0.145	0.258	0.064	0.889	1.000
	t4	0.161	-0.041	0.363	0.064	2.522	0.346
	t5	-0.334	-0.535	-0.132	0.064	-5.230	< .001
	t6	-0.049	-0.251	0.152	0.064	-0.773	1.000
	t7	0.160	-0.041	0.362	0.064	2.512	0.356
	t8	0.318	0.117	0.520	0.064	4.993	< .001
t2	t3	-0.061	-0.262	0.141	0.064	-0.951	1.000
	t4	0.044	-0.158	0.245	0.064	0.682	1.000
	t5	-0.451	-0.653	-0.249	0.064	-7.070	< .001
	t6	-0.167	-0.368	0.035	0.064	-2.613	0.268
	t7	0.043	-0.159	0.245	0.064	0.672	1.000
	t8	0.201	0.000	0.403	0.064	3.153	0.051
t3	t4	0.104	-0.097	0.306	0.064	1.634	1.000
	t5	-0.390	-0.592	-0.189	0.064	-6.119	< .001
	t6	-0.106	-0.308	0.096	0.064	-1.662	1.000
	t7	0.104	-0.098	0.305	0.064	1.623	1.000
	t8	0.262	0.060	0.463	0.064	4.104	0.002
t4	t5	-0.495	-0.696	-0.293	0.064	-7.752	< .001
	t6	-0.210	-0.412	-0.009	0.064	-3.295	0.032
	t7	-0.000	-0.202	0.201	0.064	-0.010	1.000
	t8	0.158	-0.044	0.359	0.064	2.470	0.399
t5	t6	0.284	0.083	0.486	0.064	4.457	< .001
	t7	0.494	0.292	0.696	0.064	7.742	< .001
	t8	0.652	0.450	0.854	0.064	10.223	< .001
t6	t7	0.210	0.008	0.411	0.064	3.285	0.033
	t8	0.368	0.166	0.569	0.064	5.766	< .001
t7	t8	0.158	-0.043	0.360	0.064	2.481	0.388

Note. Depicted are the mean differences in the velocity of participants' eye movements in visual degrees per second between the eight time windows. *p*-values and CI were adjusted for comparing a family of 28 estimates using the Bonferroni-Holm correction method). Results are averaged over the levels of distractor presence and optic flow.

Table A3

Post-hoc Comparisons of Mouse Cursor Distances for all Time Windows

			95% CI for Mean Difference				
		M	Lower	Upper	*SE*	*t*	*p*
t1	t2	0.013	-0.017	0.043	0.009	1.356	0.705
	t3	0.013	-0.017	0.043	0.009	1.345	0.705
	t4	-0.039	-0.069	-0.009	0.009	-4.090	< .001
	t5	-0.092	-0.122	-0.062	0.009	-9.674	< .001
	t6	-0.059	-0.089	-0.029	0.009	-6.266	< .001
	t7	0.048	0.018	0.078	0.009	5.069	< .001
	t8	0.058	0.028	0.088	0.009	6.136	< .001
t2	t3	-0.000	-0.030	0.030	0.009	-0.012	0.991
	t4	-0.052	-0.081	-0.022	0.009	-5.446	< .001
	t5	-0.104	-0.134	-0.074	0.009	-11.031	< .001
	t6	-0.072	-0.102	-0.042	0.009	-7.622	< .001
	t7	0.035	0.005	0.065	0.009	3.713	0.002
	t8	0.045	0.015	0.075	0.009	4.780	< .001
t3	t4	-0.051	-0.081	-0.022	0.009	-5.434	< .001
	t5	-0.104	-0.134	-0.074	0.009	-11.019	< .001
	t6	-0.072	-0.102	-0.042	0.009	-7.611	< .001
	t7	0.035	0.005	0.065	0.009	3.724	0.002
	t8	0.045	0.015	0.075	0.009	4.791	< .001
t4	t5	-0.053	-0.083	-0.023	0.009	-5.585	< .001
	t6	-0.021	-0.051	0.009	0.009	-2.176	0.153
	t7	0.087	0.057	0.117	0.009	9.159	< .001
	t8	0.097	0.067	0.127	0.009	10.226	< .001
t5	t6	0.032	0.002	0.062	0.009	3.409	0.005
	t7	0.140	0.110	0.169	0.009	14.743	< .001
	t8	0.150	0.120	0.180	0.009	15.810	< .001
t6	t7	0.107	0.077	0.137	0.009	11.335	< .001
	t8	0.117	0.087	0.147	0.009	12.402	< .001
t7	t8	0.010	-0.020	0.040	0.009	1.067	0.705

Note. Mean differences of participants' mouse cursor distances to the target in visual degrees between the eight time windows, with *p*-values and CI adjusted for comparing a family of 28 estimates using the Bonferroni-Holm correction method). Results are averaged over the levels of distractor presence and optic flow.

Appendix B

Abstract (English)

Driving is a complex and dangerous activity with high requirements for human perception and attention. For this reason, insights into how people manage to stay focused on relevant information without being distracted by appearing stimuli during driving could be valuable for improving drivers' safety. In our experiment with 35 participants, we simulated a continuous optic flow pattern to create the impression of three-dimensional movement and tested if abrupt onset distractors with target-matching color properties capture attention in line with contingent capture theory. Contrary to our expectations, we found higher average distances of drivers' gaze to the target when distractors were absent, possibly caused by participants' anticipatory eye movements during smooth pursuit and by look-ahead fixations. Comparison of the optic flow condition and the control condition showed that the higher perceptual noise caused by optic flow might have diminished the visibility of the distractors. Participants were also able to follow the target with the mouse more precisely when optic flow was absent, thereby showing the complexity added by three-dimensional movement on task completion. The modulation of participants' eye and hand movements by optic flow could have important implications for real-world driving. Therefore, these findings should be connected with further real-world and lab experiments assessing attentional capture during driving tasks.

Keywords: abrupt onsets, anticipatory eye movements, contingent capture, driving, optic flow, visual attention

Zusammenfassung (Deutsch)

Autofahren ist eine komplexe und gefährliche Tätigkeit mit hohen Anforderungen an die menschliche Wahrnehmung und Aufmerksamkeit. Aus diesem Grund könnten Erkenntnisse darüber, wie Menschen es schaffen, während des Fahrens auf relevante Informationen fokussiert zu bleiben, ohne durch plötzlich auftauchende Reize abgelenkt zu werden, wertvoll für die Verbesserung der Fahrsicherheit sein. In unserem Experiment mit 35 Versuchspersonen simulierten wir ein kontinuierliches optisches Flussmuster, um den Eindruck einer dreidimensionalen Bewegung zu erzeugen, und testeten, ob plötzlich erscheinende Distraktoren mit zielübereinstimmenden Farbeigenschaften die Aufmerksamkeit im Sinne der Contingent-Capture-Theorie auf sich ziehen. Entgegen unserer Erwartungen fanden wir höhere durchschnittliche Blickabstände der Fahrer zum Ziel, wenn die Distraktoren abwesend waren, möglicherweise verursacht durch die antizipatorischen Augenbewegungen der Versuchspersonen durch glatte Augenfolgebewegungen und Look-Ahead-Fixationen. Der Vergleich der Bedingung mit Optischem Fluss mit der Kontrollbedingung zeigte, dass das höhere Wahrnehmungsrauschen, das durch den Optischen Fluss verursacht wurde, die Sichtbarkeit der Distraktoren vermindert haben könnte. Die Versuchspersonen waren auch in der Lage, das Ziel mit der Maus präziser zu verfolgen, wenn der optische Fluss abwesend war, was die Komplexität, die die dreidimensionale Bewegung bei der Aufgabenerfüllung verursacht, zeigt. Die Modulation der Augen- und Handbewegungen der Versuchspersonen durch den optischen Fluss könnte wichtige Implikationen für das Autofahren haben. Daher sollten diese Ergebnisse mit weiteren Experimenten in der realen Welt und im Labor verbunden werden, die die Aufmerksamkeitserfassung während diverser Fahraufgaben untersuchen.

Schlüsselwörter: Autofahren, antizipatorische Augenbewegungen, Contingent Capture, Optischer Fluss, plötzlich auftauchende Reize, visuelle Aufmerksamkeit