Volume 30 – Issue 4 – March-April 2022
Visual Cognition
Co-Editors: Benjamin Balas & Jonathan Flombaum

Visual Cognition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/pvis20

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To cite this article: Daniel Ernst & Jeremy M. Wolfe (2022): How fixation durations are affected by search difficulty manipulations, Visual Cognition, DOI: 10.1080/13506285.2022.2063465

To link to this article: https://doi.org/10.1080/13506285.2022.2063465

Published online: 13 Apr 2022.

VISUAL COGNITION
https://doi.org/10.1080/13506285.2022.2063465

How fixation durations are affected by search difficulty manipulations

Daniel Ernst[a,b,c] and Jeremy M. Wolfe[a,b]

[a]Brigham & Women's Hospital, Boston, MA, United States; [b]Harvard Medical School, Boston, MA, United States; [c]Bielefeld University, Bielefeld, Germany

ABSTRACT

Many eye tracking studies of visual search have focused on the role of the number of fixations and the nature of scan paths. Less attention has been paid to fixation durations and to how those durations are affected by stimulus features. Previous studies have shown that fixation durations can be as important as the number of fixations in explaining search times with complex stimuli (e.g., in search for specific faces). In the present study, simple stimuli were used in a search experiment where participants searched for a closed ring among rings with a gap. We manipulated distractor heterogeneity (DH), target-distractor similarity (TDS), and stimulus density (SDY, set size within a constant search window), and estimated the contributions of these factors to gaze behaviour and trial search time. The results show that fixation durations contribute less to variation in overall search time with simple search stimuli as compared to previous studies with more complex stimuli. However, fixation durations still increased with DH, TDS, and SDY. These effects were mainly additive, and we did not find an interaction between DH and closer element spacing at high levels of SDY that might have been expected since both DH and SDY influence distractor grouping.

ARTICLE HISTORY
Received 15 September 2021
Accepted 1 April 2022

KEYWORDS
Visual search; fixation duration; distractor heterogeneity; target-distractor similarity; element spacing

Introduction

When we search for our car at the parking lot, we usually do not have to direct our gaze on every car individually to find it. Apart from the fact that we may remember the position of our car, further attentional mechanisms help us to guide the visual search process. If the searched for car is blue, neuronal activity associated with visual input having that colour feature can be increased. As a consequence, gaze fixations are more likely to be directed to blueish cars than to cars with other colours. This will reduce the overall number of cars that will be fixated, and hence the search time. Obviously, eye movements play a crucial role in these everyday visual search processes. Although search times can be modelled without much discussion of eye movements (e.g., Wolfe, 1994, 2007, 2021), investigating gaze parameters as mediators between the visual input and search performance can yield insights into the specific mechanisms that determine search time. The two basic gaze parameters which determine search time are the number of fixations and fixation durations (e.g., Horstmann et al., 2019; Hulleman & Olivers, 2017).

The number of fixations necessary to search through a display yields information about how many items can be analyzed per fixation at a given level of search difficulty. This measure is closely related to the size of the *functional visual field* (FVF, Hulleman & Olivers, 2017; Sanders, 1970). One definition of the FVF would be that it is the view field surrounding a fixation within which the target can reliably be detected (similar constructs have also been described as the *useful field of view*, Ball et al., 1988; *conspicuity area*, Engel, 1992; *visual lobe*, Widdel, 1983; or the *visual span*, Jacobs, 2017). This definition of the FVF will produce different results depending on what we mean by "reliably detected." For instance, is the location of the target given to the observer? With the observer fixating at one location, we can cue another location and ask if it contains a target item. The set of locations where the target can be identified reliably is one measure of an FVF. Alternatively, if the observer is searching for a target item with eye movements, we can ask how close to the current fixation that target needs to be in order to be found at some threshold level of performance. That will produce a related but not

CONTACT Daniel Ernst daniel.ernst@uni-bielefeld.de Department of Psychology and CITEC, Bielefeld University, PO Box 100131, 33501 Bielefeld, Germany

identical FVF for search. In either case, if the target is sufficiently difficult to detect, the FVF's size will approach the size of the search stimuli. With a 1-item FVF, each item needs to be fixated individually until the target is found, resulting in a high number of fixations per trial. If the target on average can be found with fewer fixations than would be expected by such purely serial scanning, then it follows that the FVF's size must cover more than one stimulus. Although it is difficult to estimate the FVF's absolute size by the number of fixations (but see Young & Hulleman, 2017), fixation count can still be used as a simple measure to indicate whether the FVF's size differs between search conditions.

Refixations of search stimuli have been considered special cases, revealing to which extent visual search includes memory for already inspected positions (Gilchrist & Harvey, 2000; McCarley et al., 2003; Peterson et al., 2001). Most studies suggest limited memory for prior fixations such that no more than approximately the last four fixation locations will be protected from refixation (cf. Hulleman & Olivers, 2017).

Fixation durations have been used to investigate processes of stimulus discrimination. Becker (2011) found that fixation durations increase with target-distractor similarity in the search for a closed ring among rings with varying gap sizes. She attributed this effect to a more time-consuming discrimination process between similar stimuli. In medical images, expert radiologists have longer fixation durations on low-salience abnormalities than novices, suggesting that novices sometime fail to recognize abnormalities even when they fixate them (Matsumoto et al., 2011; Van der Gijp et al., 2017; Wood et al., 2021). Fixation durations are also increased when observers encounter novel or unexpected stimuli (Ernst et al., 2020, 2018; Horstmann, Becker, et al., 2016). On the other hand, both in search displays with simple, artificial stimuli, and scenes with very short fixation durations suggest that the analysis of the current visual input is not necessarily completely finished before the saccade to the next fixation location is initiated (Hooge & Erkelens, 1996; Nuthmann et al., 2010; see also Godwin et al., 2017). When the duration is very short (typically below 100 ms) for fixation N, it can be shown that the destination of the next saccade was already determined during the fixation N-1 (Caspi et al., 2004; Findlay et al., 2004).

Overall, the role of fixation duration has received relatively little attention in the previous visual search literature. However, as will be shown in the present study, fixation durations can provide specific information about the search process that do necessarily follow the result pattern of trial reaction times or the number of fixations per trial. Since often multiple fixations are performed during a search trial, average trial fixation duration may yield a highly reliable measure for search difficulty manipulations, for instance. The duration of specific fixations within a search trial, on the other hand, can reveal attentional effects in the course of the search process, such as recognition errors in search for lung nodules as well as attentional selection duration of more or less salient abnormalities (Kundel et al., 1978; Van der Gijp et al., 2017).

In searches where the eyes move freely, there are several ways to increase search difficulty and, thus, to affect gaze behaviour. One is to make target and distractors more similar (target-distractor similarity – TDS). Alternatively, the similarity between distractors can be decreased, making the overall display more heterogeneous (distractor heterogeneity – DH). Together, the levels TDS and DH influence whether search time increases with increasing set size (the number of items in the display) (Duncan & Humphreys, 1989). If TDS and DH are low enough that the target can always easily be detected in the periphery (i.e., the FVF is large) from the beginning of the search trial, then adding further distractors to the display will not substantially increase search time.

The number of fixations needed to find the target is obviously an important component of the search time. If a larger FVF allows for fewer fixations, RT will decrease compared to a situation where every item requires fixation in order to be identified. Another component of search time is the duration of fixations. Holding the FVF fixed, overall response time will decline if the time required to reject each distractor decreases (Becker, 2011).

To simulate search performance, Hulleman and Olivers (2017) assumed a fixed fixation duration of 250 ms independent of target discriminability. Thus, they predicted search times solely based on the number of fixations. Of course, Hulleman and Olivers know that durations vary, but for the purposes of their model, this variation is assumed to be noise. The authors argue for the applicability of their FVF model to naturalistic stimuli and scenes. However, especially in the case of complex search stimuli, this assumption of a constant, if noisy fixation duration appears to be at odds with recent studies that suggest that fixation duration varies in a meaningful fashion.

Horstmann et al. (2017) investigated how the number of fixations and fixation duration determine search time in search for specific faces amongst naturalistic face photographs. Overall, about 90% of the variability in search time could be explained by gaze behaviour (see also Horstmann, Herwig, et al. 2016). Crucially, the authors found that variability in fixation duration contributed as strongly as the number of fixations. This runs counter to the assumption of a constant fixation duration.

One could argue that the search for naturalistic face photographs, as in Horstmann et al. (2017), may be a special case where distractor rejection requires a higher amount of in-depth processing that accentuates the role of variability in fixation durations. This was tested by Horstmann et al. (2020), who found that fixation duration and the number of fixations still predicted search time equally effectively in search through simpler shape stimuli. In this study, however, each search stimulus was a composition of about eight light and dark rectangles. Hence, the items were still relatively complex compared to widely used artificial search stimuli (e.g., Ts and Ls, Duncan & Humphreys, 1989; or rings, Becker, 2011; Hooge & Erkelens, 1996; Treisman & Souther, 1985). This raises the question of whether there is still meaningful variability in fixation duration with simple search items like bars and rings. If there is meaningful variability, can it be explained by factors of TDS, DH, and set size? That is the topic of the present study.

The present study

As Hulleman and Olivers (2017) point out, variability of fixation duration in search tasks using artificial stimuli can be subtle. Here, we collected a relatively large dataset that gives us enough statistical power to make it possible to measure effects on fixation duration with reasonable precision. Furthermore, the use of very simple stimuli (in this case, Landolt Cs and Os) allows for more precise control over the stimuli compared to other stimuli – certainly, if compared to scene stimuli where even specifying set size is problematic.

Using these simple stimuli, we varied TDS, DH, and set size variables in one experiment in order to evaluate a holistic mediation model that tests the unique effects of these three independent variables on search times via the number of fixations and fixation duration. Such a mediation model allows for direct comparisons of mediation effect sizes, revealing the extent that increasing search difficulty can be modelled by adjusting the number of fixations and the fixation durations. Participants searched for a single closed ring among rings with a gap, making the task comparable to many other search studies (e.g., Becker, 2011; Ernst & Horstmann, 2018; Hooge & Erkelens, 1996; Klein & Farrell, 1989; Treisman & Souther, 1985). A number of previous studies have changed TDS in order to manipulate search difficulty (e.g., Wienrich et al., 1983), but only in a few visual search studies was DH manipulated to test for effects on gaze behaviour (Porter et al., 2007, found that DH increases pupil dilation, for instance). It appears that the impact of DH on fixation duration and on the number of fixations has not been previously investigated.

According to the Attentional Engagement Theory (Duncan & Humphreys, 1989, 1992), homogeneous distractors can be grouped and rejected in a single step, which reduces search time (see also Verghese & Nakayama, 1994). Nevertheless, the extent to which this effect is mediated via the number of fixations and fixation durations has been unclear. As mentioned before, previous studies found that TDS increased fixation durations, presumably because a high level of TDS leads to a more time-consuming stimulus discrimination process (Becker, 2011; Hooge & Erkelens, 1996; Horstmann, Herwig, et al., 2016; Horstmann et al., 2017, 2019, 2020). Similarly, we expect fixation durations to increase with DH as well because of an impaired ability to reject multiple distractors at once within a fixation (Duncan & Humphreys, 1989).

How might set size affect fixation duration? In the present study, as in most search studies with a set size variation, varying numbers of search items are randomly distributed within a window of a constant size. Thus, the stimulus density increases with set size (hence, we will refer to “stimulus density” instead of set size in the following). This produces crowding effects on gaze behaviour (Vlaskamp et al., 2005). Visual crowding refers to increasingly impaired feature discrimination when multiple stimuli are presented at higher eccentricities (e.g., Levi et al., 2002; Pelli et al., 2004). As a rule of thumb, impairment emerges when inter-stimulus distances (centre-to-centre) are roughly less than half the eccentricity ("Bouma's Law," Bouma, 1970).

Motter and Simoni (2008) varied search difficulty via stimulus density (SDY) to test for effects on the FVF. In one search condition, participants were forced to keep central fixation during search. The authors found that the FVF grew during the course of the trial in the sense that more eccentric targets were more likely to be found later in the trial. However, the results of the free viewing search conditions also suggested that participants prefer to perform eye movements if eye movements were permitted. In the present study, we will more closely investigate whether SDY effects are handled by longer fixation durations in a free viewing search.

With respect to the number of fixations, previous studies demonstrated that increasing TDS produced more fixations (e.g., Horstmann et al., 2017; Hulleman et al., 2020; Wienrich et al., 1983), while the effect of DH remains to be investigated (Hulleman & Olivers, 2017). With the same rationale that has been applied to fixation duration, we assume that as DH increases, the identification of distractor groups suffers from visual acuity loss and peripheral crowding. We hypothesize that this will lead to an increasing the number of fixations.

In separate analyses, we will investigate whether the effects of TDS, DH, and SDY on fixation duration and on the number of fixations interact. Although studies usually find increasing SDY to have a prolonging effect on search time, there are studies reporting that search performance can benefit from closer element spacing (Sagi & Julesz, 1987). Bacon and Egeth (1991) attributed this effect to facilitated distractor grouping. In the present study, we will test whether impeded distractor grouping due to DH is attenuated at high levels of SDY, where close element spacing leads to a higher number of stimuli that are arranged closer to the fovea.

Methods

Participants

20 students or visitors to Bielefeld University (14 women and six men) participated in the approximately 60-min experimental session. Mean age was 25.60 ($SD = 4.54$). Participants gave written informed consent prior to participation. All were tested for normal or corrected-to-normal vision and for normal colour vision. The study was approved by the Ethics Committee of University of Bielefeld (EUB), and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Apparatus

Stimuli were presented on a 19-inch display monitor (100 Hz refresh rate; 1,024 × 768 pixels) at a distance of 71 cm. Before testing, the monitor was warmed for at least 30 min, to ensure temporal stability of luminance and colour (Poth & Horstmann, 2017). A video-based eye tracker (EyeLink 1000, SR Research, Ontario, Canada) with a sampling rate of 1 kHz was used for the recording of eye movements. The participants' head was stabilized by a chin rest, and the right eye was monitored at all participants.

Stimuli

The target was a white ring subtending 1.08° of visual angle (VA) in diameter, and having a line-width of 0.23° VA. The distractors only differed from the target in that they had a gap whose width varied between 0.04° and 0.40° VA. The size of the gap defined the level of TDS. For every trial, the gap width was randomly chosen from a uniform distribution that ranged from one to fourteen pixels. This gap width was the same for every distractor within a search trial.

On each trial, a random "average" orientation of the gaps was chosen from a uniform distribution and a maximum deviation that defined the level of DH. That maximum possible deviation from the average gap orientation was likewise chosen from a uniform distribution with a range of 0° to 179° per trial. For instance, if a relatively small maximum deviation of 10° was chosen as in Figure 1 (left), the deviation of each individual orientation was chosen from a uniform distribution with a range of −10° to +10°. Simply put, the level of DH in a trial was manipulated by varying the extent to which the gaps could point in different directions.

The number of search stimuli randomly varied between trials within a range of 80 and 220, randomly

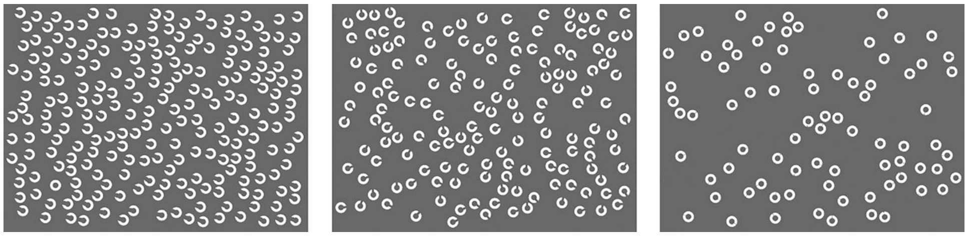

Figure 1. Examples of search displays for target present trials. Left: Maximum stimulus density, minimum TDS, almost minimum DH; middle: medium stimulus density, TDS and DH; right: minimum stimulus density, maximum TDS and DH (the target is the middle of the upper three items).

chosen from a uniform distribution. Stimulus positions were random with the restrictions that the outer border of the stimuli always had a minimum distance of 0.35° VA to the border of the search display, and that the borders of the stimuli had a minimum distance of 0.11° VA to each other. The stimuli were white (RGB: 255, 255, 255; CIE: $x = 0.280$, $y = 0.291$; 101.47 cd/m^2) and presented on grey background (RGB: 127, 127, 127; CIE: $x = 0.278$, $y = 0.287$; 31.23 cd/m^2).

The search displays were generated and presented with Python 3.6, using the PsychPy3 package (Peirce et al., 2019). Pylink (SR Research) was used to communicate with the eye tracker during the experiment.

Procedure

The participants' task was to report the presence or absence of the target with a corresponding key press (arrow left and arrow down keys of a standard keyboard, operated with the right index and middle fingers). Participants were instructed to perform the search task as fast as possible while avoiding response errors. Each trial began with a pre-display that contained a central white fixation dot with a diameter of 0.28° VA. The duration of the pre-display was the sum of an initial period of 500 ms, followed by a 500 ms period during which the gaze position could not exceed a distance of 0.85° from the centre of the fixation dot. This period could be extended if gaze was unstable. After this period of stable fixation, the search display was shown. Once a manual response was given, the search display disappeared. In case of an incorrect response, the German word for "Wrong!" was presented centrally and in white letters for 500 ms before the next pre-display was presented.

The participants performed seven blocks with 24 trials each. The first block was considered practice and not analyzed. At the beginning of every block, the eye tracker was calibrated. Between blocks, participants had the opportunity to take a short break.

Design

Every search display was a random combination of TDS, DH, and SDY (i.e., search difficulty was not blocked), all of which were manipulated in a quasi-continuous fashion. The target was present in 50% of search trials.

Results

Data pre-processing

Raw gaze data were pre-processed using the EyeLink Data Viewer (4.2.1), which parses eye position data into saccades and fixations according to an acceleration threshold (8,000 degrees/sec^2), and a velocity threshold (30 degrees/sec). Fixations were classified as eye data that exceeded neither of these thresholds for a period of 20 ms or more. Interest areas corresponded to the search stimuli's sizes and locations. Because of the relatively high overall stimulus density in the present experiment, fixations were always assigned to the nearest stimulus (as calculated by the EyeLink Data Viewer algorithm).

Further pre-processing and statistical analysis used R 4.0.5 (R Core Team, 2021). All reported *p*-values are two-tailed and a significance level of $\alpha = .05$ is used.

Pooled over all participants, there were 3,360 search trials. 2,880 trials remained after excluding the first practice block. Due to recording errors, we lost the data of 62 trials (mainly when the eye tracker had to be recalibrated). 52 of these errors occurred in non-practice trials, resulting in a remaining number of 1,428 target present and 1,400 target absent trials.

Accuracy and search slopes

Participants gave correct responses in 75% of target present trials and in 98% of target absent trials. In line with Horstmann, Herwig, et al. (2016), in the following, we analyze only the target absent trials to avoid having target presence as an additional factor. Horstmann et al. (2017) show that for similar analyses as in the present study, target present trials mainly differ from target absent trials in the degree to which the number of fixations predicts search times. Because observers can stumble on the target early in search or need to search through most of the display, target present RTs and fixation counts are very variable and tightly correlated. To see the effects of TDS and DH, it is more profitable to restrict the analysis to the target absent trials.

To analyze traditional search slopes (Wolfe, 1998) and possible speed-accuracy trade-offs, we regressed trial RTs (in ms) on the continuous independent variables TDS, DH, and SDY, as well as on the binary predictor trial response (0 = correct vs. 1 = error), and all possible interactions. A linear mixed model with random intercepts per participant was calculated to control for repeated measurements (using the lme4-package for R; Bates et al., 2019) as every participant contributed multiple trials. The resulting regression slopes (*b* in Table 1) describe the linear change in RT when the corresponding predictor increases by one unit while all remaining predictors have a value of zero. Note that we used mean centred (but not standardized) values of TDS, DH, and SDY for this analysis. As a consequence, a value of zero corresponds to the average value of the respective variable. That is, the regression slope (*b*) of TDS, for instance, actually represents the change in RT when TDS increases by one point while all remaining *continuous* predictors (i.e., DH and SDY) have an average level, and a correct response was given in that trial (as the trial response "correct" was coded with zero).

Table 1 shows the full regression model. The intercept of 14,357 in the first row represents the mean RT (ms) when all predictors have a level of zero (i.e., in correct trials with average TDS, DH, and SDY). Thus, search trials tended to be relatively long in the present study. Rows 2–4 of Table 1 show that there are significant effects for SDY, TDS, and DH. Increasing any of these factors increases

Table 1. Regression of RT on TDS, DH, SDY, and response type in target absent trials.

	b	*t*	*p*
[1]Intercept	14357	11.99	< .001***
[2]Stimulus density	57	16.09	< .001***
[3]Target-distractor similarity	739	19.96	< .001***
[4]Distractor heterogeneity	11	4.09	< .001***
[5]Trial response (correct → error)	242	0.04	.968
[6]SDY × TDS	2	2.46	.014*
[7]SDY × DH	0.1	1.28	.199
[8]TDS × DH	−1	−1.51	.130
[9]SDY × Trial response	−89	−0.59	.553
[10]TDS × Trial response	−1453	−1.46	.144
[11]DH × Trial response	−116	−0.92	.357
[12]SDY × TDS × DH	−0.01	−0.39	.694
[13]SDY × TDS × Trial response	1	0.04	.966
[14]SDY × DH × Trial response	−0.3	−0.13	.899
[15]TDH × DH × Trial response	26	1.17	.241
[16]SDY × TDS × DH × Trial response	0.3	0.62	.532

Note: Regression is calculated by a linear mixed model with random intercept for the 20 participants. Overall, 1,400 trials contributed to the analysis. * $p < .05$, *** $p < .001$.

RT. Note that the slope (*b*) of SDY represents the "traditional" search slope that has usually been reported for visual search studies (Wolfe, 1998). It shows that at average levels of TDS and DH, there is an increase of 57 ms in RT for every item that is added to the display. The significant interaction in the sixth row of Table 1 shows that the prolonging effect of SDY depends on the level of TDS. The corresponding regression slope of $b_{SDY \times TDS} = 2$ ms means that the prolonging effect of SDY (57 ms/item) increases even further by 2 ms for every point that TDS increases. As TDS has 14 levels in this experiment and a gap size of about seven pixels is the average, the search slope with the highest level of TDS can be calculated roughly by adding seven times the value of the interaction slope $b_{SDY \times TDS} = 2$ to $b_{SDY} = 57$ ms/item, which results in a search slope of 71 ms/item. In the lowest TDS condition, the same product has to be subtracted from $b_{SDY} = 57$ ms/item, which results in a search slope of about 43 items/ms. The SDY × TDS interaction does not markedly differ between trials with correct and error responses as indicated by the non-significant SDY × TDH × Trial response three-way interaction (row 13 in Table 1), which argues against any considerable speed-accuracy trade-off in target absent trials. In general, RT did not significantly differ between correct and incorrect trials, as indicated by the non-significant effect of response type in row 5 of Table 1 as well as by the non-significant Trial response interactions. Note, however, that with only 2% incorrect target absent trials, statistical power for tests of the trial response predictor is limited. Thus, speed-accuracy trade-offs cannot be completely excluded by the data.

The predictor DH has a significant prolonging effect on RT (row 4 of Table 1). However, the lack of significant interactions with other predictors indicates that the DH effect is the same for all levels of SDY and TDS. This will be scrutinized in more detail in the following sections, where gaze parameters are considered as well.

Gaze parameters and scanning behaviour

In the following, only correct target absent trials will be included in the analyses. As 22 response errors occurred in target absent trials, 1378 trials contribute to the following analyses.

With respect to the gaze measures, we distinguish between initial fixations on an item and refixations: The variable, "#Fixations" (number of fixations) is the number of unique items fixated on a trial; that is, the number of items fixated at least once. The variable, "#Refixations" (number of refixations), is defined as the number of times that the eyes fixate on any previously fixated item during in a search trial. To count as a refixation, at least one other stimulus has to be fixated in between. The variable #Refixations is strongly skewed to the right. Many trials have zero refixations. For the convenience of analysis, we added a constant of 1 to each value and used a logarithmic-transformation, which resulted in a less skewed distribution. Note that the overall small number of refixations in the present experiment is at least partially explained by the large set sizes used (80–220 items). Given that the FVF can cover more than one stimulus per fixation, even random fixation would produce relatively few refixations. Although #Refixations are not a focus of the present study, we include this measure as it solved estimation problems in the following mediation model. Furthermore, it allows for better comparability with earlier studies on this topic, which also included #Refixations (Horstmann, Herwig, et al., 2016, Horstmann et al., 2017, 2019, 2020).

The variable, "fixation duration" is defined as the average of the duration of the first fixation on each fixated stimulus in the search display per trial. The durations of refixations are not included.

Scanning behaviour

Although not central for the present study, we were interested in how the participants searched through the relatively dense search displays of the present experiment. Figure 2 gives a rough impression of the scanning behaviour. Each dot shows the destination of a saccade with the starting point set to the centre of the image. The density of the dots shows that there was an elevated probability of saccades in horizontal and vertical directions. Note that this occurs even though the stimuli were pseudo-randomly distributed on the search display. There was no underlying grid that determined the stimuli's position, which could have produced an incentive to "read" the display in a row- or column-wise manner. Similar patterns of saccade directions have been reported for natural scene images (Tatler & Vincent, 2009; see also Le Meur & Liu, 2015). For non-semantic artificial stimuli, Foulsham and Kingstone (2010) mainly found a horizontal bias in a memory-encoding task, whereas the vertical bias in the present experiment appears to be relatively strong.

Mediation model

Figure 3 provides an overview of the bivariate correlations of all variables that will be considered in our

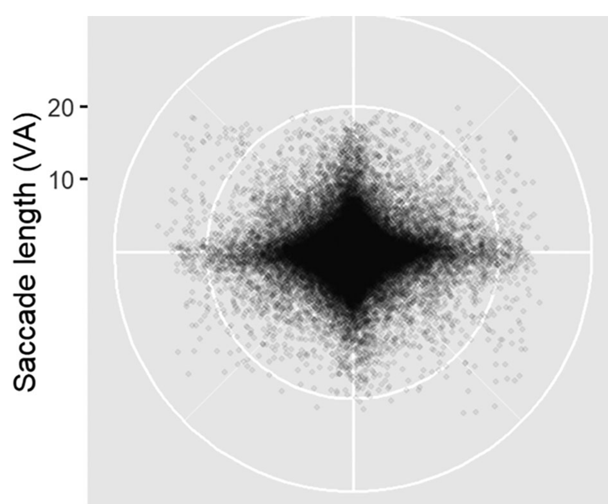

Figure 2. Polar plot of saccade direction and length. Every dot represents a saccade. The Euclidean distance from the centre of the polar plot indicates the saccade length in degrees of visual angle. The positions of the dots indicate the saccade direction relative to the previous fixation centre.

mediation model. The correlation values and the corresponding significance tests were calculated by means of linear mixed models with random intercepts per participant. A closer look at Figure 3 shows that there is some correlation between the three gaze parameters ranging from $r = .20$ to .65. This can be seen at the fourth plot in the second row of Figure 3 and at the fourth and fifth plots in the third row. Intercorrelations can lead to increased standard errors when these variables jointly predict RT as the dependent variable. To test whether this may result in a problematic level of multicollinearity in the following mediation model, we calculated the tolerance factors for the three gaze parameters when they predict RT in a multiple linear regression. The tolerance factors were .92 for fixation duration, .40 for #Fixations, and .43 for #Refixations. The tolerance factor ranges between 0 and 1. Values higher than .10 are usually considered unproblematic. Thus, we assume for the following analyses that there is no problematic level of multicollinearity, which could have considerably increased standard errors.

To test how the unique effects of TDS, DH, and SDY on search time are mediated via #fixations, #refixations, and fixation duration, a mediation model was calculated by the use of the lavaan R-package (Rosseel, 2012). A depiction of the model can be seen in Figure 4. The model allowed for random intercepts per participant, and for covariations between the three gaze measures. 95% of the variability in search time could be explained, 33% in Fixation duration, 38% in #Fixations, and 16% in #Refixations.

One requirement for a mediation is that the independent variables load significantly on the three gaze measures as mediators. Table 2 shows the regression model with fixation duration as the dependent variable. All independent variables have significant positive effects. Note that β refers to standardized slopes which range from ⍰1 to +1. The strongest effect comes from SDY ($\beta = .567$). Although much weaker, there is also an effect of DH on fixation duration ($\beta = .080$), which is comparable to the effect size of TDS ($\beta = .090$), whose effect of increasing fixation duration has already been reported in previous studies (e.g., Becker, 2011; Hooge & Erkelens, 1996; Horstmann et al., 2017).

Table 3 shows the model of #Fixation regressed on the three independent variables. All have significant positive loadings. In contrast, to the pattern for fixation duration, the effect of TDS on #Fixations ($\beta = .450$) is as strong as the effect of SDY ($\beta = .417$), whereas the effect of DH ($\beta = .080$) remains smaller.

Table 4 shows the effects of the three independent variables on #Refixations. This differs from the patterns seen in either Tables 2 or 3. DH and TDS increase

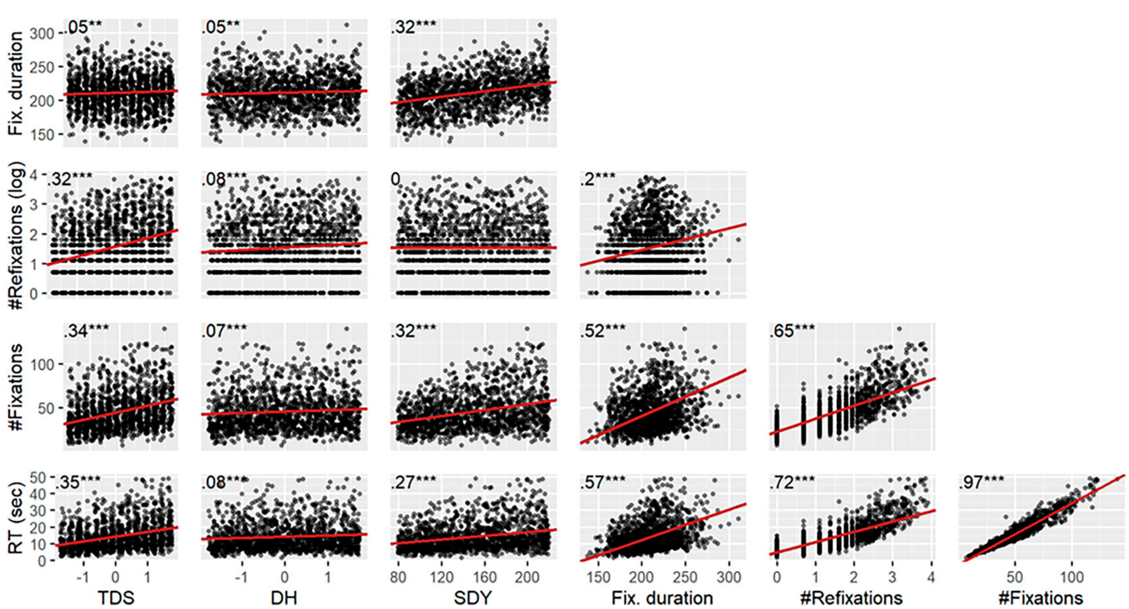

Figure 3. Overview of the bivariate correlations (quantified in the upper left corner of every plot) and the corresponding linear functions between the independent variables, gaze measures, and search times. Each datapoint represents a search trial. Note that the variable #refixations has been transformed (see text for further details). ** $p < .01$, *** $p < .001$.

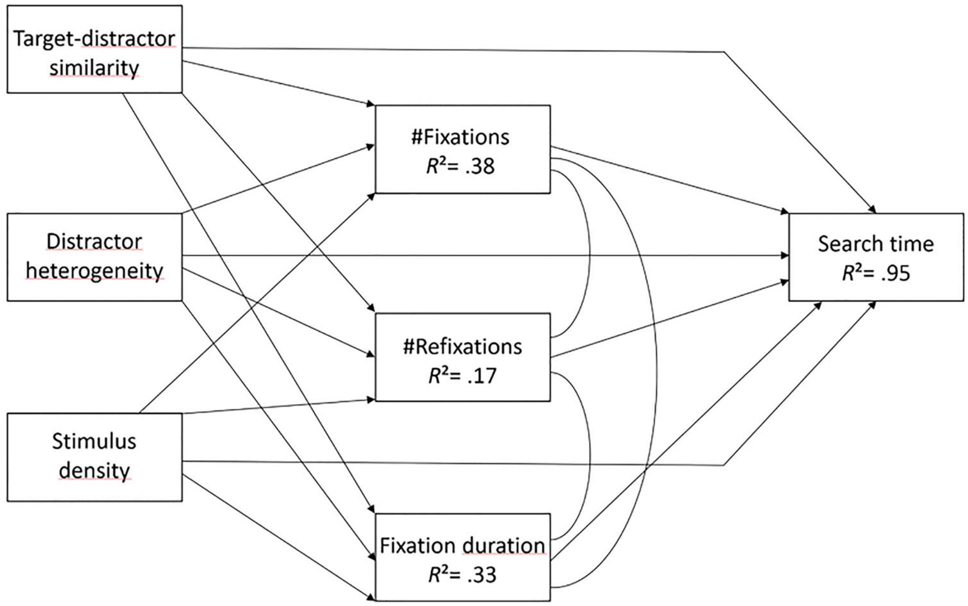

Figure 4. Visualized mediation model with #fixations, #refixations, and fixation duration mediating the effects of target-distractor similarity, distractor heterogeneity, and stimulus density on search time. R^2 describes the explained variability when these variables were predicted by the variables that have arrows pointing on them. See Tables 2–5 for the corresponding regression slopes (β).

the number of refixations with slopes of $\beta = .088$ and $\beta = .393$, respectively, whereas SDY has no significant effect. However, we remain cautious in interpreting effects on #Refixations since the reliability of this measure probably suffers from the overall high stimulus density in the present study (as described in more detail above).

Table 5 shows the regression of search time (that is, time from search display onset until keypress) on any other variable in the model. For significant mediations, it is necessary that the three mediating gaze parameters (#Fixations, #Refixations, fixation duration) have significant effects on search time as the dependent variable while controlling for the three independent variables' direct effects on search time. This is the case for all gaze variables in the model. With $\beta = .106$ the unique effect of fixation duration on search times is considerably smaller than the unique effect of #Fixations ($\beta = .854$), indicating that fixation durations contribute less to search time variability when search stimuli are simpler as compared to search displays with more complex shapes (Horstmann et al., 2020) and naturalistic face photographs (Horstmann et al., 2017, 2019).

Table 2. Regression of fixation duration on the independent variables (TDS, DH, and stimulus density).

	β	z	p
Target-distractor similarity	.090	4.07	< .001***
Distractor heterogeneity	.080	3.63	< .001***
Stimulus density	.567	25.67	< .001***

Note: The predictors explained 33% of variability in fixation duration. *** $p < .001$.

Table 3. Regression of #Fixations on the independent variables (TDS, DH, and stimulus density).

	β	z	p
Target-distractor similarity	.450	20.95	< .001***
Distractor heterogeneity	.080	3.70	< .001***
Stimulus density	.417	19.52	< .001***

Note: The predictors explained 38% of variability in #fixations. *** $p < .001$.

Table 4. Regression of #Refixations on the independent variables (TDS, DH, and stimulus density).

	β	z	p
Target-distractor similarity	.393	15.81	< .001***
Distractor heterogeneity	.088	3.57	< .001***
Stimulus density	.011	0.44	.659

Note: The predictors explained 16% of variability in #refixations. *** $p < .001$.

Table 5. Regression of search times on the independent variables (TDS, DH, and stimulus density) and eye measures (#Fixations, #Refixations, and fixation duration).

	β	z	p
Target-distractor similarity	−.005	−0.81	.420
Distractor heterogeneity	.002	0.29	.776
Stimulus density	−.064	−7.93	< .001***
#Fixations	.854	84.19	< .001***
#Refixations	.146	16.82	< .001***
Fixation duration	.106	14.44	< .001***

Note: The predictors explained 95% of variability in search time. *** $p < .001$.

A significant unique effect of any of the three manipulated variables (TDS, DH, stimulus density) on search time under the control of the three gaze variables (#Fixations, #Refixations, and fixation duration) would indicate a direct effect on search times which is not mediated via the three gaze measures. This is only the case for stimulus density ($\beta = -.064$, see Table 5). Note that the negative sign reflects a tendency for shorter search times at a higher set size (under control of the remaining predictors). There are previous studies reporting a similar result (Bravo & Nakayama, 1992; Sagi & Julesz, 1987; but see also Bacon & Egeth, 1991), suggesting that a target can be detected more easily when it is closely surrounded by distractors, making any feature differences more salient. Recall, however, that in the present study, only target absent trials were analyzed, which renders this explanation unlikely. We checked the analogue unique effect of SDY in a regression model with target present trials and found a small but significant positive slope for SDY ($\beta = .013$, $p = .014$). Thus, the negative unique effect of SDY on search time is probably specific to target absent trials, although it remains difficult to explain.

The mediation effects of the holistic model are listed in Table 6. The mediation effects are the product of the independent variables' (TDS, DH, stimulus density) loadings on the gaze measures (#Fixations, #Refixations, fixation durations; Tables 2–4) on the one hand, and the loadings of the gaze measures on RT on the other hand (Table 5), while the latter loadings are controlled for the direct effects of the independent variables on RT.

Apart from the exception of *SDY → #Refixations → RT*, all mediation effects in Table 6 were significant. With respect to mediation effect size, the significant mediations can be divided into two groups. First, there are two relatively strong mediations, being *TDS → #Fixations → RT* ($\beta = .384$) and *SDY → #Fixations → RT* ($\beta = .356$). The second group consists of the remaining significant mediations, which range from $\beta = .009$ to $\beta = .068$ and were relatively small as compared to the first group.

Table 6. Mediation effects.

	β	z	p
SDY → Fixation duration → RT	.060	12.59	< .001***
TDS → Fixation duration → RT	.010	3.91	< .001***
DH → Fixation duration → RT	.009	3.52	< .001***
SDY → #Fixations → RT	.356	19.02	< .001***
TDS → #Fixations → RT	.384	20.32	< .001***
DH → #Fixations → RT	.068	3.73	< .001***
SDY → #Refixations → RT	.002	0.44	.659
TDS → #Refixations → RT	.058	11.52	< .001***
DH → #Refixations → RT	.013	3.49	< .001***

Note: The mediation effect sizes (β) are calculated by the product of the independent variable's slopes in Tables 2–4 and the mediator's slopes in Table 5. See text for further details. *** $p < .001$.

Interaction analyses

To be consistent with previous studies conducting similar analyses (Horstmann, Herwig, et al., 2016; Horstmann et al., 2017, 2019, 2020), we did not include interactions between the manipulated variables (TDS, DH, and SDY) in the previous mediation model. However, many visual search studies centre around the fact that the (usually) positive set size effect on search time is not constant but depends on the level of target discriminability. In very easy search, there is nearly no set size effect at all, whereas the set size effect increases when target discriminability increases (Treisman & Gelade, 1980). In other words, there should be interaction (or "moderation") effects between TDS and DH as manipulations of target discriminability on the one hand, and SDY on the other hand. As Hulleman and Olivers (2017) point out, there is a strong correlation between the number of fixations and search times. Accordingly, for the number of fixations, we expect to find those interactions between TDS, DH, and SDY which have previously been reported for trial search times (e.g., Duncan & Humphreys, 1989). We calculated a linear mixed model regression with random intercepts for participants in order to predict the number of fixations per trial from TDS, DH, and SDY, as well as their interactions (see Table 7). This analysis shows that each of the independent variables has a clear effect on the number of fixations (which we already know from the mediation model) but that there are also interactions. Table 7 shows that there is an

Table 7. Regression of #Fixations on the manipulated variables and their interactions.

	β	t	p
Stimulus density	.325	19.66	< .001***
Distractor heterogeneity	.062	3.73	< .001***
Target-distractor similarity	.347	20.86	< .001***
SDY × DH	.022	1.38	.168
SDY × TDS	.042	2.52	< .011*
DH × TDS	−.035	−2.16	.031*
SDY × DH × TDS	−.008	−0.50	.615

Note: Regression is calculated by a linear mixed model with random intercept for the 20 participants. Overall, 1,378 trials contributed to the analysis. * $p < .05$, *** $p < .001$.

expected significant interaction between SDY and TDS, reflecting that the positive effect of SDY on #Fixations increases by $\beta = .042$ for every point that TDS increases (here, one point corresponds to a standard deviation unit of TDS as all variables were *z*-standardized prior to analyses). In other words, the contributions of TDS and SDY on #Fixations are not purely additive.

As we reasoned in the introduction, an interaction between SDY and DH may be special in that Bacon and Egeth (1991) report that distractor grouping (which should be facilitated with decreasing DH in the present experiment) benefits from closer element spacing in dense search displays. However, in the present study there was no significant SDY × DH interaction ($\beta = .022$, $p = .168$). It appears that the impaired ability of grouping distractors at high levels of DH was not substantially counteracted by closer element spacing in these displays with high stimulus density.

Table 7 also shows a significant interaction between DH and TDS on #Fixations. Note, however, the negative sign of the DH × TDS interaction. For every standard deviation unit that TDS increases, the prolonging effect of DH reduces by $\beta = -.035$. As will be discussed later, Duncan and Humphreys (1989) state that the prolonging effect of DH should actually *increase* if TDS also increases. The present result goes in the other direction.

The analysis, shown in Table 2, revealed the main effects of TDS, DH, and SDY on fixation duration. As shown in Table 8, reanalysis, including interaction terms, confirms those main effects and fails to find any significant interactions.

Table 8. Regression of fixation duration on the manipulated variables and their interactions.

	β	t	p
Stimulus density	.324	24.66	< .001***
Distractor heterogeneity	.046	3.67	< .001***
Target-distractor similarity	.050	3.96	< .001***
Density × DH	.017	1.37	.173
Density × TDS	.010	0.76	.449
DH × TDS	−.015	−1.17	.242
Density × DH × TDS	.017	1.39	.165

Note: Regression is calculated by a linear mixed model with random intercept for the 20 participants. Overall, 1,378 trials contributed to the analysis. *** $p < .001$.

Discussion

In the present study, we manipulated target-distractor similarity (TDS), distractor heterogeneity (DH), and stimulus density (SDY) within one visual search experiment to investigate how strongly their effects on search time are mediated via the number of fixations and fixation durations.

Previous visual search studies have been unclear about the effect of fixation duration on search time. The functional visual field (FVF) model by Hulleman and Olivers (2017) assumes a constant fixation duration of 250 ms, irrespective of target discriminability. In contrast, Horstmann, Herwig, et al. (2016) and Horstmann et al. (2017, 2019) found fixation duration to load as strongly on search time as the number of stimulus fixations in search for naturalistic face photographs and for shape stimuli that consisted of multiple rectangles (Horstmann et al., 2020). The present study, using very simple stimuli, continues to show that fixation duration plays a role, albeit a smaller role compared to the number of fixations.

Fixation duration

Our results confirm that increasing TDS, DH, and SDY lengthen search time. As expected, these effects are mediated by the number of fixations. Our more novel contribution is to show that mean trial fixation duration likewise acts as a mediator, although to a lesser extent. The prolonging effect of TDS on fixation duration has previously been attributed to an impeded target-distractor classification process (Becker, 2011). To our knowledge, however, the effect of DH on fixation duration has not been reported before.

We reasoned that DH impedes the grouping of distractors within the current fixation (e.g., Duncan & Humphreys, 1989). According to Bacon and Egeth (1991) close distractor spacing can improve search performance in that it enhances distractor grouping. Thus, one could expect that the prolonging effect of DH on fixation duration could be attenuated at high levels of SDY when a higher number of stimuli are arranged closer to the fovea, which is of high acuity and less affected by crowding. Yet, in the interaction analysis we could not find any interaction between DH and SDY that significantly predicted fixation durations. Instead, it appears that DH, SDY, and also TDS each increase fixation duration mainly in an additive manner. Note, however, that in the present experiment, stimulus positions were random, which leads to overall unstructured search displays that may limit the effects of distractor grouping and potential moderations by SDY. For future experiments, it would be interesting to test whether these interactions emerge in more structured search displays; for example, if stimuli were arranged on an imaginary grid.

While the effect sizes of both DH and TDS on fixation duration tended to be subtle, there was a larger effect of SDY. Results of Motter and Simoni (2008) suggest that longer fixations can counteract the decrease in target detection probability at peripheral regions with high SDY. In other words, the FVF may extend in the course of fixation and prolonged fixation durations could be strategically used to cope with crowding effects. However, in the relevant search condition of Motter and Simoni (2008), participants had to hold a central fixation. Although some studies report that covert search (within a fixation) and free viewing search may lead to similar results (Klein & Farrell, 1989; Motter & Simoni, 2008; Zelinsky & Sheinberg, 1997), it has also been argued that covert and overt search still involve different mechanisms (Findlay, 2004). The present study, however, provides evidence that in free viewing search, high levels of SDY in fact result in prolonged fixation durations (see also Vlaskamp et al., 2005). This effect was considerably stronger than the effects of TDS and DH.

Number of fixations

In accordance with the FVF model of Hulleman and Olivers (2017), the strongest mediations for search time involved the number of fixations. This was especially true for TDS and SDY as independent variables, while the mediation effect of DH was weaker.

Similar to the search slope differences in response times, seen is standard visual search tasks (e.g., Wolfe, 1998), our additional interaction analyses for the number of fixations showed that the effect of SDY (i.e., the set size effect) is moderated by the level of TDS (in contrast to when fixation duration is predicted). However, the interaction analysis also revealed differences with predictions from prominent search models. The Attentional Engagement Theory states that at *low* levels of TDS (i.e., the target is salient due to TDS) the effect of DH on search performance should be reduced, and vice versa (Duncan & Humphreys, 1989, 1992). In contrast, a closer look at the interaction between TDS and DH on the number of fixations in the present study suggests the opposite. Here, the positive effect of DH on the number of fixations was reduced at *high* levels of TDS. The difference in the interaction may reflect a difference in the tasks. Duncan and Humphreys (1989) used covert search tasks with brief display presentations that made eye movements ineffective. We used a task where eye movements are required. Once TDS reaches a level where each item needs to be fixated (a single-item, small FVF in Hulleman and Olivers (2017) terms), DH will have little further effect on number of fixations due to what amounts to a ceiling effect.

As we found in the interaction analysis of fixation duration, there was no negative moderating effect of SDY on DH predicting the number of fixations that would have supported the idea that closer element spacing enhanced distractor grouping (cf. Bacon & Egeth, 1991).

Similar to previous studies of Horstmann, Herwig, et al. (2016) and Horstmann et al. (2017, 2019, 2020), 95% of trial search time variability could be explained by a model including TDS, DH, SDY, and the three gaze measures (number of fixations, number of refixations, and average trial fixation duration) as predictors. Somewhat surprisingly, this high determination coefficient occurred even though the regression model did not include interactions between any predictor variables (in order to not further increase the complexity of the mediation model). However, in contrast to these previous studies we also calculated individual regressions for the gaze parameters. If the model of the number of fixations per search trial includes only TDH, DH, and SDY as factors, only 38% of variability could be accounted for by these three independent variables. As the major part of the variability in the number of fixations is not determined by the three measures to manipulate stimulus features, for future studies, it would be interesting to find out what determines this unexplained variability, and how strongly individual differences contribute (the same holds for fixation duration which had a similar determination coefficient of only 33%).

As a potential limitation, note that the relative effect sizes of TDS, DH, and SDY may be specific for the way these variables were manipulated in the current experiment. Results may differ for search stimuli where TDS and DH are manipulated in other feature dimensions like colour or orientation. It is also of note that we only focused on target absent trials in order to keep the number of independent variables and the resulting interaction combinations limited. Thus, the present findings may be specific for target absent trials. In principle, one could argue that every search fixation during a target present trial that occurs before the target has been recognized should be governed by mechanisms similar to those governing fixations on target absent trials. Testing this hypothesis will be an aspect of future studies that focus on differences in gaze behaviour between target absent and target present trials. Such experiments need to deal with the differences in the number of fixations between present and absent trials. A target can be found after a single fixation or a single deployment of covert attention. Only in the simplest of searches would this be true for confirming the absence of a target. This difference renders the type of analysis, reported here, more difficult.

Conclusion

The results of the present study suggest that distractor heterogeneity increases fixation duration and also the number of fixations. This is consistent with previous studies of the effects of target-distractor similarity. However, compared to previous studies, we find that the contribution of fixation duration to the prediction of search times on target absent trials is reduced when search stimuli are simplest. The number of fixations is the major determinant of RT. Target-distractor similarity, distractor heterogeneity, and stimulus density mainly increased fixation durations on target absent trials in an additive manner, whereas the typical moderation of the set size effect by target-distractor similarity only occurred for the number of fixations.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was supported by the German Research Foundation (DFG) grant ER 962/1-1 to Daniel Ernst.

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