

Moving foraging into three dimensions: Feature- versus conjunction-based foraging in virtual reality

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Abstract

Visual attention evolved in a three-dimensional (3D) world, yet studies on human attention in three dimensions are sparse. Here we present findings from a human foraging study in immersive 3D virtual reality. We used a foraging task introduced in Kristjánsson et al. to examine how well their findings generalise to more naturalistic settings. The second goal was to examine what effect the motion of targets and distractors has on inter-target times (ITTs), run patterns, and foraging organisation. Observers foraged for 50 targets among 50 distractors in four different conditions. Targets were distinguished from distractors by either a single feature (feature foraging) or a conjunction of features (conjunction foraging). Furthermore, those conditions were performed both with static and moving targets and distractors. Our results replicate previous foraging studies in many aspects, with constant ITTs during a “cruise-phase” within foraging trials and response time peaks at the end of foraging trials. Some key differences emerged, however, such as more frequent switches between target types during conjunction foraging than previously seen and a lack of clear mid-peaks during conjunction foraging, possibly reflecting that differences between feature and conjunction processing are smaller within 3D environments. Observers initiated their foraging in the bottom part of the visual field and motion did not have much of an effect on selection times between different targets (ITTs) or run behaviour patterns except for the end-peaks. Our results cast new light upon visual attention in 3D environments and highlight how 3D virtual reality studies can provide important extensions to two-dimensional studies of visual attention.

Keywords

Visual foraging; visual attention; virtual reality; visual search; motion; search organisation; search orientation

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Introduction

Human visual attention has predominantly been studied with single-target search tasks in two dimensions. But we live in a three-dimensional (3D) environment where there can be many targets to look out for at any given moment. Here we investigate a 3D multitarget foraging task implemented in a virtual reality (VR) environment.

Studies of foraging are increasingly being used to assess human visual attention. The orienting of visual attention in the real world can be a lot more complex than simply involving the single present/absent decision made in classic visual search paradigms (see Á. Kristjánsson & Egeth, 2020; Wolfe & Horowitz, 2017 for review). Single-target search works as an analogy for looking for your phone, but as we interact with the world our goals are usually not this limited. Foraging tasks with multiple targets may paint a

clearer picture of the functional principles behind attentional allocation (Cain et al., 2012; Gilchrist et al., 2001; Hills et al., 2013; Jóhannesson et al., 2016, 2017; Á. Kristjánsson et al., 2014; T. Kristjánsson & Kristjánsson, 2018; Prpic et al., 2019; Tagu & Kristjánsson, 2020;

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Thornton et al., 2019; Wolfe, 2013). Á. Kristjánsson et al. (2014) introduced a foraging task where participants selected multiple items from more than one target category by tapping on a two-dimensional (2D) iPad screen. In the “feature” condition, the target categories were defined by different colours (e.g., red and green discs). In the “conjunction” condition, the target categories were defined as the conjunction of colour and shape (e.g., red squares and green discs among green square and red disc distractors). Throughout feature foraging, participants were able to cancel the two target categories randomly (switching effortlessly between them), while during conjunction foraging the majority of the participants repeatedly selected the same target category in long non-random sequences of “runs” (Á. Kristjánsson et al., 2014). Run number could range from two (one target type exclusively selected before participants switched to the other) to the total number of targets (when observers switch between target categories for every target selection throughout the trial). If participants forage randomly, run number should be close to the total number of targets divided by two. Such patterns have been thought to reflect the limits of attention and working memory (Á. Kristjánsson et al., 2019). Previous foraging studies on animals (e.g., Dawkins, 1971; Giovanetti & Aronne, 2011) had indicated that predators tend to select prey of the same type in such runs even when other types of prey are closer to the focus of attention (Bond, 1982, 1983; Dawkins, 1971; Dukas, 2002; Tinbergen, 1960). When prey were conspicuous, however, predators frequently switched between prey types (Dukas, 2002; Dukas & Ellner, 1993).

Using VR

The foraging tasks discussed above are confined to two dimensions. VR experiments might provide better understanding of how we allocate attention within a 3D visual world. Since VR enables the examination of human behaviour in controlled settings while also increasing ecological validity, this may improve both internal and external validity. One benefit is that the sense of “presence” seems to increase in virtual environments in head-mounted displays compared with 2D monitor displays (Kim et al., 2014). Another benefit is the possibility of implementing a clear sense of depth (Wann et al., 1995) through stereopsis and the use of depth cues such as motion parallax that cannot be extracted from a 2D plane (Pathak et al., 2017). Finally, the affordances of locomoting for successful search completion change how search is guided in naturalistic settings (Draschkow & Vö, 2016, 2017; Hayhoe et al., 2003; Li et al., 2016; Vö et al., 2019).

Static versus moving stimuli

We will also address how target movement affects attentional orienting. Throughout the evolutionary history of

humans and animals, detecting moving prey or danger in our surroundings has had survival value. Research on motion in visual attention has often been performed with single-target searches (see, for example, Dick et al., 1987; McLeod et al., 1988; Nakayama & Silverman, 1986; Royden et al., 2001) although some multitarget studies are available (e.g., Thornton & Horowitz, 2004; Horowitz & Thornton, 2008). The focus within foraging research has mostly been on static stimuli (see, for example, Jóhannesson et al., 2016; Á. Kristjánsson et al., 2014; Wolfe, 2013), even though allocating attention not only to the correct location but also at the right time is a fundamental property of cognition (Kristjánsson et al., 2010; Nobre & van Ede, 2018). Furthermore, static stimuli may induce systematic scanning behaviour (e.g., from left to right or top to bottom; Gilchrist & Harvey, 2006) which might limit the generalisability of such findings across different scenarios. Cain et al. (2014; see also Wolfe et al., 2016) used a task where all items moved continuously. Observers were to forage for as many dots as possible that were greener than other dots. These dots moved within so-called patches, analogous to dynamic berry shrubs, and users could click “next” to go to the next patch. They found that moving dots reduced systematicity and participants started to use colour (greenness), to guide foraging instead of performing well-ordered spatial search (Cain et al., 2014). Their study was performed on a 2D screen. With our VR task, systematicity and the effects of motion can be studied in three dimensions.

How do observers organise their foraging?

Woods et al. (2013) studied what they referred to as “search organization” using a cancellation task (Mark et al., 2004; see also Woods & Mark, 2007) which involves locating and cancelling homogeneous targets among distractors, similar to foraging tasks. They recorded the order of the selected targets which made it possible to assess visual search organisation with two objective measures: the length of the cancellation path, or mean inter-target distance, and a measure of the overall path structure called *best-r*, that assesses first how organised the foraging is (the size of the *r*-value) and whether the direction of cancellation is either predominantly horizontal or vertical (depending on which *r*-value is higher).

Woods et al. (2013) also investigated where observers chose to start their search, which they referred to as “spatial orientation,” using 2D quadrants to see where people initially orient. A quadrant is any of the four areas made when *x*- and *y*-axis divide up a 2D plane. Their observers were from a left-to-right reading culture and started foraging in the upper-left quadrant of the display. Since our VR study involves 3D virtual space, we employed 3D octants. The foraging starting point is related to search organisation since it can influence the latter. For example, beginning in a corner or edge of a display should on average initiate

more organised foraging than starting at centre (Wilson et al., 1998). We will use these measures of search organisation and orientation, adapting them to three dimensions to investigate how humans organise and orient their foraging in a VR environment.

Inter-target times

One of the main measures in single-target search is response time. Since foraging tasks entail search for many targets successively, measuring the time between each target selection yields inter-target times (ITTs; Ólafsdóttir et al., 2016) that reveal foraging patterns over time and can be compared across conditions. For example, throughout most of foraging trials ITTs typically show a “cruise-phase,” where observers quickly select targets, much faster than typically seen in single-target searches (Kristjánsson et al., 2020). During the cruise-phase, ITTs remain relatively flat. One possibility is that the flat ITTs do not reflect attentional selection times, but instead the time it takes to move the finger from one target to the next and tap it. Visual attention might have identified and selected several targets in advance, and ITTs might therefore only represent the speed of the motor system. To uncover this, we will calculate the ratio of inter-target lengths (ITLs, distance) and ITTs (i.e., ITL/ITT). If motor execution is the limiting factor, these ratios should stay constant throughout foraging trials, while if they decrease as the trial progresses, this would suggest that attentional selection is the limiting factor.

Attentional demands

Towards the end of foraging trials, ITTs have increased considerably in previous studies, especially during conjunction foraging (Kristjánsson et al., 2020) and the results have also revealed peaks at the middle of conjunction foraging trials that presumably reflect the costs of switching between targets (Jóhannesson et al., 2016; Kristjánsson et al., 2020; Ólafsdóttir et al., 2016, 2019). Each time a switch occurs, ITTs increase, so the best strategy to optimise foraging time would be to minimise switches. This is more common in difficult tasks such as conjunction foraging where the attentional load is higher than during feature foraging where switch costs are much lower, and the best strategy might be to select the nearest target, resulting in more switches between target types (T. Kristjánsson et al., 2018). Á. Kristjánsson et al. (2014) speculated that this reflected limitations of attention and working memory, but later studies have revealed that observers can switch if this is the best strategy for the task (Kristjánsson, Thornton, & Kristjánsson, 2018).

In previous studies, most participants only switched once on a large proportion of conjunction trials (Á. Kristjánsson et al., 2014), typically at the middle of the

trial, explaining the mid-peaks in ITTs (Kristjánsson et al., 2020; Ólafsdóttir et al., 2016). Accordingly, the run number distributions were highly skewed with a peak at two runs while distributions for feature foraging were close to normal with a peak at set-size/2 (Á. Kristjánsson et al., 2014, 2020; Ólafsdóttir et al., 2016).

The current study

We had two main goals: first, to test foraging in three dimensions within VR using our previously tested feature versus conjunction paradigm (Á. Kristjánsson et al., 2014), and second, to assess the effects of stimulus motion on foraging performance and organisation, where static displays were contrasted with displays where the targets and distractors moved continuously.

As in previous studies (Jóhannesson et al., 2016; Á. Kristjánsson et al., 2014; Ólafsdóttir et al., 2016), we expected distributions of run number for conjunction foraging to be highly skewed with a peak at two runs, while for feature foraging, distributions should be close to normal with a higher mean. ITTs should increase towards the end of each trial, with larger increases for conjunction foraging. Furthermore, ITTs should increase at the middle of conjunction trials, reflecting switches between target categories. We also predicted that systematic “reading” behaviour would be reduced when the stimuli moved around in the “dynamic” condition (see Cain et al., 2014). In line with Woods et al. (2013), we expected participants to start their foraging in the top-left corner of the visual field.

Method

Participants

A total of 20 volunteers participated (8 females, aged between 20 and 26 years, $M=22.75$; 12 males, aged between 22 and 39 years, $M=27.5$). All had normal or corrected to normal vision, were right-handed, and gave written informed consent for participation. All aspects of the experiment were performed in accordance with the directives of the local bioethics committee and conformed to the Declaration of Helsinki for testing human participants.

Equipment

The stimuli were displayed on an HTC Vive VR system with screen dimensions of $1,080 \times 1,200$ pixels per eye ($2,160 \times 1,200$ pixels combined). The refresh rate was 90 Hz, and the field of view was approximately 110° . The sensors used were SteamVR Tracking, a G-sensor, gyroscope, and a proximity sensor. An HTC Vive controller with a SteamVR Tracking sensor was used to interact with the virtual environment. Inputs on the controller involved

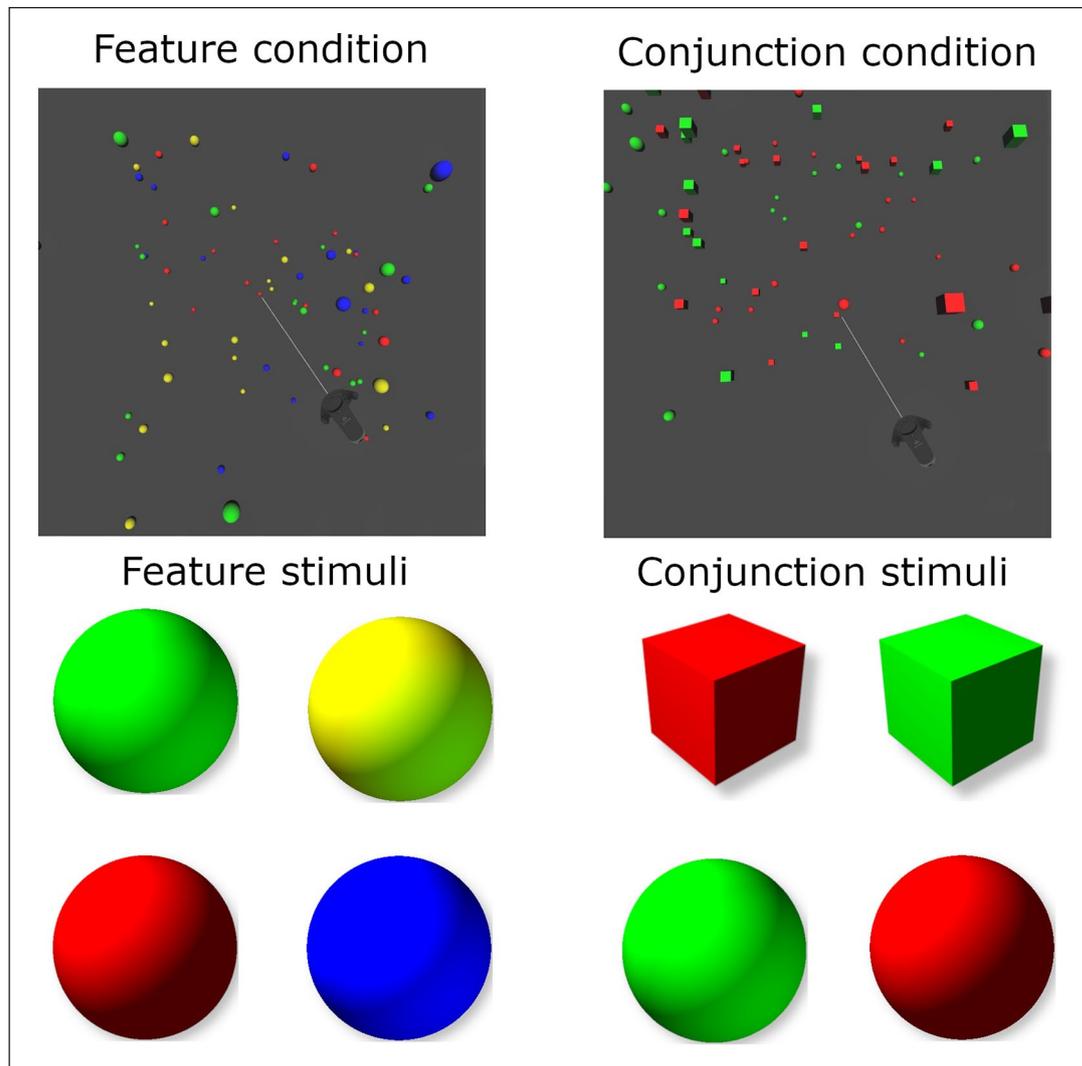


Figure 1. Examples of the stimuli and conditions: (left) examples of the feature foraging condition with the corresponding stimuli; (right) examples of the conjunction foraging condition. The two conditions were the same for static and dynamic versions except that the stimuli moved around in the dynamic condition (see the “Method” section). For a video showing the stimuli and conditions, see the following link: <https://bit.ly/2Cck8ZS>.

a multifunction trackpad, grip buttons, dual-stage trigger, system button, and a menu button. Stimulus presentation and response collection were carried out with a custom VR application written in Vizard (www.worldviz.com). Two base stations (3.13 m between them) sent signals to the headset and controller.

Stimuli

In all four conditions, there were 50 targets among 50 distractors. During static and dynamic feature foraging, the targets were red and green spheres, and distractors were yellow and blue spheres for half of the participants. For the other half, the conditions reversed (yellow and blue targets, red and green distractors). For static and dynamic

conjunction foraging, the targets were red cubes and green spheres and distractors were green cubes and red spheres for half of the participants (reversed for the other half). In the dynamic tasks, the targets and distractors moved in random directions within a $10 \times 10 \times 10 \text{ m}^3$ virtual cube. The movement of both targets and the distractors involved a random walk at a constant speed sampled randomly between 0.1 and 0.25 m/s towards a random location constrained by a 10-m^3 invisible cube. In cases of collision with a different item, a new speed and direction was sampled for each item. The sphere radius was 10 cm, and the cube dimensions were $20 \times 20 \times 20 \text{ cm}^3$ (see Figure 1). The distance between stimuli was random within the invisible cube. For a video showing the stimuli and conditions, see the following link: <https://bit.ly/2Cck8ZS>.

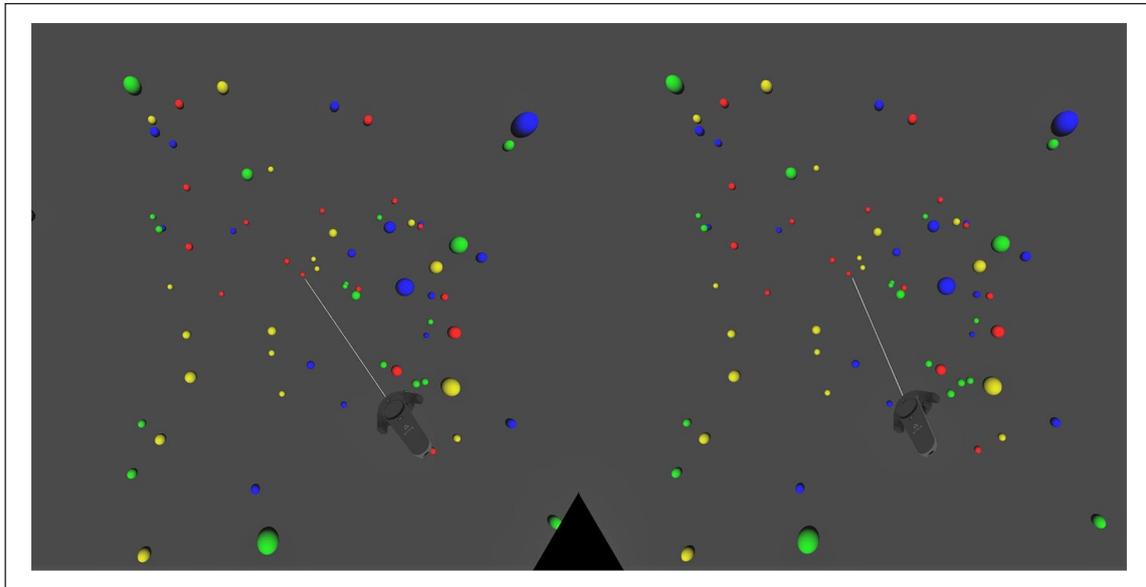


Figure 2. Example of the virtual reality environment from the participants' point of view. The image depicts two displays—one presented to each eye. The black mushroom-shaped object is the controller as it appears in the VR environment. The grey line depicts the “laser beam” used to “shoot” the targets (see the “Procedure” section).

Environment

The VR environment had a grey background, and the stimuli were drawn randomly within the VR environment inside a $10 \times 10 \times 10 \text{ m}^3$ invisible cube. Coordinates were X (left to right) = -5.0 to 5.0 Y (bottom to top) = 0.2 to 10.2 and Z (back to front) = 0.2 to 10.2 . Participants were placed in front of the invisible 10^3 m^3 (coordinates = $X=0$, $Y=0.2$, $Z=0.2$; see Figure 2). A blue arrow, pointing in the direction of the stimuli, guided participants on which way to turn at the start of a foraging trial.

Procedure

The experiment was carried out in a small room with minimal distraction. Participants stood within a $1.96 \times 3.07 \text{ m}^2$ space. Interpupillary distance was measured for each participant and the settings were adjusted accordingly on the VR device. The participants were positioned in the middle of the room and instructed not to walk around once the experiment started. However, they were allowed to bend and duck to search for targets since distractors could occlude targets. Participants went through two practice trials before the experiment started.

Participants were instructed to “shoot” the targets as quickly as possible by pressing a trigger that beamed a “laser” from the controller. They were instructed to try to minimise errors. When the beam hit a target, the controller vibrated and the target immediately disappeared. Participants were informed that errors were counted, but that there was no penalty. Participants completed 4 blocks of 10 trials, and following each trial, an information box

appeared, notifying participants of the number of completed trials. A trial was complete when all 50 targets had been shot. Before every block, instructions appeared, informing participants of the target categories. Participants could take breaks between blocks. After being familiarised with their surroundings, the controllers and having finished the practice trials, participants pressed the “menu” button. Consequently, text appeared informing participants that the first trial would begin in 5 s.

Data analysis

First, the total run number per trial was calculated (ranging from 2 to 50, the total target number). If participants forage randomly (shoot targets no matter the target type), average run number should be roughly 25 (the total number of targets divided by 2). ITTs (the time between cancellations of two successive targets) were measured for each target. The independent variables in the repeated measures analyses of variance (ANOVAs) were condition (feature vs. conjunction) and motion (static vs. dynamic). The first target within a trial is not an ITT measure since ITTs are defined as the time between cancellations of the previous and current target, and the first target has no preceding target, so the target number variable ranges from 2 to 50. We used the Greenhouse–Geisser correction to correct degrees of freedom for non-sphericity. For each dependent variable, means were calculated for each participant. Since the raw data consisted of 40,000 data points and there were no signs of outliers, they were not removed.

For the second part of the analysis (search organisation), the same experimental conditions and number of

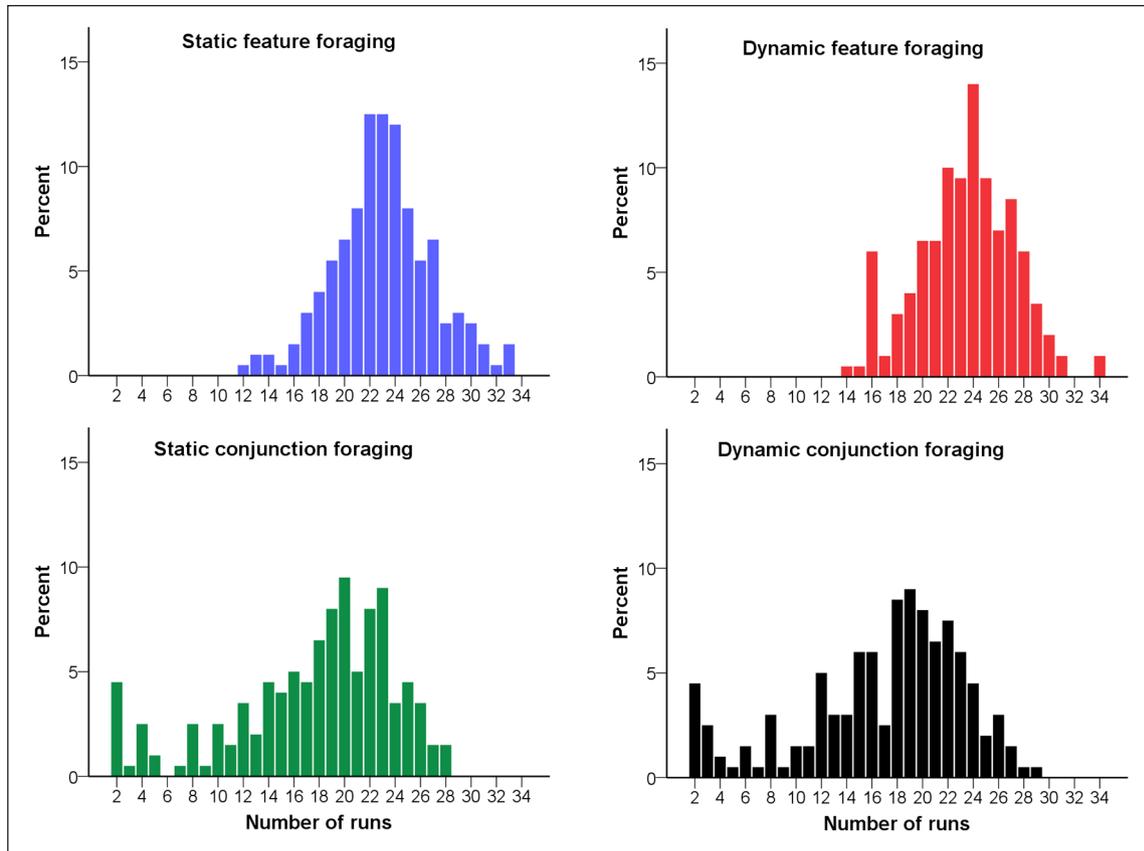


Figure 3. Number of runs per trial for each condition. The upper half shows histograms for feature foraging (static on the left and dynamic on the right). The bottom half shows histograms for conjunction foraging (static on the left and dynamic on the right).

Table 1. Descriptive statistics for the number of runs and error rates by condition.

	Motion	NR (<i>M</i>)	NR (<i>Mdn</i>)	NR (<i>SD</i>)	Errors per trial
Feature foraging	Static	23.03	23	3.91	0.66
	Dynamic	23.42	24	3.79	0.805
Conjunction foraging	Static	17.6	19	6.41	0.81
	Dynamic	16.94	18	6.42	1.19

NR: number of runs; *SD*: standard deviation.

targets were used. For the repeated measures ANOVA, the same independent (condition, motion, and target number) and dependent variables were used. ITLs (the distance in space between cancellations of two successive targets) were measured for each target. Best-*r*, a measure of the total path composition (see Ólafsdóttir et al., 2016, 2019; Woods et al., 2013), was calculated within the fifth trial for each participant for each experimental condition. To analyse foraging starting points octants were used, the eight parts into which 3D space is partitioned by three right-angled planes that intersect at a single point. Frequency analysis was conducted on the first target within each trial for each experimental condition. Finally, to assess potential motor bottlenecks, a linear regression was conducted

using the ratio between ITLs and ITTs for each target with target number within trials as a predictor.

Results

Run behaviour

Histograms showing the number of runs within each foraging trial are shown in Figure 3 for the four conditions (see descriptive statistics in Table 1). The distributions for feature foraging are close to normal, indicating that participants switched randomly between target categories, while for conjunction foraging, they are negatively skewed. No participant had fewer than 12 runs for feature foraging, but

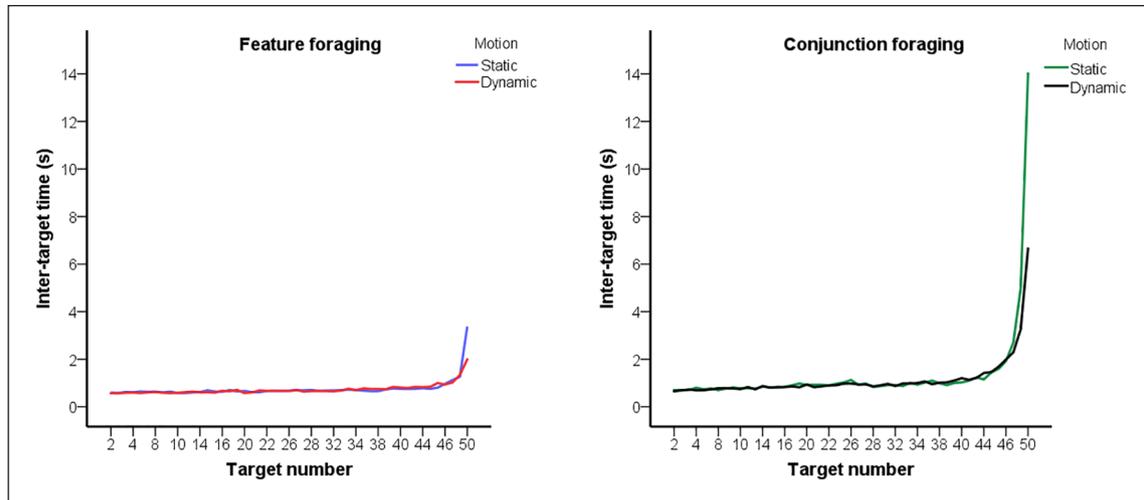


Figure 4. Inter-target times (ITTs) in seconds for each target as a function of when it was selected within the trial. The left panel shows the results for feature foraging, while the right panel shows the results for conjunction foraging. The different line colours show static versus dynamic foraging.

for conjunction foraging, run number was as low as 2. Surprisingly, the distributions for static versus dynamic foraging are very similar for both feature and conjunction foraging. Interestingly, the histograms for feature versus conjunction are not as vastly dissimilar as we have seen previous studies with 2D displays. This may indicate that the difficulty in differences between the two tasks may not be as large as in those previous studies.

A 2 (static and dynamic) \times 2 (feature and conjunction) repeated measures ANOVA on the average number of runs revealed a significant difference between the feature and the conjunction conditions, $F(1, 19)=33.45$, $p < .001$, $\eta_p^2 = .638$, indicating that participants switched more frequently between target types during feature than conjunction foraging. Neither the main effect of motion nor the interaction between motion and condition was significant. This is, to our knowledge, the first investigation of the effects of motion on run behaviour, and surprisingly motion does not appear to affect the number of runs. Importantly, this suggests that planning ahead during foraging does not account for as much of the ITTs as has been suggested, since the motion should, on average, interfere with any such planning.

ITTs

Figure 4 shows average ITTs in seconds for each target as a function of when it was selected within a foraging trial. In previous studies, three distinct phases appeared within trials (Kristjánsson et al., 2020; Ólafsdóttir et al., 2016): (1) the cruise-phase, which involves all ITTs except the last ITT and the middle-peak ITT; (2) end-peaks, involving the last ITT on each trial; and (3) mid-peaks, reflecting ITTs after half of the targets have been tapped ($N/2 + 1$, where N is the number of targets). In contrast to these

results, we did not find any mid-peaks (Figure 4). Paired t -tests comparing ITTs at the middle of foraging trial and during the cruise-phase were not significant for any condition (all $ps > .17$). The mid-peaks were in previous studies thought to reflect switches between target categories. Here, switches during conjunction foraging were more frequent than in previous studies, indicating that switching between target types was not particularly difficult during conjunction foraging. Only the cruise-phase and the end-peaks are therefore included in the following analyses (see Table 2).

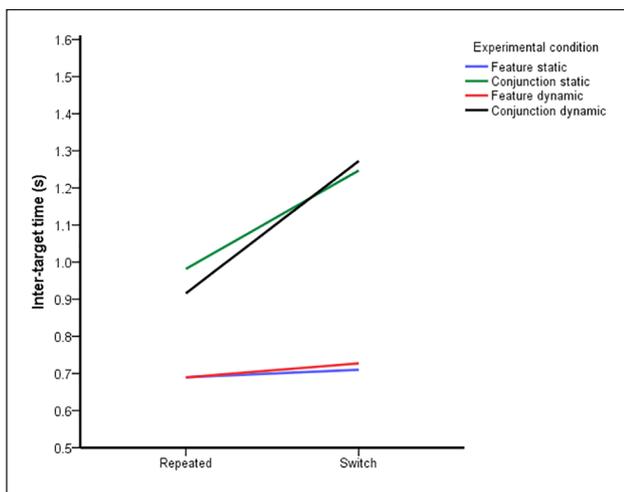
A 2 (feature, conjunction) \times 2 (motion: static, dynamic) repeated measures ANOVA was conducted for the end-peaks and the target number within the cruise-phase (from 2 to 49). The dependent variable was the mean ITT for each participant in each condition.

During the so-called cruise-phase, there was a significant effect of condition (feature, conjunction), $F(1, 19)=173.35$, $p < .0001$, $\eta_p^2 = .901$, but not of motion, $F(1, 19)=0.511$, $p = .483$, $\eta_p^2 = .026$, and their interaction was not significant, $F(1, 19)=1.04$, $p = .321$, $\eta_p^2 = .052$. The ITTs were larger for conjunction than feature foraging, but the difference between static and dynamic foraging was not significant. In all conditions, ITTs remain relatively flat during the “cruise-phase” (Kristjánsson et al., 2020).

For the end-peaks, there were main effects of condition (feature, conjunction), $F(1, 19)=28.30$, $p < .0001$, $\eta_p^2 = .598$, and motion, $F(1, 19)=8.43$, $p < .009$, $\eta_p^2 = .307$, but despite a strong numerical relationship, no significant interaction, $F(1, 19)=3.95$, $p < .061$, $\eta_p^2 = .172$. End-peaks were visible in all four conditions, but they were considerably larger for conjunction than feature foraging and interestingly, also larger for static than dynamic foraging. The main suggestion from this is that motion helps with finding the last target.

Table 2. Cruise-phase and end-points of each experimental condition.

	Motion	Phase	<i>M</i> (s)	<i>SD</i> (s)
Feature foraging	Static	Cruise-phase	0.70	0.53
		End-points	3.39	8.77
	Dynamic	Cruise-phase	0.71	0.51
		End-points	1.99	1.51
Conjunction foraging	Static	Cruise-phase	1.07	2.24
		End-points	14.01	28.31
	Dynamic	Cruise-phase	1.03	1.10
		End-points	6.65	6.98

**Figure 5.** Difference in ITTs between when the same target type is repeated and when observers switch between target categories. The different coloured lines represent different experimental conditions.

Switch costs

Figure 5 shows that switch costs are larger for conjunction than feature foraging, consistent with previous results, and switch costs are roughly similar for dynamic and static foraging. A 2 (feature, conjunction) \times 2 (motion) \times 2 (repeat, switch) repeated measures ANOVA using average ITTs for each participant was conducted. The main effects of switch type and condition (feature, conjunction) were significant, $F(1, 19)=10.74, p=.004, \eta_p^2=.361$, and $F(1, 19)=23.49, p<.0001, \eta_p^2=.553$, and their interaction was also significant, $F(1, 19)=9.12, p<.007, \eta_p^2=.324$, indicating greater switch costs during conjunction foraging. The main effect for motion was not significant, $F(1, 19)=1.34, p=.262, \eta_p^2=.066$. There was no interaction between motion, switch type, or condition.

Potential motor bottleneck?

ITTs during the “cruise-phase” may potentially reflect a motor bottleneck. They may, in other words, simply reflect how long it takes observers to move their hands to specific

targets instead of reflecting attentional limitations. This would mean that attentional mechanisms are sufficiently fast to process several targets ahead in the foraging sequence but the time this attentional processing takes might be masked by a motor bottleneck. In addition, increased ITTs might also reflect that a target is further away, requiring a larger motor act.

One way of addressing this involves calculating the ratio between the ITLs and ITTs for each target, or distance in metres divided by length in seconds. We can then perform a simple linear regression on the ratios for each target to see if they are flat, which would suggest that the motor component is solely involved, or if they rise or fall linearly, suggesting that the ITTs capture the workings of visual attention.

Figure 6 shows the relationships between the target number and the ratio between ITLs and ITTs in metres divided by seconds. According to the Loess trendline in the figures, there is a slight but significant linear drop in every experimental condition as target number within trials progresses. The results from the linear regression are as follows: (1) for static feature foraging, $F(1, 971)=91.50, p<.001$ with $R^2=.09$; (2) for static conjunction foraging, $F(1, 969)=295.40, p<.001$ with $R^2=.23$; (3) for dynamic feature foraging, $F(1, 968)=334.73, p<.001$ with $R^2=.26$; and (4) for dynamic conjunction foraging, $F(1, 969)=572.70, p<.001$ with $R^2=.37$. This linear relationship between target number and the ratio between ITLs and ITTs (m/s) supports that the ITTs in our task reflect the processing of the visual attention system rather than a motor bottleneck (in which case the lines should be flat).

We should also note that the ITTs during the static and dynamic conditions were virtually identical (see above), which also makes it unlikely that planning ahead to a number of locations plays a major role in the ITTs since motion should disrupt any planning ahead.

Foraging organisation: mean ITL

ITL can give insights into how observers organised their foraging. Organised foraging should presumably involve directing attention to the nearest successive target. Figure 7 shows ITLs in metres for each target, which represents the

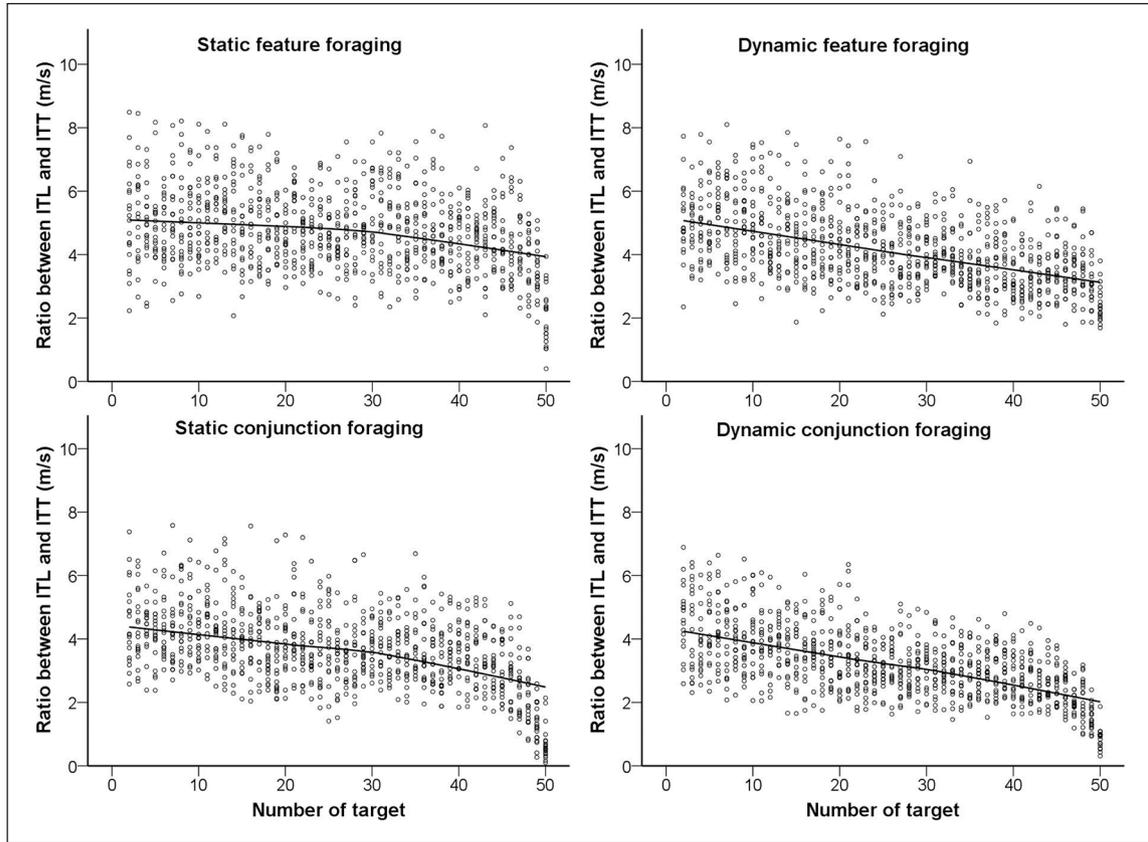


Figure 6. Ratio between inter-target lengths (ITLs) and inter-target times (ITTs) for each target within a trial for the different conditions.

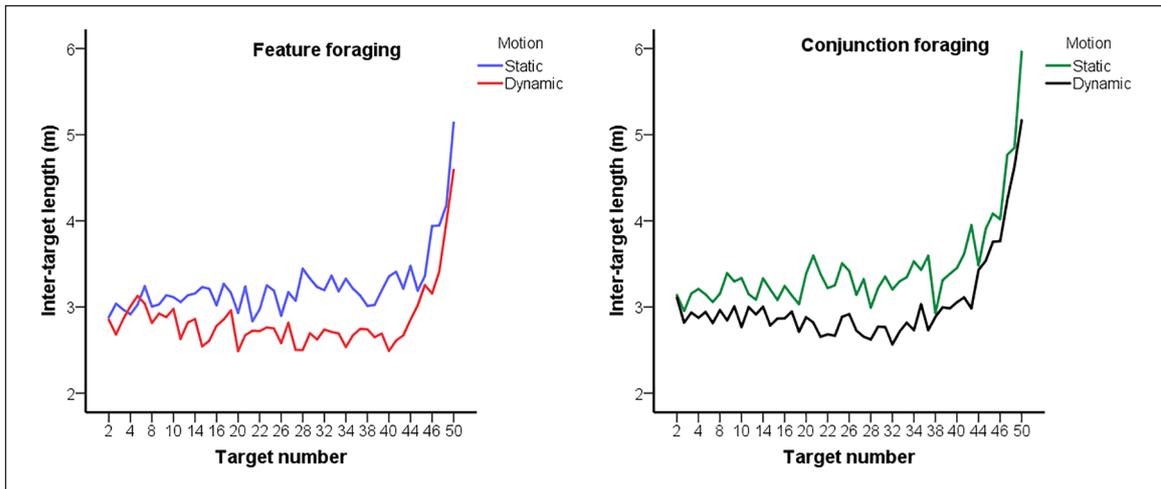


Figure 7. Inter-target lengths (ITL) in metres for each target within a trial. The lines represent the static versus dynamic conditions. Panel A shows the results for feature foraging, while panel B shows the results for conjunction foraging.

Euclidean distances between targets at serially different locations in 3D virtual space within the trial. The figure reveals a cruise-phase that is analogous to the corresponding phase in the ITT analysis, where the ITLs remain flat and small for the most part (with more variability than the ITTs) with a rise in ITLs towards the end. The ITLs of the

end-peaks in the figure are considerably larger than the other ITLs. Descriptive statistics for ITLs are displayed in Table 3 for each phase.

A 2 (motion: dynamic and static) \times 2 (condition: feature and conjunction) repeated measures ANOVA was carried out for the ITLs. For the cruise-phase, the independent

Table 3. Cruise-phase and end-points for each experimental condition.

	Motion	Phase	M (m)	SD (m)
Feature foraging	Static	Cruise-phase	3.21	1.89
		End-points	5.14	3.12
	Dynamic	Cruise-phase	2.81	1.58
		End-points	4.59	2.30
Conjunction foraging	Static	Cruise-phase	3.40	2.00
		End-points	5.96	2.93
	Dynamic	Cruise-phase	2.98	1.67
		End-points	5.17	2.31

variable target number (which ranges from 2 to 49) was used with the variables motion and condition in the repeated measures ANOVA analysis. The dependent variable was the average ITL for each participant in each condition. During the cruise-phase, there were main effects of both condition, $F(1, 19)=34.254, p<.001, \eta_p^2=.643$, and motion, $F(1, 19)=325.12, p<.001, \eta_p^2=.945$, but the interaction was not significant, $F(1, 19)=0.058, p=.813, \eta_p^2=.003$. The ITLs were larger for conjunction foraging and for static foraging in the cruise-phase. For the end-peaks, there were main effects of both condition, $F(1, 19)=6.922, p=.016, \eta_p^2=.267$, and motion, $F(1, 19)=14.739, p=.001, \eta_p^2=.437$, but the interaction was not significant, $F(1, 19)=0.625, p=.439, \eta_p^2=.032$.

The difference between the static and the dynamic conditions may also reflect that observers may, to some extent, have adopted a sit and wait strategy in the dynamic condition, keeping the focus of their attention at centre, waiting for the targets to appear there.

Foraging organisation: best-*r*

One way of assessing whether foraging is systematic is to calculate the Pearson correlation coefficient (*r*) from the linear regression for each dimension of the targets relative to the order in which participants shot them. Then the highest, or best, *r*-value is selected from the three linear regressions conducted for each participant in each experimental condition, revealing how systematic the scanning behaviour is. For example, if participants search from left to right and right to left within a 2D plane, it would result in an *r*-coefficient on the x-coordinate regression that is near zero, while it would be close to 1 on the y-coordinate regression. So, a high *r*-value suggests organised foraging, while whether it is higher for x or y indicates the direction of the organisation. The same basic reasoning applies for 3D, with the added z-dimension.

A 2 (motion: dynamic and static) \times 2 (condition: feature and conjunction) repeated measures ANOVA on best-*r* showed a significant effect of condition, $F(1, 19)=14.548, p=.001, \eta_p^2=.434$, but not of motion, $F(1, 19)=0.082, p=.778, \eta_p^2=.004$, and their interaction was not significant, $F(1, 19)=0.104, p=.751, \eta_p^2=.005$.

Table 4. Descriptives of best-*r* for each experimental condition.

	Motion	M	SD
Feature foraging	Static	0.59	0.17
	Dynamic	0.60	0.16
Conjunction foraging	Static	0.48	0.13
	Dynamic	0.46	0.14

Table 4 displays the descriptive statistics of best-*r* for each experimental condition. The best-*r* values were larger for feature than conjunction foraging, but the difference between dynamic and static foraging was not significant.

We calculated the Pearson correlation coefficient between best-*r* and the correlation coefficients from the linear regressions for each dimension mentioned above. The results demonstrate that participants tended to forage horizontally, since the correlation between the *r*-coefficients from the x-coordinate regressions and best-*r* values was by far the highest and significant ($r=.767, p<.001$), but best-*r* was not correlated with the *r*-coefficients from the y- and z-coordinate regressions ($r=.054, p=.633$; $r=.087, p=.441$). Table 4, which shows descriptive statistics across all conditions for each *r*-coefficient from the x-, y- and z-coordinate regressions, supports this since the *r*-values from the x-coordinate regression are by far likeliest to be highest (56.3%). Frequency analyses then showed that participants were slightly more likely to search from left to right (56.3% compared with 43.8% for right to left).

Where do observers initiate foraging?

We measured where observers start their visual foraging that can set the stage for the systematicity of the upcoming foraging (Wilson et al., 1998; Woods et al., 2013). Figure 8 shows the percentages in which octant the first target is cancelled. For static feature and conjunction foraging and dynamic feature foraging, the most frequent first target was located in octant number 8 (34.0%, $n=68/200$; 34.5%, $n=69/200$; 35.5%, $n=71/200$, respectively), while for dynamic conjunction foraging, the most frequent first

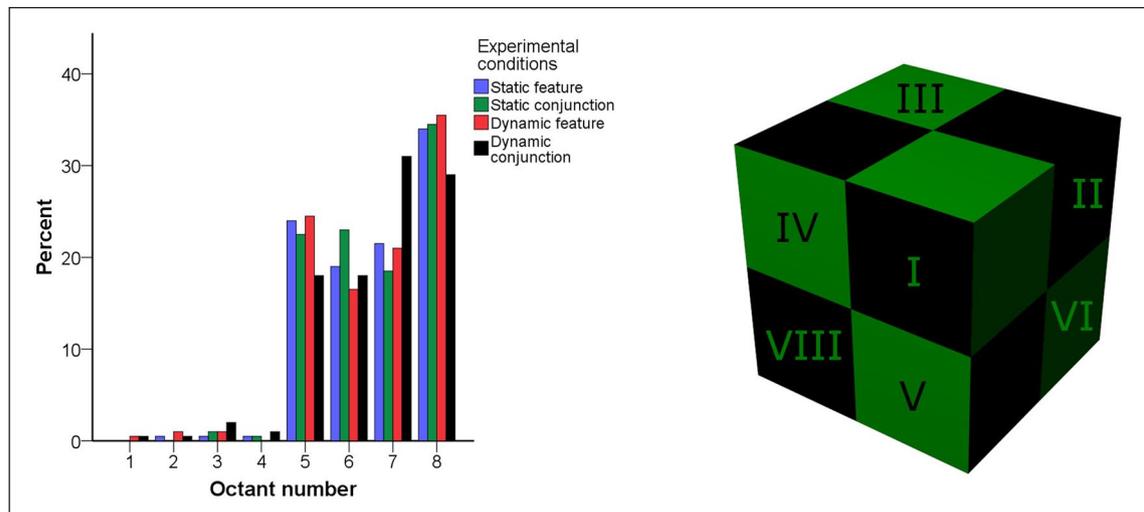


Figure 8. Foraging initiation in space. The cube on the right represents the eight octants in three-dimensional space used for analysis of where observers initiate foraging (the seventh octant is invisible behind the others). The left panel shows the percentages for octants where participants cancelled the first target.

target was in octant 7 (31.0%, $n=62/200$). The most frequent first target was therefore located at bottom left.

An important observation from Figure 8 is that it is by far most common for observers to initiate foraging within the bottom half in space (97.7%; $n=781/800$). There was also a small tendency to initiate foraging on the left (57.9% vs. 42.2% for the right).

Discussion

We investigated visual foraging for feature and conjunction targets in a 3D virtual environment. The following are among the main conclusions we draw from the results:

1. Differences in run length and run number between feature and conjunction foraging are smaller than in 2D foraging studies. This may suggest that as we approach the real world, differences between feature-based and conjunction-based processing decrease.
2. ITTs and switch costs are higher for conjunction than feature foraging, consistent with previous studies. The differences in this study partly reflect that switch costs are included in the ITTs for conjunction foraging (see below).
3. The differences between the static and dynamic conditions were remarkably small. One conclusion from this is that the cruise-phase is unlikely to simply reflect planning ahead of attention shifts.
4. Observers tend to initiate their foraging in the bottom half of the display—indicating a strong ground plane bias. Although there was a slight left-to-right “reading” bias, this was much smaller than the ground plane bias.

5. In contrast with 2D studies, no mid-peaks in the ITT pattern emerged for conjunction foraging.
6. An overall conclusion is that investigating attentional orienting in VR can provide insights above what 2D displays allow.

ITTs and run behaviour patterns

Run behaviour differed significantly between feature and conjunction foraging. Runs were typically longer during conjunction foraging where participants repeatedly shot the same target category to a larger degree, while during feature foraging, shorter runs and random switching between target categories were typical. The distributions for conjunction foraging had negative skew and lower mean run number than those for feature foraging and there was a slight peak at two runs, although importantly this was far smaller than in our previous 2D foraging studies. Our results show that people can switch between target categories during conjunction foraging and suggest that the strong two-run tendency seen in previous studies (Jóhannesson et al., 2017; Á. Kristjánsson et al., 2014, 2020) is at least partly a strategy rather than a limitation of the attentional system. When participants perform a task of higher difficulty, they prefer to stick to one category, clear a few targets, and then switch to the other category and clear a few targets, but they can switch if this is of benefit, as a recent study with time limits on foraging showed (Kristjánsson, Thornton, & Kristjánsson, 2018).

The end-peaks were clear in all four conditions, but largest for static conjunction foraging. Interestingly, the end-peaks were larger for static than dynamic foraging which suggests that motion can help observers find the last

target, which proves harder during static foraging as our previous results show (Kristjánsson et al., 2020; Ólafsdóttir et al., 2016).

As predicted, switching between target categories took longer than selecting the same category during both feature and conjunction foraging, although switching was considerably harder for conjunction than feature foraging.

The cruise-phase showed the same characteristics as in other experiments (T. Kristjánsson et al., 2018; Ólafsdóttir et al., 2016). Observers quickly selected targets and the ITTs remained relatively flat. The mean ITTs during the cruise-phase were significantly higher during conjunction foraging, a difference that can be explained by the attentional load conjunction foraging adds to the task, especially when switching between categories. The latter has a larger effect on mean ITTs during the cruise-phase, or about 600 ms more per switch during conjunction than feature foraging, while repeating a target category during conjunction foraging takes only 250 ms longer on average than repeats during feature foraging. Observers switched more often during conjunction foraging than in previous studies and the switches were more evenly distributed throughout trials, not concentrated at the middle of conjunction trials. In these previous experiments, cruise-phase ITTs could be calculated without this mid-peak. Since this is now evenly distributed throughout the cruise-phase during conjunction foraging, the ITTs are probably overestimated and mid-peaks underestimated. A notable aspect of the results, one which we have seen before (see, for example, discussion in T. Kristjánsson & Kristjánsson, 2018), is that observers seem to be able to maintain two templates simultaneously, which contrasts with some foraging results from animals. We believe that reflects to what extent observers can load their working memory and that the working memory contents then influence how observers allocate their visual attention. Since working memory capacity seems to allow observers to maintain two colour values in memory (at least in the feature condition), this enables them to focus on these two colours and ignore others, and they can therefore switch almost randomly between the different target types.

Foraging organisation

The results from the two organisation measures, mean ITL and best- r , differed slightly. For ITLs, a pattern analogous to the ITT pattern emerged. First, there was a “cruise-phase” throughout the trial, where participants selected targets that were close to the preceding one. There were also end-peaks for the last target of the trial. The ITLs were larger for conjunction than feature foraging and, perhaps unexpectedly, larger for static than dynamic foraging in both phases. For the best- r analysis, there was only a significant difference between feature

and conjunction foraging, while there was no significant effect of motion (static vs. dynamic). Feature foraging was more organised than conjunction foraging, as shown by higher best- r scores for feature foraging. Notably, the discrepancy of the results between best- r and mean ITLs suggests that these measures reflect different aspects of foraging organisation (see Woods et al., 2013).

In Cain et al. (2014), systematicity of foraging dropped when items on a 2D display moved continuously. In contrast, our results indicate that systematicity either increases when the stimuli move, as shown by larger ITLs during static than dynamic foraging, or that motion (static vs. dynamic) has no effect, as the best- r analyses suggest. The participants were slightly more likely to forage horizontally from left-to-right (56.3% versus 43.8%). These results may correspond to the leftward bias that develops as people grow older in left-right reading cultures (Chokron & De Agostini, 1995; Wilson et al., 1998; Woods et al., 2013). Notably, observers did not use depth much to organise foraging as the low r -values from the z coordinate regressions reveal.

Foraging initiation

Where observers initiate their foraging sets the stage for its systematicity (Wilson et al., 1998; Woods et al., 2013). Our results show that participants had a preference for the bottom left corner. Furthermore, participants showed a strong bias for initiating foraging in the lower half of the visual field (97.7%), which stands in strong contrast with the upper-left bias in Woods et al.’s (2013). The added third dimension probably explains this—the reading bias seen in previous studies probably reflects that people typically read from a 2D surface. Again, this shows the value of testing attention in a 3D environment. These results are, to our knowledge, the first visual search or foraging results to reveal a bias towards the lower visual field in 3D visual attention tasks.

Such depth related biases to the lower visual fields were predicted in Edgar Rubin’s famous doctoral thesis *Visually experienced figures* (*Synsoplevede Figurer*, defended at the University of Copenhagen in 1915; Rubin, 1915). Rubin listed rules for which of two contiguous areas might be visually perceived as figure, and which as ground. One is that if two areas are partitioned in half by a horizontal contour, there is a strong tendency to see the bottom half as figure, and the upper part as ground. In his thesis Rubin gave a similar explanation for the bottom half bias as we do:

This rule for the perception of figures has a certain relation to the world of things. Objects, such as trees, towers, humans, vases, lamps, are usually observed so that what surrounds them, for example the heaven or a wall, will generally constitute the upper part of the visual field. (Pind, 2014, p. 102; Rubin, 1915, p. 79).

According to this, a 3D foraging display is essential for observing this bias.

The slight preference to initiate foraging from the left half of space then corresponds to the leftward orientation that develops over time in left-right reading cultures (Chokron & De Agostini, 1995; Woods et al., 2013), but this is dwarfed by the strong ground bias.

Potential motor bottlenecks?

The question has been raised whether ITTs in our preceding foraging studies reflect attentional processing or if they simply reflect a motor bottleneck. For example, ITTs during the cruise-phase might reflect upper limits on motor action although attentional mechanisms may have been fast enough to process several targets in advance. We addressed this in two ways: first, by having the items move around on the screen which should affect the planning ahead, but surprisingly there was little difference between the dynamic and static conditions which suggests that planning ahead does not play a particularly large role in foraging; and second, we calculated the ratios of ITLs and ITTs throughout foraging trials. If the ITTs reflect a motor bottleneck, this ratio should be constant (because of the bottleneck) but there was a significant negative slope across all experimental conditions.

A final point we wish to make is that the motion that we used in the dynamic condition was not particularly natural and future studies should aim at testing foraging in dynamic environments that involve what is more likely to occur in natural environments.

Conclusion

We moved our previously tested foraging paradigm from a 2D plane into a virtual 3D environment. While foraging patterns were in many ways similar to 2D versions, some notable differences emerged. First, the differences between feature-based and conjunction-based foraging were not as dramatic as previously seen, especially with regard to run number. This may reflect that the frequency of switches between target categories may be partly strategy-based rather than a limitation of the attentional system. This also suggests that as we move into the real world, differences between feature and conjunction processing may be smaller than seen for simpler displays. Participants had a strong bias to orient to the bottom half of the virtual space and were slightly more likely to initiate their foraging on the left. Finally, we demonstrated that the ITT patterns are not solely a consequence of a motor bottleneck.

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