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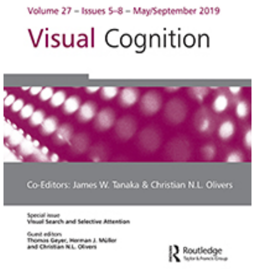

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The influence of selection modality, display dynamics and error feedback on patterns of human foraging

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ABSTRACT

In previous studies, we have used an iPad task to explore how humans "forage" through static displays containing multiple targets from two categories. When demands on attention were increased, foraging patterns tended to shift from random category selection to exhaustive category selection. Here, we used the same task on a vertically oriented touch-screen. In separate blocks, static or dynamic target items were selected using different modalities, specifically: (a) mouse (b) touchscreen or (c) infrared hand tracker. Although the different selection modalities varied considerably in terms of familiarity and difficulty of use, there was a minimal effect on the patterns of foraging. While there was a consistent reduction in the number of category switches with increased attentional load, the tendency to use exhaustive runs was much reduced, particularly with dynamic displays. We suggest that this pattern is a consequence of generally slowed response times. These findings indicate that in addition to capacity limits, temporal constraints are likely to be an important determinant of foraging patterns in humans. We introduce the term "foraging tempo" to capture this latter notion and to emphasize the probable role played by the overall pace of the regular, repetitive selections required during multi-target search tasks.

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Foraging; visual search; attention; foraging tempo; dynamic displays; error feedback; temporal constraints

In traditional studies of human visual search, participants are asked to locate a single target item embedded within a variable set size of distractor items (Treisman & Gelade, 1980; Wolfe, 2010; Wolfe & Horowitz, 2004, 2017). Examining behaviour in such tasks, for example by measuring search efficiency, has yielded many useful insights into the relationship between vision and attention (see Hulleman & Olivers, 2017; Á. Kristjánsson & Egeth, 2019; Wolfe & Horowitz, 2017 for recent discussions). Taking inspiration from the animal foraging literature (Dawkins, 1971; Heinrich, Mudge, & Deringis, 1977; Jackson & Li, 2004; Pietrewicz & Kamil, 1979; Tinbergen, 1960), a number of research groups have begun to explore tasks that involve multiple target items and/or target categories, with the aim of extending our knowledge about search in more complex scenarios (Cain, Vul, Clark, & Mitroff, 2012; Fougnie, Cormiea, Zhang, Alvarez, & Wolfe, 2015; Gilchrist, North, & Hood, 2001; Hills, Jones, & Todd, 2012; Hills, Kalff, & Wiener, 2013; Á. Kristjánsson, Jóhannesson, & Thornton, 2014; Pellicano et al., 2011; Wolfe, 2013; Wolfe, Aizenman, Boettcher, & Cain, 2016; Wolfe, Cain, & Aizenman, 2019).

In our own group, we have used a simple iPad cancellation task to explore human foraging under conditions of varying attentional load (Á. Kristjánsson et al., 2014). In a typical trial, participants would be required to use their finger to touch and thus cancel 40 items – 20 each from two different target categories – randomly distributed amongst 40 distractor items from two other categories. There were three main findings. First, when target items were distinguished from distractor items by a single feature (e.g., colour), responses were rapid (300 ms per touch) and items were selected randomly from the two target categories. Second, under conjunction conditions, when targets were defined in terms of both colour and shape, responses were always slower (at least 350 ms per touch) and search typically

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proceeded in an exhaustive manner, such that all targets from one category were cancelled before the other. We interpreted this finding as indicating that under higher attentional load, participants were unable or unwilling to switch rapidly between search templates, a phenomenon also discussed in the literature on animal foraging (Bond, 1983; Dawkins, 1971; Dukas & Ellner, 1993; Kamil & Bond, 2006; Tinbergen, 1960). Third, for approximately 25% of participants, there was no difference in selection patterns between feature and conjunction conditions, suggesting that individual differences in capacity or strategy also play a role. Focusing on the former explanation, we labelled this group "super-foragers" (Á. Kristjánsson et al., 2014).

In the current paper, we wanted to examine feature/conjunction foraging patterns in conditions where the display and interaction method were varied, relative to the original iPad task. We have already replicated the main findings discussed above in several independent publications (Jóhannesson, Kristjánsson, & Thornton, 2017; Jóhannesson, Thornton, Smith, Chetverikov, & Kristjánsson, 2016; T. Kristjánsson & Kristjánsson, 2018; T. Kristjánsson, Thornton, & Kristjánsson, 2018) but always using a very similar iPad task. Here, we presented stimuli on a desktop touchscreen monitor, and had participants select items using three different interaction methods: a standard computer mouse, touching the screen via a stylus, and controlling selection via an infrared hand tracker (see Figure 1). As described in more detail below, with all three methods, once an item was selected, it was cancelled by a subsequent keypress using the non-dominant hand. The other main modification, relative to our iPad task, was that here we included both static and dynamic displays (where targets and distractors moved around the screen), in different blocks of trials.

There are several ways in which these changes might influence foraging patterns. As the three selection methods vary greatly in familiarity and ease-of-use, they might also vary in overall cognitive/task demands. Thus, we might predict a tendency for longer "runs" of selecting targets from the same category with a less familiar/more demanding method (e.g., hand tracker), relative to the more familiar/less demanding method (e.g., mouse).

All three target selection methods would be expected to give rise to slower responses than those seen with the iPad task. Not only is the item selection itself less direct, but there is also the need for an additional keypress response. Recently, we have described a 3D foraging task in which participants play the role of a squirrel foraging for food in a park (Prpic et al., 2019). Our main finding was that in this scenario, feature/conjunction manipulations had no effect on the pattern of target selection from categories, with frequent switching and many runs always being observed. While this consistently random foraging pattern may have arisen due to a number of differences between the 2D and 3D versions of the task, we suggested that an important factor was the temporal separation between individual target selections.

As already mentioned, in the 2D iPad task, participants could make up to three responses per second, whereas in the 3D task, this was reduced to a single response every 4 s. While response times using the current selection methods should be much closer to those in the original iPad task, it remains possible that any slowing of consecutive responses could affect foraging patterns. As we expand on later in the paper, we predict that the *tempo* of consecutive responses will come to be seen as a major determinant of foraging patterns in these types of task.

Experiment 1

On each trial of Experiment 1, participants had to select and cancel 20 target items as quickly as possible, ignoring 20 distractor items that were also in the display (see Figure 2). The nature of the targets and the method of target selection varied across 12 blocks, with each block containing 10 trials. Our goal was to examine whether foraging behaviour, as indexed in terms of run patterns, would change depending on these manipulations.

The blocks of trials were organized into 3 phases, corresponding to 3 different selection modalities: mouse, touch or hand tracker. The order of these phases was counterbalanced across participants. Within a four-block modality phase, two blocks of trials contained moving items and two contained static items. The dynamic-static order was also counterbalanced across participants, with each motion condition having both a Feature and then a Conjunction block of trials. Participants first completed a block of trials where the targets were distinguished by a

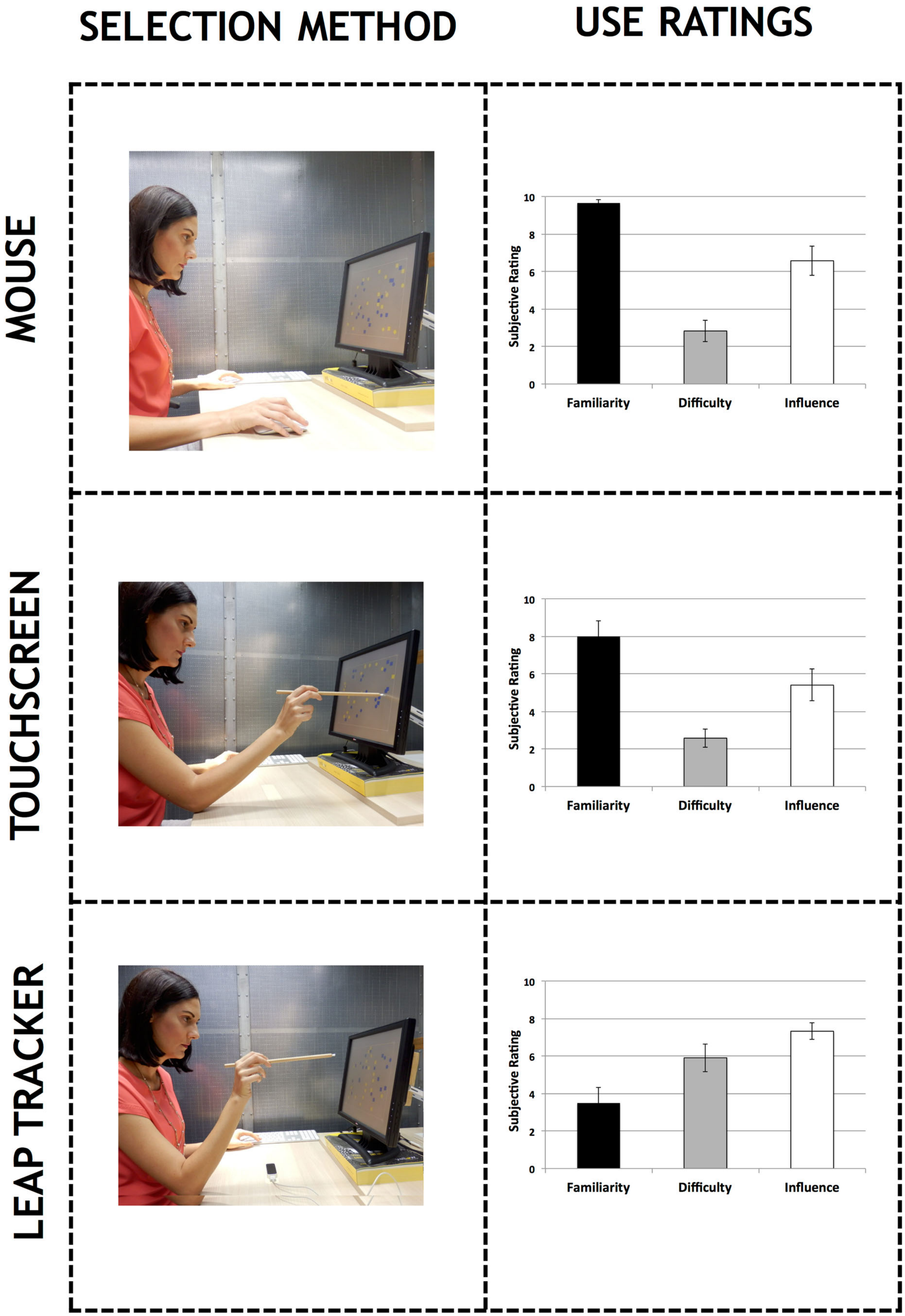

Figure 1. Selection modalities and usability ratings for the three phases of Experiment 1. Error bars represent standard error of the mean.

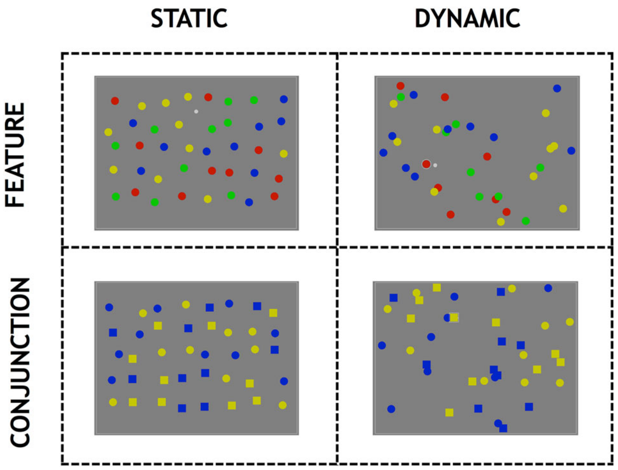

Figure 2. Stimuli used in Experiments 1 & 2. The position of items was randomized on a trial by trial basis, using an invisible 8 × 5 grid, with position within grid slots varied slightly to reduce regularity. During Static blocks, items remained in this initial position throughout the trial. In Dynamic blocks, stimuli were moving at approximately 2°/s throughout the trial, changing direction at independent, random intervals. Items passed through each other, but bounced off of the display edge. See text for further details.

single feature, and then one block of trials containing conjunction targets, in this fixed order, before moving to the next motion condition. By deciding to treat the less-demanding Feature condition as a baseline, we are thus asking the specific question: do observed changes in run patterns as attentional load is increased – in the more demanding conjunction condition – vary as a function of our novel independent variables (i.e., modality and motion)? We note that in our previous studies we have used both a fixed (Jóhannesson et al., 2017) and counterbalanced (Á. Kristjánsson et al., 2014) order for Feature and Conjunction blocks, finding qualitatively identical patterns (i.e., random switching in Feature blocks and exhaustive category selection in Conjunction blocks) irrespective of order.

Methods

Participants

A total of 12 participants (Mean age = 26.8, SD = 2.2; 6 Female; 11 right handed) were recruited from the University of Malta academic community. Group sample size was determined prior to data collection based on effect sizes observed in three of our previous studies (Jóhannesson, Kristjánsson et al., 2017; Jóhannesson, Thornton et al., 2016; Á. Kristjánsson et al., 2014). Cohen's d_z calculations for the difference in run behaviour between Feature and Conjunction conditions in these studies – the primary patterns of interest here – yielded values of between 1.6 and 2.3. We used G*Power 3.1.9.4 (Faul, Erdfelder, Lang, & Buchner, 2007) to conduct *a priori* power analysis based on these estimates, with assumed power of 0.95 and an alpha of 0.05. This analysis indicated that a minimum sample size of between 5 and 7 participants would be required to detect stable differences. We chose to be conservative and recruit a larger group of participants than this as the current work introduced additional experimental manipulations (i.e., Modality and Motion) that could well impact the measurement of run behaviour. All participants had normal or corrected to normal vision and gave written informed consent before taking part in the experiment. They were naïve as to the purpose of the research and were not experienced psychophysical observers. All methods and procedures conformed to the Ethics and Data Protection Guidelines of the University of Malta, Malta and were reviewed by the appropriate Faculty Research Ethics Committee. The work was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Equipment

Stimuli were presented on a FayTech 17″ Resistive Touch Monitor connected to a 15″ MacBook Pro computer running OSX 10.10.5. The monitor had a visible area of 34 × 27 cm, a pixel resolution of 1280 × 1024 and a refresh rate of 60 Hz. Custom scripts were developed in Matlab, using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). These were used to present the stimuli, collect responses and implement the experimental design. Copies of the experimental scripts are available on request. Participants sat in a quiet room with no overhead lighting. Viewing distance was approximately 70 cm.

A light, wooden stylus (30 cm) was used as the tool with which participants interacted with the displays during Touchscreen and Tracker blocks (Figure 1). The stylus had a diameter of 0.8 cm, was 30 cm in length and was always held in the dominant hand. A new plastic cotton bud was inserted into one end of the stylus for each participant, allowing firm contact with the Touchscreen. During Tracker blocks, a Leap Motion Controller (Leap Motion, www.leapmotion.com) was used to track the position of the stylus and translate movements in space into screen coordinates (Bachmann, Weichert, & Rinkenauer, 2015). A standard Apple USB keyboard and mouse were also attached to the MacBook Pro. The keyboard was vertically oriented and placed to the left or right of the participant, depending on their handedness. For all three modalities, once an item had been selected, observers could cancel it by pressing the spacebar on the keyboard with their non-dominant hand. The mouse was positioned centrally only during the relevant blocks of trials.

Note that we intentionally chose input modalities that had different gain factors, or spatial mappings, between device movements and screen positions. During Touchscreen blocks, physical movements in space were mapped approximately 1:1 with positions on the screen. When using the Leap Motion Tracker, the default tracking volume gave rise to a slightly negative gain of 1.3:1, where larger movements in space were required to cover the screen distance between two objects. For the Mouse, the gain was not fixed but was subject to a standard acceleration profile, where slow movements tend to have close to 1:1 or even slightly negative gain, and fast movements a positive gain. With the short, rapid movements characteristic of the current foraging task, we estimated the average Mouse gain to be in the order of 0.7:1, although we note this is only a rough approximation.

Stimuli

At the start of each trial, 40 simple geometric shapes appeared on the screen (Figure 2). In the Feature condition, all shapes were circles and target and distractor items were distinguished only by colour. There were two target categories (red & green circles) and two distractor categories (blue & yellow circles). In the Conjunction condition the two target categories (blue circles & yellow squares) were distinguished from the distractor categories (yellow circles & blue squares) by both colour and shape. In previous studies, we typically varied target/distractor categories and counterbalanced them across participants. As there was never any influence of category, and as the current design involved counterbalanced selection methods (see below), we opted to use fixed target/distractor category assignments, and these were selected arbitrarily.

The 40 items were randomly distributed within an invisible 5 × 8 grid. The grid itself was positioned within a display area at the centre of the screen that subtended 22° × 18° visual angle and was delineated by a white border. Each target and distractor item had a diameter of 40 pixels (0.82°), and the position of items within the individual grid cells (2.5° × 2.5°) was horizontally and vertically jittered between 0° and 1.2° in the *X* and *Y* directions so that the regularity of the grid was reduced, but no items ever initially overlapped. We note that the current set size of 40 items is exactly half of that used in our original iPad study (Á. Kristjánsson et al., 2014). This reduction was made as we had increased item size – to accommodate lower selection resolution – and did not want to use an overly large display area. We note, however, that in other work from our group, we have explicitly manipulated set size (including the current 20 targets/20 distractors) and found that differences in run patterns between feature and conjunction foraging, the focus of the current paper, were largely unaffected by this manipulation (T. Kristjánsson, Thornton, Chetverikov, & Kristjánsson, 2019).

In *static* blocks of trials, the position of items within the grid did not change. In *dynamic* trial blocks, items immediately started to move in random directions at a speed of approximately 2°/second. The initial direction of each item was selected from the full 360° range and this direction was recomputed after a random time period of between 1.6 and 3.3 s or when an item reached the edge of the display area. Random direction changes were again drawn from the full 360° range, whereas contact with a boundary caused a direction reversal. Items did not bounce when they collided with each other, but passed smoothly through. These dynamic parameters were based on previous studies from our group where participants were required to interact with moving objects (de'Sperati & Thornton, 2019; Thornton, Bülthoff, Horowitz, Rynning, & Lee, 2014; Thornton & Horowitz, 2015).

Task & input modalities

The task was always to select and cancel the 20 target items as quickly and accurately as possible. A trial only ended when all 20 items had been successfully located. Target items were selected in different ways, depending on the phase of the experiment, as detailed shortly, but were always cancelled by pressing the spacebar on the keyboard. When an item was selected, it was identified by adding a white "halo" outline, which remained visible until the item was cancelled, or another item was selected (Figure 2). During the Mouse phase, a small (0.5°) circular cursor was also drawn in white on the screen (Figure 2, top panels), and this was controlled via the standard Apple USB mouse to collide with, and thus select items. During the Touch phase, participants held the stylus between the thumb and index finger of their dominant hand, and directly touched the screen to select items. During the Hand tracker phase, participants held the stylus as before, but directly above the infrared Leap tracker device placed on the table in front of them (Figure 1, bottom panel). Horizontal and vertical movements of the stylus were translated into *X*/*Y* shifts of the same white cursor used during the Mouse phase.

Procedure & questionnaire

After reading the information sheet and signing the consent form, participants were given further oral instructions about the nature of the tasks they would be asked to perform. Prior to the start of each phase, they were familiarized with the method of selection and were given the opportunity to practice until they felt comfortable with performing the task. This introductory period lasted approximately 5 min. They then completed the 4 experimental blocks for that phase, with the order of the Dynamic and Static blocks counterbalanced across participants.

When the four blocks of a given selection modality were complete, participants were asked to subjectively assess their experience using a series of 10-point scales. Specifically, they were asked (1) How familiar are you with this type of device/technique? The anchor points for this item were "Not at all" (1) and "Very" (10); (2) Did you find the device/technique easy to use in this context? The anchor points for this item were "Easy" (1) and "Hard" (10); (3) Did the device/technique influence the way you selected items? The anchor points for this item were "Not at all" (1) and "A lot" (10). Each phase of the experiment took between 15 and 20 min to complete. Participants were encouraged to take short breaks between phases, and the entire experiment lasted approximately 1 h.

Data analysis

To explore the questionnaire data, we conducted separate one-way repeated measures ANOVAs for each of the items, Familiarity, Difficulty & Influence, with Modality as the repeated, independent factor. To more directly assess the impact of input modality on selection performance, we made use of the objective index of difficulty ($ID = \log_2(2D/W)$) formulated by Fitts (1954), where D = distance between two successive targets and W = target width. The slopes obtained by regressing movement time (MT) on ID ($MT = a + b * ID$) provides a standard method to compare human performance with different input modalities (e.g., Bachmann et al., 2015; Card, English, & Burr, 1978; MacKenzie, 1992). Here, we analyzed the Fitts' Law slopes using a 2 (Condition: Feature/Conjunction) × 2 (Motion: Dynamic/Static) × 3 (Modality: Mouse/Touch/Tracker) repeated measures ANOVA.

This same ANOVA model was also used to analyse the remaining dependent variables. To specifically focus on foraging patterns, we analyzed the average number of runs per trial. A "run" refers to a sequence of selections from the same target category. When the number of runs per trial is close to the total number of targets divided by 2, this indicates that items are being selected at random. Fewer runs per trial suggest category-based selection. In our previous studies (Jóhannesson, Kristjánsson et al., 2017; Jóhannesson, Thornton et al., 2016; Á. Kristjánsson et al., 2014), participants typically selected targets at random during feature foraging, but used exhaustive category selection (i.e., only two runs) during conjunction foraging trials. While there are additional quantitative techniques for establishing whether a trial contains random runs, such as the one sample runs test (Dawkins, 1971; Á. Kristjánsson et al., 2014) or random simulation (Wolfe et al., 2019), these typically provide results that correspond very well with the heuristic just described. As our goal was to characterize the overall difference in run behaviour between feature and conjunction conditions, and as additional analyses with the one sample runs test yielded qualitatively identical patterns, we opted to base our analysis simply on the number of runs.

To capture overall levels of performance, we report error rates, trial completion time and total movement distance. For all relevant analyses, when violations of sphericity were detected, we adjusted the degrees of freedom using the Greenhouse-Geisser method. Additional post-hoc tests are described in the relevant sections, and corrections for multiple comparisons were always made.

To supplement our main null-hypothesis significance tests we also conducted Bayesian analysis, using the approach outlined by Masson (2011). For all of our analyses (see Supplementary Table 1), we estimated the weight of evidence in favour of the null hypothesis, and report both BF_{01} and $p(H_0|D)$ in the text where appropriate. Where only weak evidence was obtained – specifically $BF_{01} < 3.0$ and $p(H_0|D) < 0.75$ (Jeffreys, 1998; Raftery, 1995; Wagenmakers, Wetzels, Borsboom, & van der Maas, 2011) – this is noted in the relevant Results and/or Discussion sections.

Note that all analysis scripts and files are available on request and that the raw data files have been uploaded to the Open Science Foundation (OSF) page associated with this paper: https://osf.io/pvm5y/.

Results

Figure 1 (right hand panels) shows the subjective assessment data from the questionnaires that participants completed after each phase of Experiment 1. The Mouse and Touchscreen modalities were rated as being highly familiar, whereas most individuals reported being unfamiliar with the Tracker. This pattern gave rise to a main effect of Modality, $F(2,22) = 31.3$, $MSE = 3.9$, $p < 0.001$, $\eta_p^2 = 0.74$, with post-hoc comparisons indicating that Tracker blocks significantly differed from both of the other two selection modalities. Consistent with this pattern, the Tracker was also rated significantly more difficult to use than the other two modalities, $F(1.2,12.7) = 12.6$, $MSE = 5.7$, $p < 0.01$, $\eta_p^2 = 0.54$. There were no significant differences between the modalities in the extent to which they were thought to affect selection strategies, $F(2,22) = 1.9$, $MSE = 5.8$, $p = 0.17$, $\eta_p^2 = 0.15$, $BF_{01} = 4.55$, $p(H_0|D) = 0.82$.

Overall, movement time was well predicted from the objective index of difficulty ($M_{Slope} = 0.197$, $SE = 0.003$, partial correlation = 0.371, $p < 0.001$), suggesting that foraging behaviour in the current task obeyed Fitts' law. We obtained this overall slope estimate through multiple linear regression with a model that also included Modality, Motion and Condition as predictors (see Supplementary Table 2 for details). Interestingly, as shown in Figure 3, the Fitts' law slopes also varied consistently across our experimental manipulations. Complementing the subjective assessment of difficulty, the Tracker blocks gave rise to the steepest (i.e., least efficient) slopes ($M = 0.26$, $SE = 0.01$). There also appear to be a clear difference between Mouse ($M = 0.21$, $SE = 0.01$) and Touch ($M = 0.16$, $SE = 0.01$) blocks. These patterns were confirmed by analysis, with a main effect of Modality, $F(2,22) = 22.3$, $MSE = 0.005$, $p < 0.001$, $\eta_p^2 = 0.71$, in which all pairwise post-hoc comparisons were significant. There was also a main effect of Condition, such that the increased demands of the Conjunction condition ($M = 0.26$, $SE = 0.01$) gave rise to less efficient movements than the Feature condition ($M = 0.16$, $SE = 0.01$), $F(1,11) = 90.2$, $MSE = 0.004$, $p < 0.001$, $\eta_p^2 = 0.89$. Interestingly, there was no main effect of Motion, $F(1,11) = 0.1$, $MSE = 0.004$, $p = 0.77$, $\eta_p^2 = 0.01$, $BF_{01} = 3.3$, $p(H_0|D) = 0.77$. None of the interactions were significant, although relatively weak evidence for the null hypothesis with respect to Condition × Motion interaction ($BF_{01} = 1.4$, $p(H_0|D) = 0.59$) should be noted.

Figure 3(b) summarizes the patterns of runs across all conditions. There are several clear patterns in this data. First, the number of runs is consistently lower in all Conjunction conditions ($M = 6.0$, $SE = 0.58$) relative to the Feature conditions ($M = 10.1$, $SE = 0.17$). Although there appears to be a clear tendency to use fewer, longer runs in the Conjunction conditions, the average data do not suggest that the majority of participants used an exhaustive, two-run strategy, as we found in our iPad tasks. Second, foraging appears to have always been random when targets were defined by a single feature. That is, in the Feature condition, the number of runs remains close to half the overall set size divided by 2 (i.e., 10), the hallmark of random selection, across all conditions. Thirdly, selection modality and motion appear to have had little influence on the overall pattern of runs, except for a slight reduction under the static conditions during Touch trials.

Consistent with these observations, there was a main effect of Condition, $F(1,11) = 63.9$, $MSE = 9.0$, $p < 0.001$, $\eta_p^2 = 0.85$. There was no main effect of Modality, $F(2,22) = 2.5$, $MSE = 2.3$, $p = 0.1$, $\eta_p^2 = 0.19$,

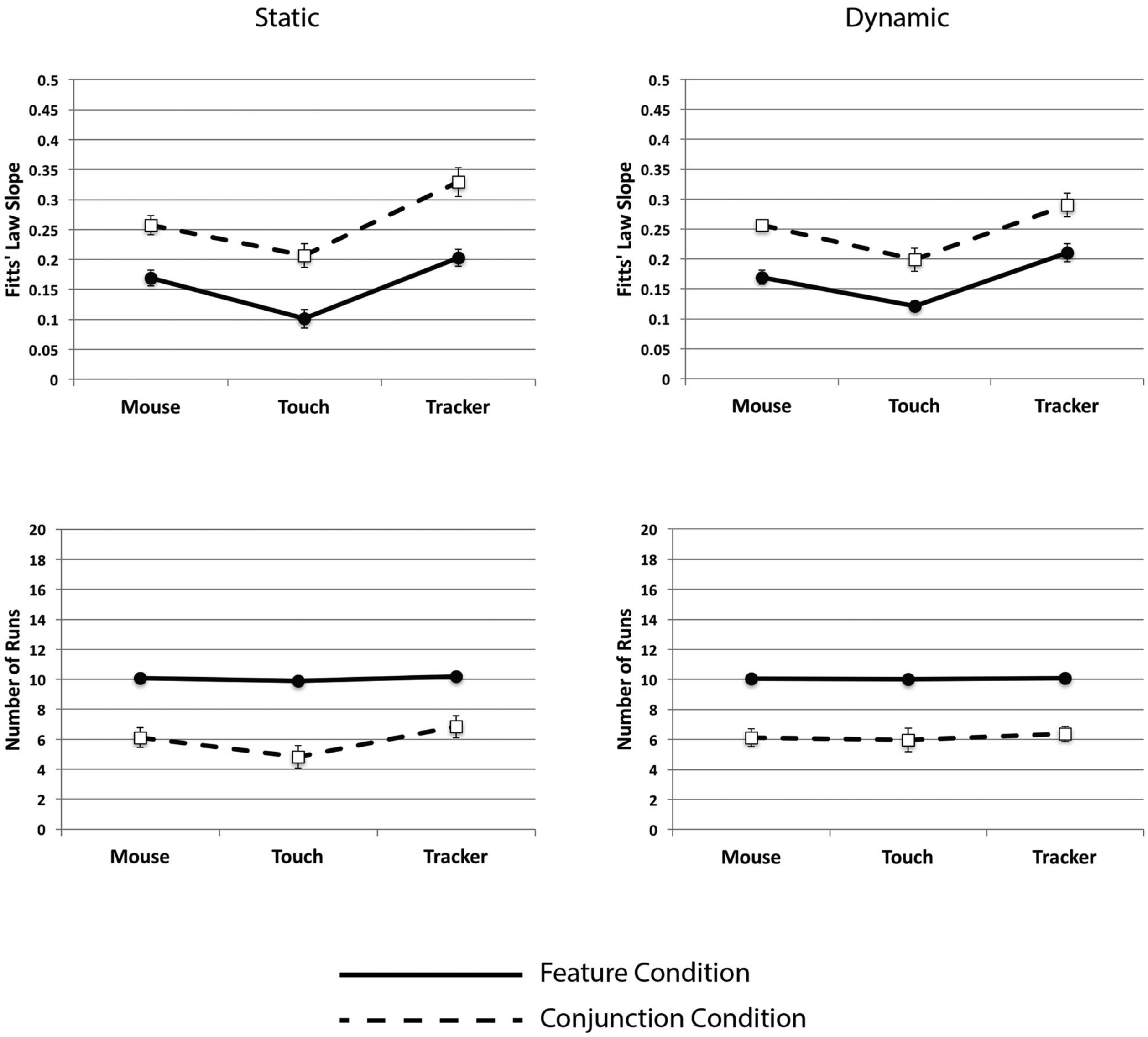

Figure 3. Average Fitts' Law slopes and number of runs from the Static (left panels) and Dynamic (right panels) displays of Experiment 1 as a function of condition and selection modality. Solid lines/bars show data from the Feature condition, dashed lines/open bars from the Conjunction condition. Error bars represent standard error of the mean.

$BF_{01} = 3.5$, $p(H0|D) = 0.78$ and no Modality × Condition interaction, $F(2,22) = 1.8$, $MSE = 1.8$, $p = 0.19$, $\eta_p^2 = 0.14$, $BF_{01} = 4.8$, $p(H0|D) = 0.83$. There was a significant Modality × Motion interaction, $F(2,22) = 8.0$, $MSE = 0.33$, $p < 0.01$, $\eta_p^2 = 0.42$, which appears to be driven by the reduction in runs during static Touch conditions. While the main effect of Motion, $F(1,11) = 0.6$, $MSE = 0.7$, $p = 0.56$, $\eta_p^2 = 0.05$, $BF_{01} = 2.5$, $p(H0|D) = 0.72$, and the Motion × Condition interaction, $F(1,11) = 1.5$, $MSE = 0.34$, $p = 0.25$, $\eta_p^2 = 0.12$, $BF_{01} = 1.6$, $p(H0|D) = 0.62$, failed to reach significance, we note that the current data provide only weak evidence in favour of the respective null hypotheses. The Condition × Modality × Motion interaction was not significant, $F(2,22) = 1.6$, $MSE = 0.95$, $p = 0.22$, $\eta_p^2 = 0.13$, $BF_{01} = 5.2$, $p(H0|D) = 0.84$.

To examine whether the overall pattern of runs was stable across time, we also conducted a follow-up 2 (Condition) × 2 (Phase: Early = Trials 1–5/Late = Trials 6–10) repeated measures ANOVA. Note that for this analysis, we collapsed across Motion and Modality to provide more observations for the time course estimate. As expected, there was a main effect of Condition, $F(1,11) = 61.3$, $MSE = 3.3$, $p < 0.001$, $\eta_p^2 = 0.85$. There was a very slight, but consistent, reduction in runs as a function of Phase, with fewer runs during the Late ($M = 7.9$, $SE = 0.36$) versus Early ($M = 8.2$, $SE = 0.35$) parts of the block, $F(1,11) = 5.5$, $MSE = 0.24$, p

< 0.05, $\eta_p^2 = 0.33$. This pattern of reduction was apparent for both Feature (10.2 vs 10.0 runs) and Conjunction Trials (6.3 vs 5.8 runs) trials, and the Condition × Phase interaction was not significant, $F(1,11) = 0.8$, MSE = 0.42, $p = 0.39$, $\eta_p^2 = 0.07$, $BF_{01} = 2.3$, $p(H0|D) = 0.7$. Even though we note that the current data do not strongly support the lack of an interaction, the magnitude of changes across the two phases suggests that average runs provide a fairly stable estimate of performance across time.

Figure 4 summarizes the pattern of runs for individual observers across all conditions. While the overall pattern of less runs during Conjunction than Feature foraging is obvious in all panels, there are two sources of variation which are noteworthy. First, as in our previous work, there are clear individual differences, with some observers switching from a random strategy with approximately 10 runs in the Feature condition, to only 2 or 3 runs in the Conjunction condition (see PPTs 2 & 7 in all panels). Other observers have largely similar numbers of runs in the two conditions, maintaining a random strategy of close to 10 runs in all conditions (see PPTs 4, 6 & 9 in all panels). The latter type of participant we previously labelled "super-foragers", as the increased attentional load associated with conjunction foraging did not seem to affect their performance (Á. Kristjánsson et al., 2014). Figure 5, however, makes it clear that in the current experiment, patterns of foraging span the whole range between these two extreme patterns. That is, while the number of runs during the Feature condition is fairly constant at around 10 runs/trial, in the Conjunction condition patterns are much more diverse. Note that as this diversity was apparent in all conditions, we have collapsed across motion and selection modality when describing the data. Another way to visualize individual foraging patterns is to plot run data for each participant on every trial, as we did for average run length data in our original study (Á. Kristjánsson et al., 2014; Figure 4). Here we provide separate figures showing the number of runs on each trial – our main dependent measure – for each modality (Supplementary Figures 1–3). Clearly, these figures can also provide useful information about the stability of run patterns across time.

The second source of variation relates to the influence of selection modality. Although the average pattern of runs in Figure 3 suggests little influence of how participants selected items, there do appear to be subtle effects of selection modality on Conjunction foraging. As just noted, and in contrast to our previous work, few observers in Experiment 1 appear to have used exhaustive strategies during conjunction foraging, where one category of targets is cancelled before the other, giving rise to only two runs (see Figure 5). The tendency to use fewer runs (i.e., <5), however, does appear to be influenced by modality. Figure 6 shows the number of participants whose average run behaviour was either above or below 5 for each of the modalities. As random behaviour is characterized by approximately 10 runs, we chose the cut-off of "fewer" runs to be below the midpoint of 5 runs. There is clearly a difference in the occurrence of fewer runs as a function of modality, with more participants using this strategy with the Touch screen selection method. Cochran's *Q* non-parametric test indicated that the difference between modalities was significant, $\chi^2(2) = 8.4$, $p < 0.05$.

Figure 7 shows the trial completion time, error rates and total distance moved for all conditions. Participants were consistently faster in static ($M = 12.5$ s, SE = 0.39) versus dynamic ($M = 18.1$ s, SE = 0.62) blocks, $F(1,11) = 128.0$, MSE = 8.7, $p < 0.001$, $\eta_p^2 = 0.92$. As expected from our previous studies, they were also faster in Feature ($M = 14.3$ s, SE = 0.45) compared to Conjunction ($M = 16.3$ s, SE = 0.49) conditions, $F(1,11) = 68.8$, MSE = 2.2, $p < 0.001$, $\eta_p^2 = 0.86$. There was also a significant main effect of Modality, $F(2,22) = 4.5$, MSE = 10.6, $p < 0.05$, $\eta_p^2 = 0.29$, which appears to be driven by generally slower responses in the Tracker condition, although no pairwise comparisons survived Bonferroni correction.

The only other significant effect was a Motion × Modality interaction, $F(2,22) = 21.3$, MSE = 2.2, $p < 0.001$, $\eta_p^2 = 0.66$. As can be seen in Figure 7, this arises due to consistently faster responses in Static blocks when responding with the Touchscreen interface, for both Feature and Conjunction trials. There was a marginally significant Motion × Condition interaction, $F(1,11) = 4.8$, MSE = 1.2, $p = 0.05$, $\eta_p^2 = 0.30$, which would appear to reflect slightly greater slowing in the Conjunction condition during Dynamic blocks. No other effects were significant.

The pattern of Distance data appears very straightforward. As expected from our previous work, the total distance moved was greater in the Conjunction condition ($M = 4468$ pixels, SE = 62) than in the Feature condition ($M = 3823$, SE = 33), reflected in a main

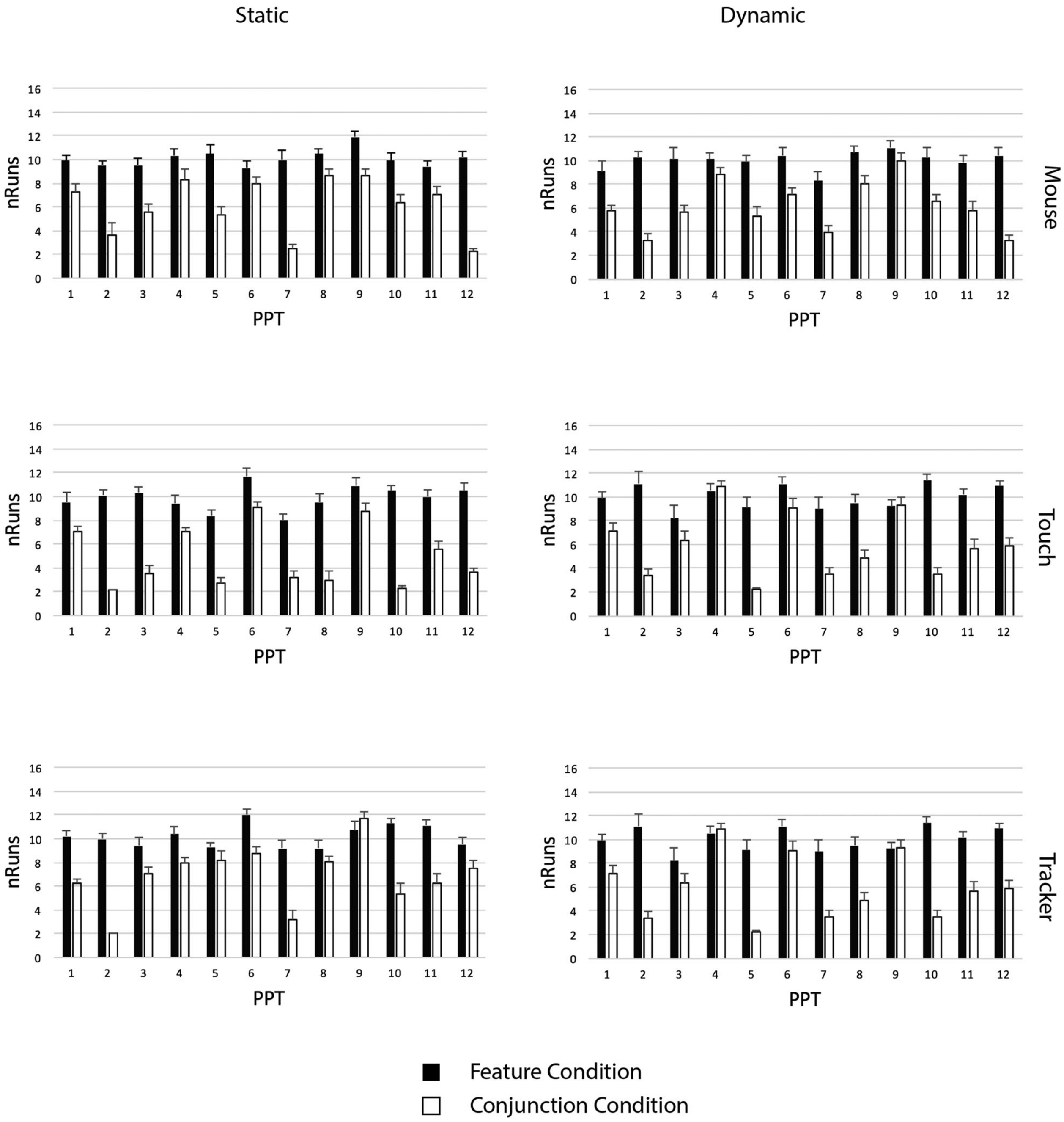

Figure 4. Number of runs per participant in the Static (left column) and Dynamic (right column) blocks of trials. Successive rows show data from the Mouse, Touch and Tracker conditions respectively. Solid bars are Feature condition, open bars Conjunction condition. Error bars represent standard error of the mean.

effect of Condition, $F(1,11) = 143.7$, $MSE = 104472$, $p < 0.001$, $\eta_p^2 = 0.93$. There was also a main effect of Modality, $F(1,11) = 16.8$, $MSE = 78605$, $p < 0.001$, $\eta_p^2 = 0.60$, with post-hoc comparisons indicating that movement was significantly greater in Touch ($M = 4336$ pixels, $SE = 67$) blocks compared to both Mouse ($M = 4067$ pixels, $SE = 53$) and Tracker blocks ($M = 4034$ pixels, $SE = 36$), which did not differ from each other. Finally, there was also a main effect of Motion, with greater distances being travelled in Dynamic ($M = 4629$ pixels, $SE = 39$) compared to Static blocks ($M = 3662$ pixels, $SE = 59$), $F(1,11) = 313.0$, $MSE = 107376$, $p < 0.001$, $\eta_p^2 = 0.97$. None of the interactions were significant, all $BF_{01} > 3$, $P(H0|D) > 0.75$.

Finally, turning to the error data, the clearest pattern in Figure 7 is the large increase in errors when target items are moving ($M = 12.3$, $SE = 1.4$) compared to when they were static ($M = 2.0$, $SE =$

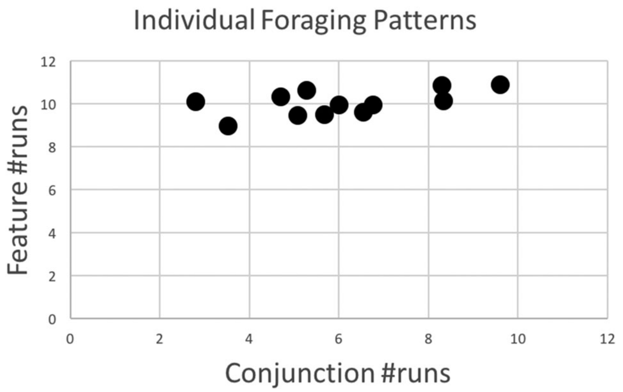

Figure 5. Variability in run patterns for the 12 participants of Experiment 1 as a function of Feature and Conjunction conditions. Data have been collapsed across selection modality and display dynamics.

0.31), giving rise to a main effect of Motion, $F(1,11) = 72.6$, $MSE = 51.9$, $p < 0.001$, $\eta_p^2 = 0.87$. There was also a main effect of Condition, $F(1,11) = 8.8$, $MSE = 19.9$, $p < 0.05$, $\eta_p^2 = 0.45$, with more errors in Conjunction blocks ($M = 8.3$, $SE = 1.0$) than Feature blocks ($M = 6.1$, $SE = 0.69$). The main effect of Modality was marginally significant, $F(2,22) = 3.3$, $MSE = 35.9$, $p = 0.06$, $\eta_p^2 = 0.23$, which appears related to slightly worse overall performance when selecting with the hand Tracker (see Figure 7). The only other significant effect was a Condition × Modality interaction, $F(2,22) = 3.9$, $MSE = 9.3$, $p < 0.05$, $\eta_p^2 = 0.63$. While error rates did not vary as a function of Modality during Feature blocks, in Conjunction blocks, there was a slight reduction in errors when selecting via the Touchscreen, and a corresponding increase when selecting via the Tracker. The remaining interactions were not significant.

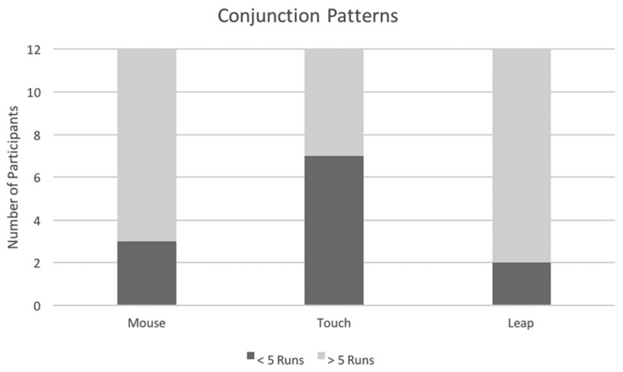

Figure 6. Number of participants using <5 runs/trial (darker shading) or ≥5 runs during Conjunction conditions as a function of selection modality. Data have been collapsed across display dynamics.

Discussion

The goal of Experiment 1 was to determine whether selection modality and/or display dynamics would affect patterns of foraging as attentional demands were increased across the Feature and Conjunction blocks of trials. We had suggested that increased difficulty in using some methods of selection might lead to a reduction in the tendency to switch between target categories, the hallmark of increased attentional load (Dukas, 2002; Dukas & Ellner, 1993). This was not the case. There were clear differences in both subjective and objective measures of difficulty of use across the selection modalities, but these were not accompanied by a corresponding reduction in switching. Rather, and in line with our second prediction, the subtle change in run behaviour as a function of selection modality, seems to have been mediated by overall time/fluency constraints imposed by the method of responding. That is, when using selection methods that encouraged slower responses (i.e., Mouse and Tracker), participants tended to switch more often than in the touchscreen condition, where faster and more fluent responses were accompanied by fewer, longer runs (Figure 6). We return to these patterns, and how they relate to our previous findings in the General Discussion.

In terms of display dynamics, the overall pattern of foraging in static and dynamic displays was remarkably similar (Figure 3). The only clear difference in the average data was the slight reduction in runs during static touchscreen blocks. Examination of individual run patterns (Figure 4), suggests that this difference may actually reflect a broad rise in the number of conjunction switches during the slower Mouse and Tracker phases.

Turning to our other dependent measures, for response speed, the main patterns of data were as expected. Participants were slower in Dynamic than Static blocks, and slower under Conjunction than Feature conditions. The less familiar and more difficult hand tracker selection modality also led to slower overall responses. However, the most interesting aspect of these data is the absolute speed, relative to responses we would typically measure using the iPad. That is, with average completion times of approximately 15 s for a display containing 20 items, participants were cancelling a target, on average, every 750 ms. This is exactly twice as slow

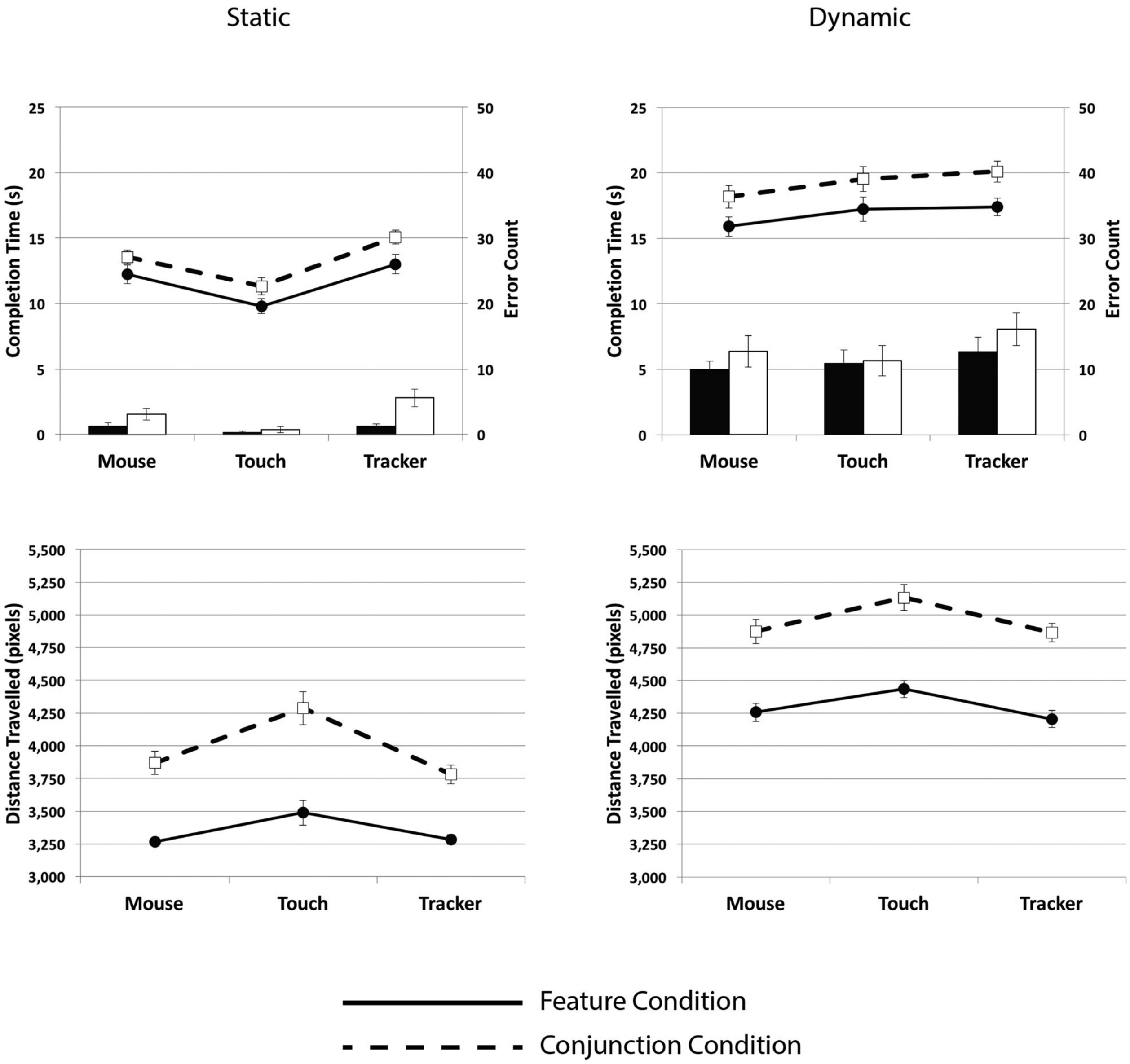

Figure 7. Average completion times, error counts and distance travelled from the Static (left panels) and Dynamic (right panels) displays of Experiment 1 as a function of condition and selection modality. Solid lines/bars show data from the Feature condition, dashed lines/open bars from the Conjunction condition. Error bars represent standard error of the mean.

as the average cancellation times seen for the iPad where participants were able to cancel 40 targets in approximately 13 s (325 ms/item). As we expand on in the General Discussion, the additional time taken to make responses in the current experiment – an overall slowing of *foraging tempo* – may well be a main factor in explaining the reduction of exhaustive run behaviour. The distance measure showed very clearly how our main manipulations of modality and display dynamics could affect responses. For example, the increase in distance travelled with the Touch interface – together with the reduction in response speed, and related Fitts' slope measures – clearly indicates that selection was less costly/more fluent with this modality than with either the Mouse or Tracker devices. However, not only is the corresponding deflection in run behaviour shown in Figure 3 much more muted, but the direction of change is also opposite to our prediction based on ease of use. That is, we had predicted that more fluent selection should lead to an increase, not a decrease in the number of switches per trial.

Finally, in terms of error data, our pilot studies had indicated that participants would make substantially more selection errors during Dynamic blocks, and this was indeed the case here.

Experiment 2

The goal of Experiment 2 was to determine whether the nature of error feedback plays a major role in determining foraging patterns. In all of our previous studies, a trial terminated when a distractor item was selected. In Experiment 1, we had anticipated – and subsequently found – quite high levels of selection errors during dynamic trials. As these appeared to be due to slips of action, rather than erroneous intentional selections, and as pilot testing indicated that participants could become quite frustrated, we removed the trial termination and simply counted the errors. Thus, in Experiment 1, if a distractor item was selected and an attempt was made to cancel it via a keypress, the display was not updated (i.e., the item was not removed) and the error count was simply increased.

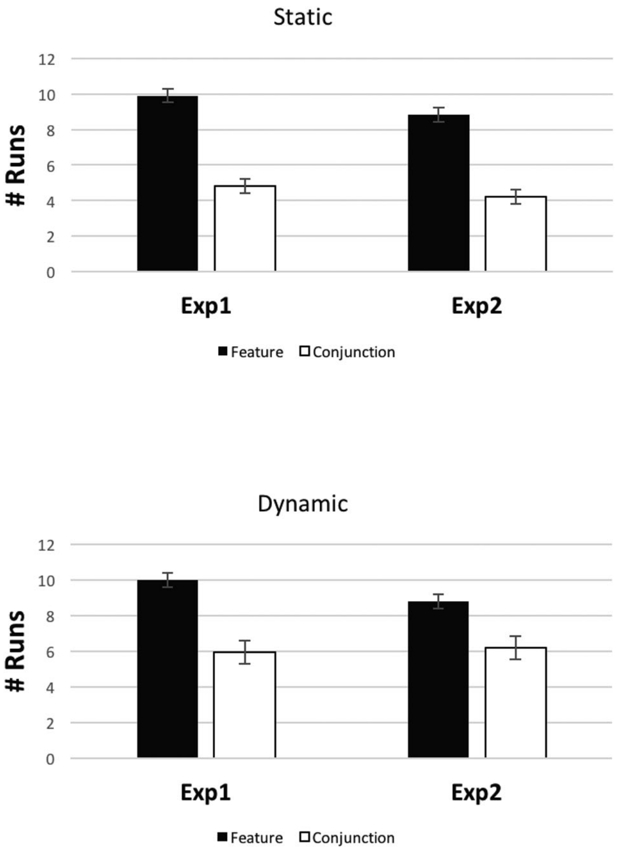

Figure 8. Average number of runs per trial for the Touch condition of Experiment 1, without terminal error feedback and the Touch condition of Experiment 2, with terminal feedback. Data are show separately for the Static (top panel) and Dynamic (bottom panel) conditions. Solid bars show data from the Feature condition, open bars from the Conjunction condition. Error bars represent standard error of the mean.

However, as the majority of participants no longer used "exhaustive" category selection during the Conjunction conditions of Experiment 1, a pattern that was present in all of our iPad studies, it is important to examine whether this change was caused by the less severe consequences of making an error. In Experiment 2, we therefore asked 12 new participants to complete the Touch Screen conditions of Experiment 1 but with the original error regime from our iPad studies reinstated. Thus, if a distractor item was selected and cancelled, an error message was displayed, and the trial was terminated, and replaced. We directly compared their performance with the corresponding conditions of Experiment 1.

Methods

Participants

A new group of participants ($N = 12$; Mean age = 24.5 years, SD = 2.9; 8 Female; 9 right handed) were recruited from the University of Malta academic community. The sample size was chosen to match that of Experiment 1. All participants had normal or corrected to normal vision, and none had taken part in Experiment 1. They were naïve as to the purpose of the research and were not experienced psychophysical observers. All methods and procedures conformed to the Ethics and Data Protection Guidelines of the University of Malta and were reviewed by the appropriate Faculty Research Ethics Committee. The work was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Equipment, stimuli, task & procedures

These were identical to Experiment 1, with the following two exceptions. First, participants only selected items using the stylus on the touchscreen. Second, they completed 20 trials of each block, rather than 10. As the overall experiment was much shorter than Experiment 1, without the additional 2 selection modalities, we increased the repetitions within a block to improve precision. As in Experiment 1, movement within the displays was counterbalanced across participants, with half completing the static blocks and then the dynamic blocks, and the other using the opposite order. Within each motion phase, participants completed the Feature condition before the Conjunction condition.

Data analysis

We used a 2 (Experiment: Exp1/Exp2) × (Condition: Feature/Conjunction) × 2 (Motion: Dynamic/Static) mixed ANOVA to explore the data, with Experiment as a between subject measure, and Condition and Motion as repeated measures.

Results

Figure 8 presents the pattern of runs in Experiment 2, contrasted with those seen in the Touch condition of Experiment 1. There is a clear effect of Condition, with fewer runs during conjunction trials ($M = 5.3$, SE $= 0.44$) than feature trials ($M = 9.4$, SE $= 0.24$), $F(1,22) = 114.2$, MSE $= 3.5$, $p < 0.001$, $\eta_p^2 = 0.84$. Although it appears that the difference between the two conditions is reduced in Experiment 2, there was no main effect of Experiment, $F(1,22) = 1.3$, MSE $= 8.4$, $p = 0.26$, $BF_{01} = 2.4$, $p(H0|D) = 0.71$. and no Condition × Experiment interaction, $F(1,22) = 1.5$, MSE $= 3.5$, $p = 0.23$, $BF_{01} = 2.2$, $p(H0|D) = 0.69$, although we note that the evidence in favour of these null hypotheses is relatively weak.

There was a main effect of Motion, $F(1,22) = 17.2$, MSE $= 0.9$, $p < 0.001$, $\eta_p^2 = 0.44$, with fewer runs during Static trials ($M = 6.9$, SE $= 0.32$) than Dynamic trials ($M = 7.7$, SE $= 0.30$) and a Motion × Condition interaction, $F(1,22) = 10.5$, MSE $= 1.3$, $p < 0.01$, $\eta_p^2 = 0.32$. This latter effect reflects the fact the reduction in runs during Conjunction conditions was less pronounced during Dynamic blocks than Static blocks. There were neither a Motion × Experiment interaction, $F(1,22) = 0.83$, MSE $= 0.9$, $p = 0.37$, $\eta_p^2 = 0.04$, $BF_{01} = 3.1$, $p(H0|D) = 0.76$ nor a Motion × Experiment × Condition interaction, $F(1,22) = 1.1$, MSE $= 1.3$, $p = 0.31$, $\eta_p^2 = 0.05$, $BF_{01} = 2.0$, $p(H0|D) = 0.73$, although evidence for the null hypothesis in this latter case was relatively weak.

Figure 9 summarizes the pattern of runs for individual observers in Experiment 2, and the corresponding conditions from Experiment 1. The tendency to use fewer runs during Conjunction conditions does appear to be slightly more pronounced in the Static blocks of Experiment 2, than in Experiment 1, although there is clearly still considerable variation. The overall increase in Conjunction runs during Dynamic trials appears to be very consistent across participants.

Figure 10 compares completion times, error rates and total distance moved for Experiment 1 and Experiment 2. The pattern of completion times exactly mirrors that found with the pattern of runs. There was a main effect of Condition, $F(1,22) = 39.7$, MSE $= 1.63$, $p < 0.001$, $\eta_p^2 = 0.64$, with faster responses during Feature blocks ($M = 14.3$ s, SE $= 0.45$) than Conjunction blocks ($M = 15.9$ s, SE $= 0.47$). There was also a main effect of Motion, $F(1,22) = 295.4$, MSE $= 6.3$, $p < 0.001$, $\eta_p^2 = 0.93$, and a Motion × Condition interaction, $F(1,22) = 4.8$, MSE $= 0.8$, $p < 0.05$, $\eta_p^2 = 0.18$. Participants were very consistently slower in Dynamic ($M = 19.5$ s, SE $= 0.6$) than Static ($M = 10.7$ s, SE $= 0.39$) trials, with this Feature/Conjunction difference being amplified when targets were in motion. No other effects were significant, although the Experiment × Condition ($BF_{01} = 1.9$, $p(H0|D) = 0.65$) and Experiment × Motion ($BF_{01} = 1.7$, $p(H0|D) = 0.63$) interactions did not provide strong evidence in favour of the null hypothesis (see Supplementary Table 1).

For the distance data, there was a main effect of Condition, $F(1,22) = 222.4$, MSE $= 106209$, $p < 0.001$, $\eta_p^2 = 0.91$, with less distance travelled during Feature blocks ($M = 4061$ pixels, SE $= 49$) than Conjunction blocks ($M = 4744$ pixels, SE $= 70$). There was also a main effect of Motion, $F(1,22) = 150.3$, MSE $= 122985$, $p < 0.001$, $\eta_p^2 = 0.87$, with greater distances travelled in Dynamic ($M = 4841$ pixels, SE $= 54$) than in Static ($M = 3964$ pixels, SE $= 77$) trials. In contrast to the pattern of runs and completion times, there was no Motion × Condition interaction, although we note that evidence in favour of the null hypothesis was very weak, $F(1,22) = 3.1$, MSE $= 30806$, $p = 0.09$, $\eta_p^2 = 0.12$, $BF_{01} = 1.0$, $p(H0|D) = 0.51$. There was no main effect of Experiment, $F(1,22) = 1.4$, MSE $= 298656$, $p = 0.2$, $\eta_p^2 = 0.06$, $BF_{01} = 2.3$, $p(H0|D) = 0.70$ and no Experiment × Condition interaction, $F(1,22) = 2.1$, MSE $= 50298$, $p = 0.16$, $\eta_p^2 = 0.09$, $BF_{01} = 1.6$, $p(H0|D) = 0.62$. There is a hint of a distance cost for Experiment 2 visible in Figure 10 that seems more pronounced in the Feature conditions. Again, however, we note that evidence in favour of the null hypotheses for these two effects was relatively weak. No other effects were significant.

Finally, in terms of errors, the only significant effect was a main effect of Motion, $F(1,22) = 57.0$, MSE $= 0.3$,

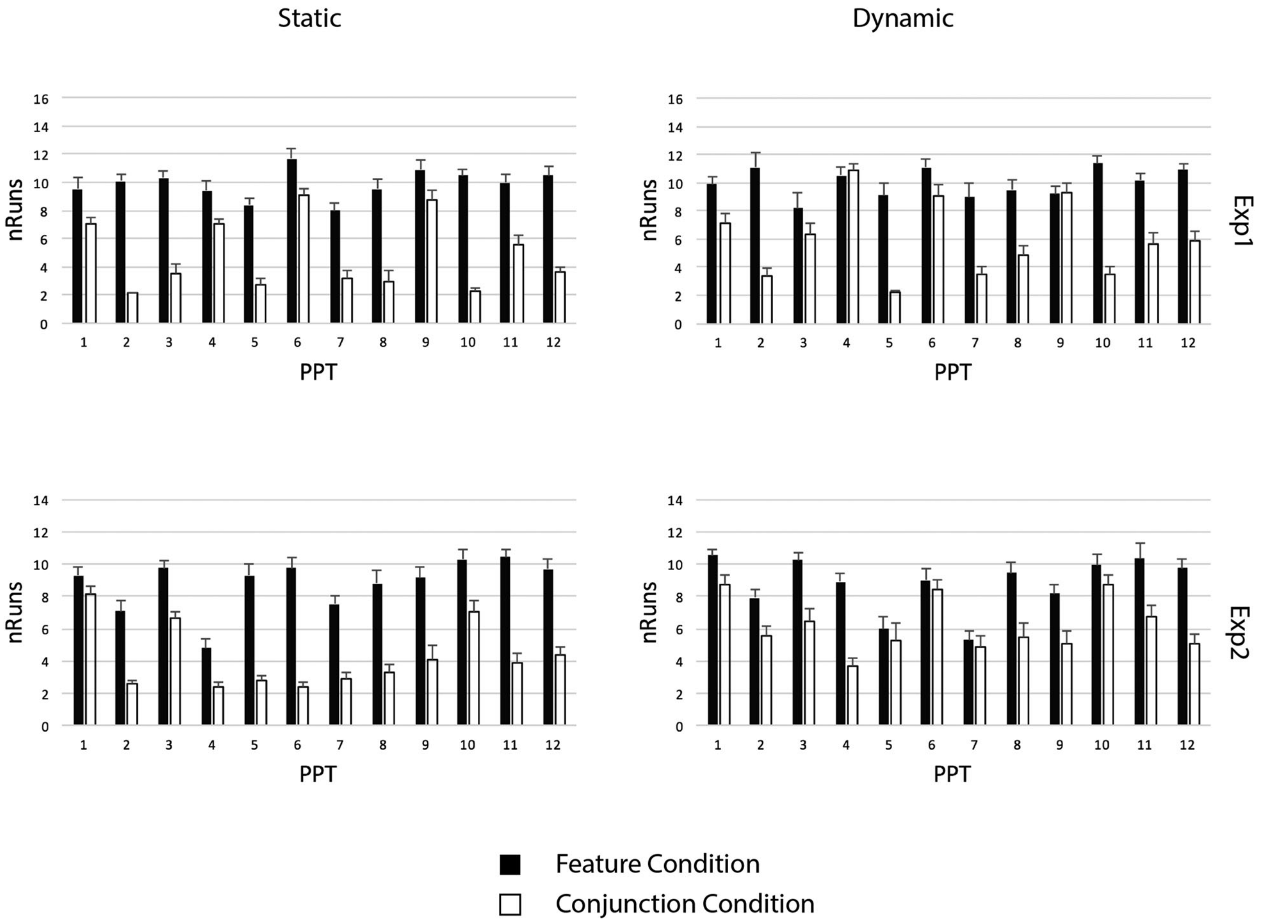

Figure 9. Number of runs per participant in the Static (left column) and Dynamic (right column) blocks of trials. Top row shows data from the Touch condition of Experiment 1, bottom row the data from Experiment 2. Solid bars are Feature condition, open bars Conjunction condition. Error bars represent standard error of the mean.

$p < 0.001$, $\eta_p^2 = 0.72$, with more errors per trial during Dynamic ($M = 0.91$, SE = 0.11) than Static ($M = 0.07$, SE = 0.02) trials. There was a marginal Experiment × Motion interaction, $F(1,22) = 3.6$, MSE = 0.3, $p = 0.07$, $\eta_p^2 = 0.14$, which reflects the pattern seen in Figure 10, where slightly greater Static errors for Experiment 2 give rise to a considerable reduction during Dynamic trials. Coupled with the trend seen in the completion time data, this suggests a tendency for participants to slow their foraging down under the harsher feedback regime of Experiment 2, thus reducing errors, a classic speed/accuracy trade-off. Again, though, none of these trends reached significance. While there were no other significant effects, we note that for the main effect Experiment ($BF_{01} = 1.2$, $p(H0|D) = 0.55$), as well as the Motion × Condition interaction ($BF_{01} = 2.72$, $p(H0|D) = 0.73$), and the Experiment × Motion × Condition interaction ($BF_{01} = 2.72$, $p(H0|D) = 0.73$), there was only weak evidence in favour of the null hypotheses.

Discussion

The goal of Experiment 2 was to determine whether the reintroduction of terminal error feedback would lead to major changes in patterns of foraging. This does not appear to have been the case. In particular, comparison of the run patterns in Figure 8 suggests that the feedback regime is unlikely to have been the main reason for the lack of exhaustive runs, as there is little modulation across experiment. Furthermore, when directly comparing run behaviour with the comparable condition of Experiment 1, there were no significant main effects or interactions involving the factor Experiment. Before concluding that error feedback has no influence on patterns of runs, however, additional studies with more sensitive within-subjects designs are probably warranted, as several of the null-effects relating to the factor Experiment received only weak support in our Bayes Factor analyses.

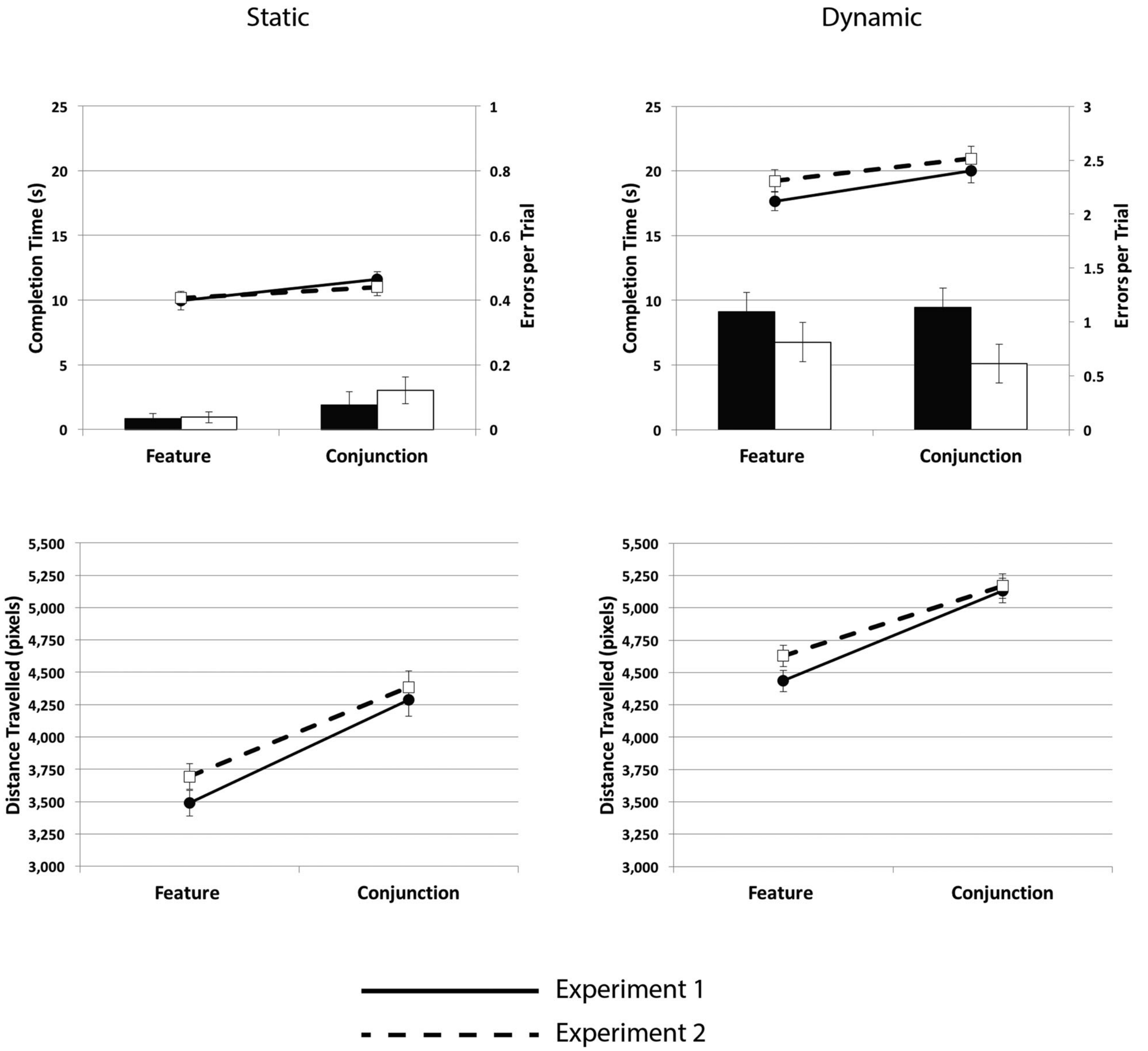

Figure 10. Average completion times, error counts and distance travelled for the Touch phase of Experiments 1 (solid lines/bars) and Experiment 2 (dashed lines/open bars). Static (top panel) and Dynamic (bottom panel) conditions are shown as a function of the Feature/Conjunction manipulation. Error bars represent standard error of the mean.

Turning to the other dependent measures, during dynamic blocks, participants in Experiment 2 did appear to use a more conservative response strategy, slowing down and moving further, resulting in fewer errors. The additional cost of making an error in Experiment 2 – having to restart the trial – clearly made participants keen to avoid this, and they appear to have used a classic speed-accuracy tradeoff to accomplish this. Again, though, this was not reflected in the pattern of runs.

One interesting pattern that did emerge by isolating the Touchscreen modality, was the clear impact of display dynamics. As can be seen in Figures 8 and 9, when targets are in motion in the conjunction condition, there is a greater tendency to switch between target categories, relative to the static condition. There are at least two possible explanations for this pattern. First, as the items are in motion, top-down strategic planning, for example, the decision to cancel targets from one category, may be interrupted when a target from the other category moves into the effective field of action. Second, as we discuss in more detail below, the consistent increase in the number of runs during dynamic conjunction foraging could simply reflect the influence of response speed. Participants are forced to slow down due to the additional demands of accurately selecting moving targets, and the additional inter-target response time makes it easier to switch search templates.

General discussion

In two experiments, we explored the impact of selection modality, display dynamics and error feedback on patterns of human foraging in a simple cancelation task. Replicating our previous work using iPad apps, we found that participants appeared to use random category selection when targets were defined by a single feature (i.e., colour), but consistently fewer runs when targets were defined by the conjunction of colour and shape (Jóhannesson, Kristjánsson et al., 2017; Jóhannesson, Thornton et al., 2016; Á. Kristjánsson et al., 2014). However, in contrast to our previous work, we did not find that the majority of participants used an exhaustive selection strategy during conjunction foraging, selecting all targets from one category before the other. Rather, there was a broader spectrum of individual differences in response to the increased demands of conjunction foraging. Overall, the impact of selection modality and display dynamics appeared to be minimal and indirect, both affecting the speed of responses, which in turn may have constrained the pattern of run behaviour. Error feedback did not directly affect performance, with no significant differences between Experiment 1, which did not provide feedback, and Experiment 2, which used the same "trial-termination" feedback used in our iPad studies. However, as we noted in Experiment 2, further exploration of this latter finding is recommended before firm conclusions can be reached about the role error feedback.

There appear to be two major implications from this set of findings. First, the "attentional constraints" we had identified in our previous work do not appear to depend solely on the complexity of the target items i.e., the need to combine more than one feature. Rather, there appear to be important, task-specific, time constraints that modulate whether switching between complex target templates is a preferred or non-preferred strategy. Second, it appears that we need to modify our conception of "individual differences" in these tasks to reflect the fact a given participant may adapt their preferred category selection pattern depending on overall task demands. We discuss each of these implications in turn.

As we have already noted, in our previous 3D foraging study (Prpic et al., 2019), given several seconds in which to choose the next target, all participants randomly switch between conjunction target categories. In the current experiments, there was a less extreme increase in response times than seen in the 3D study. Nevertheless, the time between consecutive selection episodes essentially doubled relative to the original iPad data. Our suggestion is that this more moderate *foraging tempo* increases the likelihood that participants will switch during Conjunction trials. There was still clearly a reduction in switching relative to Feature trials, but the slower pace seems to have eliminated the tendency to use exhaustive category selection.

In addition to the Squirrel foraging data already mentioned (Prpic et al., 2019), two other studies from our group also appear to support a link between response speed and category selection. Jóhannesson et al. (2016) had the same observers complete our standard iPad task as well as a version of the task where participants cancelled items with the aid of an eye tracker. During such *gaze-foraging*, fixating targets presented on a standard computer monitor – and maintaining fixation for 100 ms – would directly cancel them. One of the main findings was that category switching during conjunction conditions was much more prevalent during *gaze-foraging*, than during the traditional *finger-foraging*. We initially suggested that such differences might relate to eye gaze being a more basic, less complex behaviour than finger movements (e.g., Jóhannesson, Ásgeirsson, & Kristjánsson, 2012; Leigh & Zee, 2015). From this perspective, the lower demands of controlling the eyes might free resources that could aid in category switching. However, it is also the case that the need for a 100 ms stable fixation period in order to cancel items in the eye gaze version of the task, appears to have reduced the *foraging tempo*. Similar to our previous iPad studies, average *finger-foraging* speed was approximately 375 ms/item, whereas in the *gaze-foraging* task it was substantially slower at approximately 563 ms/item. Thus, the higher prevalence of switching during *gaze-foraging* conjunction trials could have been caused by an overall slowing of *foraging tempo*.

In another series of studies, we have modified the classic "Space Invaders" game, to create a task in which rows of 4 items (two targets, two distractors), move down the screen at a fixed pace towards a selection zone. We call this task "Choice Invaders". In our initial studies with this task, a new row of items reached the selection zone – and thus required a response – once every second. At this fixed, relatively slow tempo, category selection was always completely random, regardless of whether targets were distinguished by a single feature or a conjunction of features (Thornton, Jóhannesson, & Kristjánsson, 2015).

Aside from the work of our own group, two other recent papers provide data that also appear to support the notion that *foraging tempo* might modulate patterns of selection. In a very elegant series of studies – which we discuss further below – Wolfe et al. (2019) explore a number of factors that affect "hybrid foraging search", the term they use to describe the current foraging paradigms (Wolfe et al., 2016). Experiment 1 of Wolfe et al. (2019), was specifically designed as a close replication of Kristjánsson et al. (2014), with the following main modifications: (i) stimuli were presented on a regular (touchscreen) monitor; (ii) all items were always in motion; and (iii) there was no requirement to select all target items on a given screen. This latter modification allowed participants to freely move to the next display as soon as the number of available targets reduced to some level.

Consistent with our previous findings, while participants selected randomly from the two available target categories during Feature trials, the number of runs during Conjunction trials was significantly lower than would be expected by chance. Importantly, and mirroring the findings of Experiments 1 & 2 of the current work, there was little evidence of exhaustive run behaviour. More precisely, Wolfe et al. (2019)'s Feature displays contained an average of 25.5 targets, and participants used approximately 9 runs on average before moving to the next display. Their Conjunction displays contained on average 24.5 targets, and participants used an average of 5.6 runs. These figures are very similar to the dynamic patterns seen in the current work, see for example Figure 8, lower panels.

Wolfe et al. (2019) attribute the lack of exhaustive runs to the fact that participants were not required to find every target in a display before moving to the next (modification iii above). However, this would not appear to be the critical factor. In the current work, we maintained the requirement to cancel all targets, as we had done in the original iPad studies, and also did not see exhaustive runs. Rather, examination of their Figure 3, suggests that the *foraging tempo* was considerably slower than in the iPad version of the task. For example, even at the very smallest effective sets sizes, Conjunction trial reaction times are well above 500 ms for successive items.

In another paper, Clarke, Irons, James, Leber, and Hunt (2018) included a computer-based, mouse-click version of our iPad task as part of a study of individual strategy differences within and between visual search tasks. Their main finding was that individual differences were stable over repetitions of the same task, but did not generalize across tasks. In terms of the replication of our task, they found a very similar pattern, with many short runs during Feature trials and fewer, longer runs during Conjunction trials. As their raw data was included as supplementary materials, we also looked at individual foraging patterns and the speed of responses. Consistent with the findings in Experiments 1 & 2 of the current work (Figures 4 and 9), their sample contained a number of individuals who appeared to use exhaustive or near-exhaustive (<5) runs during Conjunction trials. However, these accounted for less than a third of participants, not the 75% majority we had seen in our previous iPad studies. In line with the role of *foraging tempo* we are proposing here, average response rates were much slower than in the iPad task, at approximately 745 ms/item, quite comparable to what we found in the current experiments.

Returning to the Wolfe et al. (2019) paper, the authors identify two important factors that they believe help determine when foraging behaviour is likely to proceed in extended runs. First, perceptual priming from the immediately preceding selection may bias the next one to the same target type (see also; Á. Kristjánsson & Ásgeirsson, 2019). Second, the desire to avoid "switching" costs – that might arise, for example, from having to replace one conjunction target with another – can cause repeated selection of the same target. These points align well with our own previous findings and conclusions (Á. Kristjánsson et al., 2014; T. Kristjánsson & Kristjánsson, 2018; T. Kristjánsson et al., 2018). Knowing these factors, Wolfe et al. (2019) continue, may help us predict what a searcher will do next at any point during a foraging episode, and more importantly, may help us understand why targets are sometimes missed.

Based on the current findings, and the preceding discussion, we think it might be appropriate to add a third factor that clearly modifies the tendency to use long runs when repeated responses are required in a multiple target scenario. That is, it seems crucial to be aware of the general *foraging tempo* afforded by a given task. If that tempo is too slow, and the interval between typical successive collection episodes exceeds some critical time window, participants are likely to switch at random, even during conjunction conditions. If the *foraging tempo* is close to the maximum pace where correct responses are still possible, the prevalence of long runs will increase, and switching will be avoided, possible only occurring once during a trial.

Our emphasis here is intentionally on how the overall pace of responding may vary between foraging tasks/conditions, rather than on individual differences in response time within a task. This is not to say that such individual variation is uninformative. Indeed, in our original iPad study, those "super-foragers" who continued to switch during conjunction conditions did have consistently slower response (Figure 3(d); Á. Kristjánsson et al., 2014). Thus, they were "super" only in the sense that their pattern of runs was unaffected by an attentional manipulation (Watson & Strayer, 2010), not because they were overall better at performing the task.

Furthermore, it is important to realize that in all of the studies discussed above, the overall *foraging tempo* was only indirectly imposed and/or manipulated. In fact, to a large extent, the precise speed of responding would have been determined by individual participants, as a reaction to particular task demands. Participants were encouraged to respond quickly, but to our knowledge, were not penalized if they did not. The maximum *foraging tempo* can obviously be expected to be strongly influenced by the particular tasks demands and selection methods, as already discussed. Our speculation is that the lower limit, whether a participant has a predisposition for *allegro* or *largo* responding, perhaps, will also prove to be a major factor in explaining individual differences in these tasks. We return to the topic of individual differences shortly.

A final word on the idea of a "foraging tempo". While our focus here has been on the rate of responding, perhaps the more basic insight is that in multiple target scenarios, participants do seem to prefer using regular response patterns. Elsewhere, we have documented this tendency, and noted how the majority of responses occur at very regular intervals, something we previously termed the "cruise phase" of a foraging trial (T. Kristjánsson et al., 2018). Further exploring the nature of *foraging tempo*, how it interacts with other aspects of attentional control in a given individual, as well as more directly manipulating the temporal window within which responses must be made, all seem like very useful future directions, and these issues are the focus of our ongoing work in this area.

We now return to the second main implication of the current work: individual differences. As already mentioned, in our previous iPad studies, we had found that close to 75% of participants changed from random category selection in Feature trials to an exhaustive 2-run strategy in Conjunction trials, while the remaining 25%, labelled "super-foragers", used random category selection in both conditions. As indicated in Figure 5, in the current tasks, behaviour was much more variable. Rather than only falling into two "extreme" behaviours, here different participants display a range of strategies. Furthermore, it is clear that some participants change their strategy according to the task demands. For example, Figure 6 shows that very few participants used a strategy involving runs with <5 items when using the Mouse or Tracker interfaces, but that this changed when using the Touchscreen. Similarly, the Touchscreen data from Experiments 1 & 2 (Figures 8 and 9) clearly shows differences in switching during Dynamic trials and Static trials. For example, consider participants 5 & 6 from Experiment 2 in Figure 9.

In other studies from our group, we have also seen this sort of within-participant flexibility in terms of run strategy. For example, the finger-foraging versus gaze-foraging study mentioned above showed clear differences in foraging patterns in the same participants as a function of response modality (Jóhannesson et al., 2016). In another study (T. Kristjánsson et al., 2018), we varied the amount of time participants were given to complete individual foraging trials (e.g., 5 s, 10 s or 15 s). Although quite a subtle effect, participants tended to switch more frequently in conjunction foraging as the overall duration was reduced, and their switch costs were much lower with the short time limits. We speculated that limiting overall foraging time in this way encouraged the use of short bursts of concentration, that would be too effortful if maintained throughout the whole duration of a normal forging trial. Indeed, going back to our original iPad experiment, a pattern that was clear in the trial-by-trial plots of individual participants (Á. Kristjánsson et al., 2014; Figure 4) were occasional conjunction trials in which a participant would swap from exhaustive foraging to switching quite frequently. Such trials were quite rare for these individuals, and again we speculated that they might represent an attempt to switch between conjunction categories that proved too effortful to maintain.

What we take from the above discussion is that rather than trying to uncover fixed individual foraging patterns – patterns that might directly reflect some general cognitive limitation or foraging trait (Jóhannesson et al., 2017) – we should acknowledge that participants are able to flexibly adapt their strategies in response to ongoing task demands. Our suggestion is that we need first to come to a better understanding of all the variables that define these task demands (e.g., the interplay between priming, switch costs and *foraging tempo*), and only then are we likely to fully understand the role of how individual differences might mediate responses to these demands.

Turning to other aspects of the current data, the fact that the presence or absence of terminal error feedback had little effect on foraging patterns was somewhat surprising. Our intuition was that the fear of making such a costly error would encourage the use of exhaustive runs. This was clearly not the case. Although there appeared to be a trend for fewer overall runs in Experiment 2, where terminal feedback was provided, there were no significant differences to the run patterns found in Experiment 1, where terminal feedback was absent. From a practical point of view, this is very useful information, as participants often find this sort of feedback quite frustrating, particularly in Dynamic trials, where selection errors could often reflect motor limitations, rather than category selection mistakes. If it has no measureable effect on foraging patterns, we can certainly remove it from future designs.

There were clear differences between foraging patterns in Static and Dynamic blocks of trials. The tendency to switch categories typically increased during Conjunction trials when the targets were in motion. As already noted, this could be a side effect of a slower overall *foraging tempo* during these phases of the task. Another possibility is that predictable layout of Static displays encourages anticipatory behaviour, where participants search ahead for future targets as they plan and execute the response to the current target. This may not simply reflect conscious planning strategies, but rather, the stability may also aid perceptual priming mechanisms, fostering the use of runs. While such planning ahead occurs to a limited extent even in dynamic displays (e.g., Wolfe et al., 2019), it is likely to play an even larger role in static displays. Indeed, we have previously shown that in static displays, blocking the ability to plan ahead by "shuffling" future locations has measureable effects even as far ahead as 4 items in a sequence (Thornton & Horowitz, 2004). It may be interesting to further explore the consequences of such planning in the context of foraging, rather than just eliminating it by using dynamic displays.

Similarly, it is well known that participants tend to adopt specific "reading" strategies when searching through static displays, with some preferring to scan top to bottom, others from left to right (Woods et al., 2013). Previously, with our iPad task, we have found that the tendency to use such search organization varied as a function of foraging condition. Participants tended to use structured responding during feature conditions, but less organized foraging during conjunction trials (Jóhannesson et al., 2016). Again, while it may sometimes be desirable to eliminate these search strategies by using dynamic displays, they may be of interest in and of themselves, they might interact in interesting ways with other task demands and they might help uncover more general individual differences.

The choice of using static or dynamic displays, then, may well depend on particular research goals. We note that the differences in foraging behaviour observed in the current experiments appeared quite moderate and were quantitative (slightly more switching in dynamic trials) rather than qualitative in nature. From an ecological validity point of view, we probably spend more real-world time searching for targets that don't change position. As methodologically it may also be easier to implement and present static displays, and to elicit fast, accurate responses, there are clearly a number of factors that encourage the continued use of static foraging arrays.

Finally, we return to the issue of selection modality. While we were able to measure clear differences in both subjective and objective usability – and show that these probably impacted our time and distance measures – there was only a modest impact on foraging behaviour, and not in the direction we had predicted. For example, rather than increasing the tendency to use extended run behaviour, the novel, and somewhat difficult to use, hand tracker gave rise to very similar patterns as the familiar mouse interface, with both leading to more conjunction category switches than the touch interface.

As already noted, our speculation is that the modest reduction in switching behaviour when directly touching the targets probably comes about via an overall increase in *foraging tempo,* itself made possible by the more direct/fluent interface. We should note that Wolfe et al. (2019) had different groups of participants complete one of their tasks (Exp.2) either with a touchscreen or a mouse-click interface. They report "no broad differences" between the groups, although interestingly there was a (non-significant) trend for the mouse group to respond more quickly, contrary to what we found in the current Exp.1. The between-participant design, and modest speed differences in their study may well have masked the sort of tempo effects we report here. To date, then, the most compelling difference in foraging patterns as a function of selection modality remains the one in Jóhannesson et al. (2016) discussed above, comparing finger-foraging to gaze-foraging. Here again, the slower modality led to an increase in conjunction switches, although factors other than *foraging tempo* may clearly have also influenced this pattern. Overall then, the direct influence of selection modality appears to be modest at best, and our main suggestion for future studies is to pay close attention to task demands that may influence the overall *foraging tempo*.

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