A serious game to explore human foraging in a 3D environment

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Abstract

Traditional search tasks have taught us much about vision and attention. Recently, several groups have begun to use multiple-target search to explore more complex and temporally extended "foraging" behaviour. Many of these new foraging tasks, however, maintain the simplified 2D displays and response demands associated with traditional, single-target visual search. In this respect, they may fail to capture important aspects of real-world search or foraging behaviour. In the current paper, we present a serious game for mobile platforms in which human participants play the role of an animal foraging for food in a simulated 3D environment. Game settings can be adjusted, so that, for example, custom target and distractor items can be uploaded, and task parameters, such as the number of target categories or target/distractor ratio are all easy to modify. We demonstrate how the app can be used to address specific research questions by conducting two human foraging experiments. Our results indicate that in this 3D environment, a standard feature/conjunction manipulation does not lead to a reduction in foraging runs, as it is known to do in simple, 2D foraging tasks. Differences in foraging behaviour are discussed in terms of environment structure, task demands and attentional constraints.

Introduction

When humans or animals explore an environment, their behavior is guided by a variety of factors. These may include internal goals (e.g., hunger, arousal), internal constraints (e.g. memory capacity, available attentional resources), or external aspects of the scene, such as overall lighting conditions or salient visual features. Traditionally, two largely separate disciplines have been used to explore these factors. In humans, “visual search” studies typically use simplified displays in which a single target item is presented in the context of a varying number of distractor items. (Treisman & Gelade, 1980; Wolfe, 2010; Wolfe & Horowitz, 2004, 2017). In other species, more complex “foraging” behavior has been studied -- often involving rich environments, extended search episodes and multiple target items -- using a variety of paradigms both in the laboratory and in the wild (Dawkins, 1971; Heinrich, Mudge, & Deringis, 1977; Jackson & Li, 2004; Pietrewicz & Kamil, 1979; Tinbergen, 1960).

The purpose of the current paper is to introduce a new research tool in the form of a serious game that incorporates aspects of both traditional visual search and animal foraging paradigms. Specifically, we have developed a serious game for mobile platforms, in which human participants play the role of an animal foraging for food in a simulated 3D environment. Figure 1A shows the title screen of the game and Figure 1B a snapshot from a typical game scene, while in Movie S1 it is possible to see the game in action. The game environment can be easily adapted by the researcher. For example, the identity of target items can be fully customized, and task parameters, such as target/distractor ratio, number of trials and trial duration are all easily modified (Figure 2). Data relating to a wide range of foraging behavior is directly recorded on the device and can easily be accessed in standard text format.

In the following sections, we provide background information on serious games and the specific research questions that prompted us to develop the current tool. We then provide a detailed description of the app and present data from two initial experiments where we used it to ask a specific question about human foraging. We conclude with a discussion of our findings and suggestions for future studies and possible modifications of the app.

Serious Games

The term “serious games” refers to full-fledged games with a purpose other than entertainment (Michael & Chen, 2005). This sets them apart from regular games, whose primary purpose is entertainment, and from gamification, which refers to the use of game elements in non-gaming contexts (Deterding, Dixon, Khaled, & Nacke, 2011). Serious games leverage the positive effects of videogames, such as entertainment value and high levels of engagement, in order to achieve a secondary objective (e.g. learning or training). Common applications of serious games can be seen in domains of education (Connolly, Boyle, MacArthur, Hainey, & Boyle, 2012), marketing (Bogost, 2007), health (Graafland, Schraagen, & Schijven, 2012), and the military (Crookall, 2010).

Another increasingly common use of serious games is within various academic disciplines, most notably within psychology (Boot, 2015; Washburn, 2003). Here, games -- particularly when used in tandem with mobile devices (Miller, 2012) -- are thought to have great potential as research tools (Dufau et al., 2011; Killingsworth & Gilbert, 2010; Mitroff & Biggs, 2014). Serious games are appealing as tools for studying human behavior as they are more motivating to engage with than standard experiment tasks and allow for real-time data collection of a wide variety of in-game behavior (Järvelä, Ekman, Kivikangas, & Ravaja, 2014). They can also be used to simulate situations that are physically difficult or even impossible to study, and to provide safe, virtual scenarios that could be deemed unethical when studied in reality.

Background

In our previous work (Á. Kristjánsson, Jóhannesson, & Thornton, 2014), we have already explored the use of simple, 2D games as a way to move beyond traditional studies of visual search. Classic visual search studies have taught us a great deal about vision and attention (Hulleman & Olivers, 2017; Treisman & Gelade, 1980; Wolfe, 2004; Wolfe & Horowitz, 2004, 2017). However, these tasks typically involve only a single target, and search ends once the target has been found or observers decide that no target is present. Search behavior in the real-world is often more complex than this, for example, involving multiple target episodes with less clearly defined end states. Traditional studies, with their limited selection scenarios, may therefore offer only a limited picture of attentional selection in the wider environment.

To address these concerns, a number of labs have sought inspiration from the animal literature mentioned above and have begun to investigate how humans “forage” for multiple targets (Cain, Vul, Clark, & Mitroff, 2012; Fougnie, Cormiea, Zhang, Alvarez, & Wolfe, 2015; Gilchrist, North, & Hood, 2001; Hills, Jones, & Todd, 2012; Hills, Kalff, & Wiener, 2013; Klein & MacInnes, 1999; Á. Kristjánsson et al., 2014; Pellicano et al., 2011; Wolfe, 2013). Overall, the findings seem consistent with the idea that there is a common evolutionary thread that links the foraging behavior of humans and animals in complex scenarios. For example, a number of key findings from the animal literature have been found to have parallels in human behavior, including search in extended “runs” (Á. Kristjánsson et al., 2014), Lèvy flights (Hills et al., 2013), the predictions of Marginal Value Theorem (Wolfe, 2013) and “area-restricted search” (Kalff, Hills, & Wiener, 2010).

Our own interest in this area was stimulated by the classic laboratory study of (Dawkins, 1971). She demonstrated that when feeding, chicks often selected the same type of food item in long “runs”, rather than selecting at random from two available categories. A “run” simply refers to a sequence of selections from the same target category. In general, when there are many short runs, this suggests that an animal is selecting at random. Fewer, longer runs, suggest that feeding is being guided in some way. Tinbergen (1960) had previously noted the tendency towards long-run behavior in wild-feeding birds, leading him to postulate that their behavior was being guided by some form of internal “search-image” (see Nakayama, Maljkovic, & Kristjánsson, 2004 for discussion). Later work suggested that reliance on such templates might increase when preys were cryptic or attentional demands increased for other reasons, such as fear of predation (Bond, 1983; Dukas, 2002; Dukas & Ellner, 1993; Kamil & Bond, 2006).

The 2D foraging game we created for humans conceptually replicated the study of Dawkins (1971). As can be seen in Figure 3, we did this by presenting multiple target stimuli on an iPad (Á. Kristjánsson et al., 2014). Observers were required to tap on target dots from two categories (e.g., red and green dots) while ignoring stimuli from distractor categories (e.g. blue & yellow dots). Tapping on a target made it disappear, and the task was to forage until all targets had been cancelled. Participants found the task engaging and intuitive, and typically completed a trial (i.e. cancelling all 40 targets) in well under 20 seconds.

During feature-based foraging (Figure 3A), where the two target categories differed from the two distractor categories only in terms of a single feature (i.e. colour), participants switched randomly between target types. This gave rise to many short runs, suggesting random selection from the two target categories (black bars, Figure 3C). The pattern was very different during conjunction-based foraging (Figure 3B) where the attentional load was increased as targets differed from distractors in terms of two features (Treisman & Gelade, 1980). For example, the targets could be red squares and green dots, while the distractors were green squares and red dots, or vice versa. In this case, the majority of participants foraged using far fewer runs, repeatedly selecting for the same target category, rather than switching between categories (white bars, Figure 3C). This indicates that they had trouble using more than one conjunction template to guide their selection. Thus, with a simple, game-like task, we were able to provide the first demonstration of extensive run-like behavior in humans, suggesting that human foraging may be constrained by attention in the same way as it is with animals (Dukas, 2002; Dukas & Ellner, 1993).

Motivation for current work

While the simple feature-conjunction manipulation we used in our 2D game had quite a dramatic effect on foraging behavior, the nature of the task itself clearly differs in many respects from foraging behavior that might take place in the wild. The general motivation for the current work was to try and eliminate some of these differences. Staying within the context of game-based studies in the lab, the two main manipulations we introduced in the current work concerned the overall spatial layout of the search environment, and the time interval between successive target selections. In our 2D game, participants had a global view of all targets and distractors at all times and made selections approximately twice a second. As described in the next section, our 3D game aimed to more closely simulate the visual experience of a foraging animal by presenting a complex environment within which food items were quite sparsely distributed. This ensured that only a subset of items would be visible from a given position and that it would take several seconds to move between items. Our research question was therefore whether the conjunction manipulation would continue to strongly modulate performance under these conditions, as it had in our 2D game.

App Details

The serious game that was developed is a single-player tablet game for iOS called “Squirrel Away”, using the freely available game engine Unity3D. Based on the 2D task described earlier, we took the same “foraging” concept and applied it to a 3-dimensional, virtual environment. Since navigation of a 3D environment tends to be challenging for people who are inexperienced with videogames or other 3D software, making the game accessible was a key concern during the design. The way we approached this was through the use of simple to understand, straight-forward game mechanics and flexible control options.

In the game, the player takes on the role of a squirrel gathering food for its family. The player controls the squirrel from a first-person perspective and explores a park where ‘target’ and ‘distractor’ objects are spread across the environment. The default mode for the game has players on a two-minute timer in which they try to gather as many of the target objects as possible. Objects are collected upon collision, meaning players simply run into the objects to collect them. Collecting target objects grants points, while distractor objects temporarily restrain the player and negatively impact the score by resetting it to zero.

The game utilizes simple mechanics of points and time-constraints that are reminiscent of older-style ‘arcade’ videogames. In order to emphasize the exploratory aspects of the game, we created an interesting game-play experience by giving players the perspective of a small animal exploring a large environment. This was done through the scale and design of the virtual environment, the positioning of the camera and its field of view, the player’s movement speed, and the use of sound effects. The park environment simulated a 20 x 20 meter space, and speed of movement was constrained to be no higher than 0.7 meters/second.

We developed two control types for this game. The first involved an on-screen virtual joystick on the bottom right of the screen. This mimics a standard video game controller and control schemes found in commercial tablet-based 3D games. The second control type was motion-based, and involved the use of the tablet’s gyroscope to orient the first-person camera to where the player points the device. In this sense, it works as if one would take a picture using the tablet's camera, but instead of looking at real-life surroundings, the camera looks into the virtual environment instead. In practice, this has the player physically turning full circle to turn around in the game, as well as point the tablet up and down to look above or below in the game environment. We have found that participants find this method of control to be more intuitive, as it mimics the use of the camera that they are familiar with from their own devices. The only other control in the game is the ‘move’ button, which is located at the bottom left of the screen. By holding the button pressed the player will move forward in the direction the camera is facing. Releasing the button will make the player stop moving.

Besides choosing which controls to use, the game features a menu that allows the customization of several features. On the title page the researcher can change the game level from day to night; when playing at night the player’s vision will be limited due to low lighting levels. This also changes the music and sounds in the game. When going into the settings menu, the researcher can put in a subject ID for data logging purposes, as well as a seed number that controls the randomization of the collectible items (i.e. putting in the same number will result in the same random distribution between experiments). Other options include the length of a game session (with the default of two minutes), the amount of times the player will play a game session before returning to the main menu (i.e. game ‘loops’), the ratio of target to distractor items, and the target number of items to collect. The target amount is unused when the winning condition is set to ‘Timed’, in which case the player has until the timer runs out to collect as many items as they can. If the win condition is set to ‘Target’ the game ends once the player has collected the required number of items. When the win condition is set to ‘Both’, the game round will end either when the timer runs out or when the player has collected the target amount. The researcher can also load in images (in PNG format) for the target and distractor items, with a maximum of three images per category. These act as ‘billboards’ in the virtual environment, meaning that they are flat pictures that always face the camera. A trick from older videogames, this gives the effect of a 3-dimensional object within the virtual space. Finally, the researcher can turn the music, as well as the data logging capabilities, on or off.

When data logging is turned on, the game will log the key events and player movement to an Excel file on the tablet’s drive. The data that is logged includes: amount and types of items collected (both distractor and target), player position (recorded at 10 Hz), and camera rotation (10 Hz). All data is logged with a time-stamp, which allows the plotting of the route taken by the players, as well as the ability to check the game metrics against other data (e.g. biometric readings).

Experimental Studies

To illustrate how the game can be used as a research tool, we conducted two laboratory-based experiments in which we varied the attentional demands of individual target selection using the same feature/conjunction manipulation used in our original 2D study (Á. Kristjánsson et al., 2014). As already noted, this manipulation consistently led to a very clear change in search strategies, such that participants selected randomly from target categories during feature conditions, yielding short runs of the selection of the same target type, but used long, non-random runs during conjunction conditions. Our current question was whether a similar shift would occur with a task that more closely approximates a real-world environment.

We should be clear that these initial experiments were not designed to provide direct quantitative comparisons with our previous work. It is obvious that a lot of display parameters and task demands separate the two tasks. However, it is clearly a valid question to ask whether the same attentional manipulation, that has such a strong influence in the 2D case, has any influence on search behavior when viewing conditions and time constraints more closely approximate real exploration in a 3D environment.

General Methods

As the two experiments conducted here only differed in two small details, we will note these immediately, and then report the common aspects of the methodology. In Experiment 1, participants were seated and used virtual joysticks to orient themselves in the virtual world. In Experiment 2, they were standing, and used full-body movements to change their viewpoint. This change was made to explore whether the method of interaction affected performance. The second difference concerned the target/distractor ratio. In Experiment 1 there was a 50/50 target/distractor ratio in both feature and conjunction conditions. In Experiment 2, we changed the ratio in the conjunction condition to 30/70 in order to further increase the level of difficulty.

Ethics Statement

All aspects of the experimental procedures were reviewed and approved by the relevant Faculty Research Ethics Committee at the University of Malta and thus conformed to the ethical guidelines set out by the Declaration of Helsinki for testing human participants. All participants gave written informed consent and were paid a previously agreed amount that reflected the standard payment in the department.

Participants

A total of 24 participants took part in the two experiments. In Experiment 1, 12 members of the University of Malta community took part in the study (11 females; 14 right handed; M= 23.1 years, SD =4.5 years, range 19-33). In Experiment 2, a further 12 participants from the same population took part (10 females; 17 right handed; M= 24.9 years, SD =6.6 years; range 18-44 years). All participants reported normal or corrected to normal vision and none took part in both studies.

Equipment

The app was deployed to an iPad 2, which was used for stimulus presentation and data collection. The iPad has a screen dimension of 20 x 15 cm and an effective resolution of 1024 x 768 pixels. An Xcode project was created directly from the Unity 3D game environment and this was compiled to produce the iPad version of the app. The iPad was in landscape mode and it was held with both hands by the participants. Details of the virtual viewing dimensions are given above. In Experiment 1, participants were seated in a sound-attenuated booth with dim illumination. In Experiment 2, they were standing in a screened off area of the lab, again with low background illumination.

Stimuli

In the current experiments Target and Distractor stimuli were food items in keeping with the overall theme of a foraging squirrel. As already noted, custom images of any kind can be loaded as part of the app setup menu. Here, in the feature condition, the targets were red and blue acorns and the distractors were yellow and purple acorns (see Figure 4A). In the conjunction condition, the targets were red walnuts and blue acorns and the distractors were blue walnuts and red acorns.

The stimuli were randomly distributed across the park scene using the grid structure shown in Figure 4B. Note how this “plan view” of the 3D world is conceptually similar to the 2D distribution of target items in our original 2D task (Figure 3). In Experiment 1 there were approximately 200 items and the target/distractor ratio was 50/50, meaning there were equal numbers of each type of stimuli. In Experiment 2, the only change was that the target/distractor ratio was reduced to 30/70 in the conjunction condition.

Task

Participants were asked to play the mobile app game, "Squirrel Away". In this game, participants played the role of a squirrel searching for food in a 3D virtual environment. As described above, the game used a first-person perspective, thus participants experienced the viewpoint of the character as it moved through the park scene.

In Experiment 1, a virtual joystick and a ‘move’ button were displayed at the bottom of the screen to control movement. By keeping the left button pressed the character travelled forward in the 3D environment, by releasing the button the character stopped. The joystick on the right of the screen was used to change direction. In Experiment 2, the joystick was replaced by a motion interface, where direction was controlled by changing body position. Participants were standing with the device and changed the visible part of the scene as they turned to the left or right. Forward motion was controlled with the left button as before.

The goal of the task in both experiments was to collect 30 target items from either target category. The character had to be made to collide with stimuli in order to collect them. When a target was collected, audio feedback was provided and a target counter, displayed centrally at the bottom of the screen, updated the number of collected targets. When a distractor was mistakenly collected, distinctive error audio feedback was provided and the target counter was set back to zero.

Procedure

Both experiments consisted of three parts: a familiarization phase and two testing phases consisting of both feature and conjunction conditions. In the familiarization phase, participants were given the opportunity to experience the environment and the task controls. They were asked to collect 20 feature targets within a time limit of 2 minutes. Both a target counter and a 2 minute countdown were displayed at the bottom of the screen. Participants could take as many attempts as they needed and were allowed to proceed to the next phase of the experiment only when they were able to complete the task.

In the first testing phase, participants completed the feature foraging condition. On each trial they had to collect 30 targets without time limit. There were 5 trials to complete the whole phase. Although there was no explicit time limit, participants were instructed to complete the task as quickly as they could. A timer was displayed at the bottom of the screen and participants were encouraged to use 5 trials to improve their completion time. Accuracy was also stressed in the instructions and participants were aware that by collecting a distractor they would lose all the targets they had collected in the current trial. As a consequence, the time required to complete the trial would be greatly increased. In practice such errors were extremely rare (< 1% of total collection episodes) and our data analysis only focused on the final 30 correct selection episodes in a given trial.

In the second testing phase, participants completed the conjunction condition. As in the previous condition, they had to collect 30 targets to complete a trial. They were given one trial to practice with the new targets, and then completed 5 trials as before. Remaining task instructions were the same as in the previous phase.

Participants were allowed to take a break after every trial and every phase of the experiment. The total time required to complete the experiment varied, but was usually around 40 minutes.

Results

The main dependent variable was the number of target "runs" produced on each trial (Dawkins, 1971; Á. Kristjánsson et al., 2014). As already mentioned, a run refers to a sequence of selections from the same target category. When the number of runs per trial approximates total-targets/2 or greater, this indicates that targets are being selected at random. Fewer runs per trial suggest category-based selection. In addition to the number of runs, we report two other measures that have been shown to vary as a function of the feature/conjunction manipulation: the average inter-target distance (ITD) and the average inter-target time (ITT) (T. Kristjánsson, Thornton, & Kristjánsson, 2018). For all of our dependent variables our analysis was restricted to the final 30 correct collection episodes on each trial. Raw data on these collection episodes for all of the participants in Experiment 1 and 2 are available in File S1 and S2 of the supplementary material, respectively.

In general, participants appeared to explore widely in the virtual space. Movie S2 shows the spatial distribution of each collection episode for every trial in both conditions of Experiment 1. Figure 5A shows how these collection episodes were organized in terms of runs. There are two points to note. First, average runs, collapsed across condition, are very close to what would be expected if selection from the two target categories was random (i.e. 15 runs given 30 target items). Second, it is clear that condition did not influence performance, with the conjunction condition (M = 16.7, SE = 0.3) giving rise to the same number of runs as the feature condition (M = 16.9, SE = 0.29), $t(11) = 0.38$, $p = 0.71$. The same pattern of almost identical feature/conjunction performance was observed with the other dependent variables (see Table 1).

In Experiment 2, we wanted to increase the search-related task demands, to see if the conjunction condition would influence performance. We did this by changing the target/distractor ratio in the conjunction condition from 50/50 in Experiment 1, to 30/70. We were also concerned that some participants had difficulty using the virtual joystick to navigate. If they were having difficulty moving, this may have biased them to always select the nearest item, regardless of the switch cost. We thus replaced the virtual joystick control with a whole-body movement interface, that pilot testing suggested was more user-friendly.

Movie S3 shows the spatial distribution of search episodes in Experiment 2. Figure 5B shows that the target/distractor ratio change had almost no effect on the pattern of run behavior. In fact, participants in the conjunction condition (M = 17.8, SE = 0.44) actually increased their number of runs slightly compared to the feature condition (M = 16.75, SE = 0.33), which still had a 50/50 ratio, $t(11) = -2.56$, $p < .05$. Our prediction, based on previous studies, had suggested that switching would be less common with the added attentional load of conjunction targets.

Figure 6 provides a summary of the spatial and temporal measures in Experiment 2. In Experiment 1, these measures gave rise to very similar performance across the two conditions (Table 1). Here changing the target/distractor ratio appears to have had a clear effect, even if though this manipulation did not affect run behavior. Thus, participants moved further in the conjunction condition, (M = 4.29 m, SE = 0.1) than in the feature condition (M = 2.78 m, SE = 0.07), t(11) = 19.1, p < .001. They also took longer in the conjunction condition, (M = 6671 ms, SE = 384) than in the feature condition (M = 3840 m, SE = 138), t(11) = 8.1, p < .001. More interestingly, if we compare the inter-target times (ITTs) in the feature conditions across the two experiments – which both had 50/50 target/distractor ratios – it appears that the use of the motion interface (M = 3840, SE = 138) gave rise to consistently shorter collection episodes than the virtual joysticks (M = 4597, SE = 188), $t(22)= 3.25$, $p < .01$. Again, our methodological change does appear to have been effective, but there was no difference in run patterns.

Summary & Future Directions

The goal of this paper was to introduce a new research tool that provides a search environment modelled on foraging in the wild. The current app has been optimized to work on iPads. However, having been developed in the Unity game engine, the tool could easily be modified for deployment on other hardware (e.g., Android tablets). An important feature of the app is that it provides customizable settings for flexible use. In addition to changing experimental parameters (i.e. number and duration of trials), both target and distractor items are fully customizable and the researcher can load any image to appear in the virtual environment. During the game, the app automatically records a complete dataset of player behavior, providing information regarding the use of space, temporal dynamics and items collected. While we developed the task to examine attentional constraints during human foraging, the flexibility of the app means that it could be used to address a wide range of other questions. For example, the ability to load any type of image makes it easy to explore the tendency to approach or avoid certain categories of objects, a question that may be of interest to researchers studying phobias or addiction.

Here, we tested the app in two experiments that asked a specific question about human foraging. This question was inspired by the classic laboratory study of (Dawkins, 1971) and our previous 2D foraging studies (Á. Kristjánsson et al., 2014), both of which suggested that foraging episodes sometimes consist of extended “runs” where targets are selected from only one category. We wanted to know whether similar run-like behavior would be present in a situation more closely resembling foraging in the wild. Our specific question was whether a conjunction manipulation would modulate behavior.

The results were quite clear. There was no evidence of a shift in foraging behavior between the feature and conjunction conditions in either experiment. Indeed, the number of runs was always very close to what would be expected from random selection between two target categories and there was no evidence of extensive runs. More specifically, in Experiment 1 the feature/conjunction manipulation gave rise to the same number of runs, while in Experiment 2 the number of runs was slightly higher in the conjunction condition. This contradicts our prediction that reducing the number of available targets (from 50% to 30% of available items) would increase the attentional load and reduce the tendency to switch between target categories.

This finding suggests that the exhaustive search behavior found in our original work (Á. Kristjánsson et al., 2014) -- which has been replicated a number of times, both by our group (Jóhannesson, Kristjánsson, & Thornton, 2017; T. Kristjánsson & Kristjánsson, 2018; T. Kristjánsson et al., 2018) and others (Clarke, Irons, James, Leber, & Hunt, 2018; Gil-Gómez de Liaño, Quirós-Godoy, Pérez-Hernández, Cain, & Wolfe, 2018; Quirós-Godoy, Pérez-Hernández, Cain, Wolfe, & Gil-Gómez de Liaño, 2018) -- does not rely exclusively on the feature/conjunction manipulation. Rather, it implies that this manipulation interacts with other aspects of the task design and characteristics to give rise to extended run behavior.

As noted earlier, there were two main differences between the original 2D task and our new 3D game, i.e. the field of view and the ITT's. In the 2D task, all targets and distractors were simultaneously present on the screen, resulting in a dense field of 80 items consisting of four different category types. Under these conditions, the dynamics of targets selection were extremely rapid leading to an average ITT of approximately 400ms/item. In the 3D game, only a subset of items (targets and distractors) was visible from a given position and the participants were expected to navigate in the environment in order to find and collect the targets. As a consequence, the time interval between successive target selections was an order of magnitude higher (around 4 seconds) than in the 2D game.

Although we can only speculate, it seems likely that both of these factors served to reduce the overall cognitive load in the 3D task. Having a reduced field of view, would remove any planning component, allowing participants to focus more directly on immediate selection. Previous studies have shown that when making a sequence of responses, participants automatically plan ahead, which almost certainly consumes resources (Horowitz & Thornton, 2008; Thornton & Horowitz, 2004) . Perhaps more obviously, as participants were making selections every 400 ms in the 2D task, this may have greatly increased the cost of repeatedly switching between conjunction categories. With the much slower ITTs in the 3D task, this cost would have been much reduced, allowing them to switch much more frequently.

In any event, it is likely that the conjunction manipulation was not effective in the current 3D task because the additional load it added was simply not enough to saturate the overall attentional capacity. This suggests two general approaches for future studies. First, we could restore some of the original task demands of the 2D game. For example, if our model animal were a fast-flying insect, rather than a squirrel, we could provide a larger field of view (i.e. a bird's eye view) and decrease the ITT. While such an approach is possible, it would still leave open the question of whether humans (or other ground-based animals) ever display extended run-like behavior when naturally foraging in the wild. As this is the main question that motivated the current work, a second approach, would be to retain the main components of the current simulation but to either replace the conjunction manipulation completely or supplement it with additional, ecologically valid, task-demands to ramp up overall attentional load.

There are several ways this could be achieved within the context of the current app. The most obvious approach would be to make individual target selection much more difficult. This could be done by reducing the visibility of items by manipulating contrast and/or transparency or by varying the target-distractor similarity, for example. As manipulated images can be directly imported into the app, this seems like a sensible first option to try. Another approach suggested by previous animal literature, one that would require modification of the current game, would be to manipulate fear of predation (Kamil & Bond, 2006). By adding a predator to the environment, both the attentional load of the player and the temporal dynamics of the game are likely to increase. It would, of course, be possible to combine these manipulations, and to add others.

For example, a number of other manipulations have been explored within the context of our 2D task, such as time limits on foraging (T. Kristjánsson et al., 2018), set size manipulations (A. Kristjánsson, Thornton, & Kristjánsson, 2018), manipulations of working memory load (T. Kristjánsson & Kristjánsson, 2018) and the availability of targets within a display (Fougnie et al., 2015; A. Kristjánsson et al., 2018). As our immediate goal – with respect to the question of attentional constraints on human foraging – will be to increase the overall cognitive load, several of these manipulations may provide useful starting points.

We should also not lose sight of the fact that the app could prove useful for addressing other more general behavioral questions. Thus, while our experiments focused on run-like behavior, as an index of attentional load, other measures yielded interesting insights into the app and how people forage using it. For example, the inspection of the distance travelled and the use of space suggest that participants explore widely in the virtual space. The higher distance travelled in the conjunction condition of Experiment 2 can be easily explained by the fact that the target/distractor ratio was set to 30/70 and, as a consequence, participants had to travel longer distances in order to find and collect targets.

It seems likely that this also explains why the ITT's are highest in this condition. More interestingly, by comparing ITTs in the feature condition across the two experiments, we are able to evaluate the efficacy of the two control modalities tested in this study. In Experiment 1 participants were seated in a sound-attenuated booth and used a virtual joystick, while in Experiment 2 they stood in a screened off area of the lab and used full-body movements to change their viewpoint. The significantly lower ITIs in Experiment 2 indicate that participants find the full-body navigation more intuitive and easier to use.

To conclude, we introduce a new research tool in the form of a serious game that provides a simulated environment modeled on foraging in the wild. This tool was developed to continue our exploration of attentional constraints on human foraging. Specifically, we were interested in whether a feature/conjunction manipulation could lead to exhaustive run-like behavior in this environment as we previously demonstrated using 2D apps. The answer is clearly that it does not, and we have discussed possible reasons for this difference. However, the app was developed with flexibility in mind and we are optimistic that our group and others will find it a useful tool for further exploring human foraging in a simulated 3D environment.

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TABLE. Summary of behavioural data from Experiments 1 & 2: Average number of runs, inter-target time (ITT ms) and inter-target distance (ITD meters) as a function of condition.

		Experiment 1			**Experiment 2**		
		Runs	ITT	ITD	Runs	ITT	ITD
Feature	**M**	16.9	4597	2.96	16.8	3840	2.78
	SE	0.29	188	0.07	0.33	138	0.07
Conjunction	**M**	16.7	4499	2.99	17.8	6671	4.29
	SE	0.30	262	0.11	0.44	384	0.10

FIGURE CAPTIONS

Figure 1. Screen shots from the serious game "Squirrel Away". **A)** Title Scene; **B)** In game play. This screen shot shows the first-person perspective of the player, with target items distributed relatively sparsely ahead. The lower portion of the screen also shows the control and information display bar. Here, with the traditional user interface, there are two control buttons. By pressing and holding the "Move" button, the player moves through the scene, collecting items by colliding with them. The right button is a virtual joystick that can be used to control heading. When the optional motion-based user interface is selected, the joystick is absent and heading is controlled using the on-board gyroscope as the user makes full-body movements of the device in space. A countdown timer and a running counter of the number of collected targets are also displayed for information.

Figure 2. App settings menu. From this screen, the researcher can control many aspects of the game play and experimental settings. Details are provided in the text, but note that the "Target" and "Distractor" images interfaces to the right of the screen make it possible to load fully customised stimuli into the app. This feature makes it easy to vary both search context and task difficulty. Other parameters that can be varied include the length of a game session, either in terms of number of collected items or time, the ratio of target to distractor items, and whether data is being logged.

Figure 3. Summary of previous 2D foraging iPad tasks. **A)** & **B)** Examples of the feature and conjunction foraging, respectively. In previous studies participants were asked to cancel items from two target categories (e.g., red & green dots in A, red circles, green squares in B) as quickly as possible by tapping items with their fingers. **C)** Average number of runs for each participant in one of our previous studies (Á. Kristjánsson et al., 2014). The data show that feature foraging typically involves frequent switches between the two target categories, giving rise to many runs (grey bars), whereas for most participants, conjunction foraging involves far fewer runs (white bars). This difference between feature and conjunction conditions has been replicated a number of times, and is thought to reflect changes in foraging strategy caused by an increase in attentional load. Error bars represent one standard error of the mean.

Figure 4. A) Target stimuli used in Experiments 1 & 2. During feature foraging, target items were red and blue acorns and distractors were yellow and purple acorns. For the conjunction condition, targets were red walnuts and blue acorns and distractors were blue walnuts and red acorns. These target categories conceptually replicated the conditions used in our previous 2D studies. Note that the app has been designed so that researchers can create their own target and distractor categories simply by loading new images from the Settings menu (see text for details). **B)** Plan view of the game layout. This view is never seen during game play, but is shown here to demonstrate the distribution of items throughout the park. Each dot indicates a possible item location, which become randomly populated at the start of each session. In this view, the sparse distribution resembles the layout of our 2D experiments (see Figure 3), although during 3D game play, only a sub-set is visible at one time (see Figure 1B).

Figure 5. Average number of runs per participant as a function of the feature (grey bars) versus conjunction (white bars) manipulation. **A)** Results from Experiment 1 and **B)** Results from Experiment 2. In contrast to our previous 2D studies, there was no difference in proportion of runs in the two conditions. As there were 30 possible targets, an average number of runs of approximately 15 suggests that participants were switching between categories at random (see text for details). Error bars represent one standard error of the mean.

Figure 6. A) Average inter-target time (ITT) and **B)** Average inter-item distance per participant as a function of the feature (grey bars) and conjunction (white bars) conditions in Experiment 2. Note that in the conjunction condition, the target/distractor ratio was reduced, so that increased ITTs and distance measures reflect the sparseness of the displays in these conditions. See text and Table 1 for more details. Error bars represent one standard error of the mean.

SUPPORTING INFORMATION

File S1 This file contains raw data from each of the 12 participants that took part in Experiment 1. This file is in xlsx format and does contain header information. The column labels (with explanations in parenthesis) are further reported here as follows: 1) PPT (Participant number); 2) Condition (Experimental Condition; feature vs. conjunction); 3) Trial (Trial Number); 4) ClickCount (Number of item collected; 1-30); 5) TargetName (acorn_blue, acorn_red, walnut_red); 6) Z (Target Z Position); 7) Y (Target Y Position); 8) X (Target X Position); 9) ITT (Inter-Target Time); 10) Distance (Inter-Item Distance).

File S2 This file contains raw data from each of the 12 participants that took part in Experiment 2. This file is in xlsx format and does contain header information. The column labels are the same as for File S2.

Movie S1 This movie shows the game in action.

Movie S2 This movie shows the spatial distribution of each collection episode for every trial in both conditions of Experiment 1.

Movie S3 This movie shows the spatial distribution of each collection episode for every trial in both conditions of Experiment 2.

FIGURE 1A – APP Title Screen

FIGURE 1B – Example of game scene

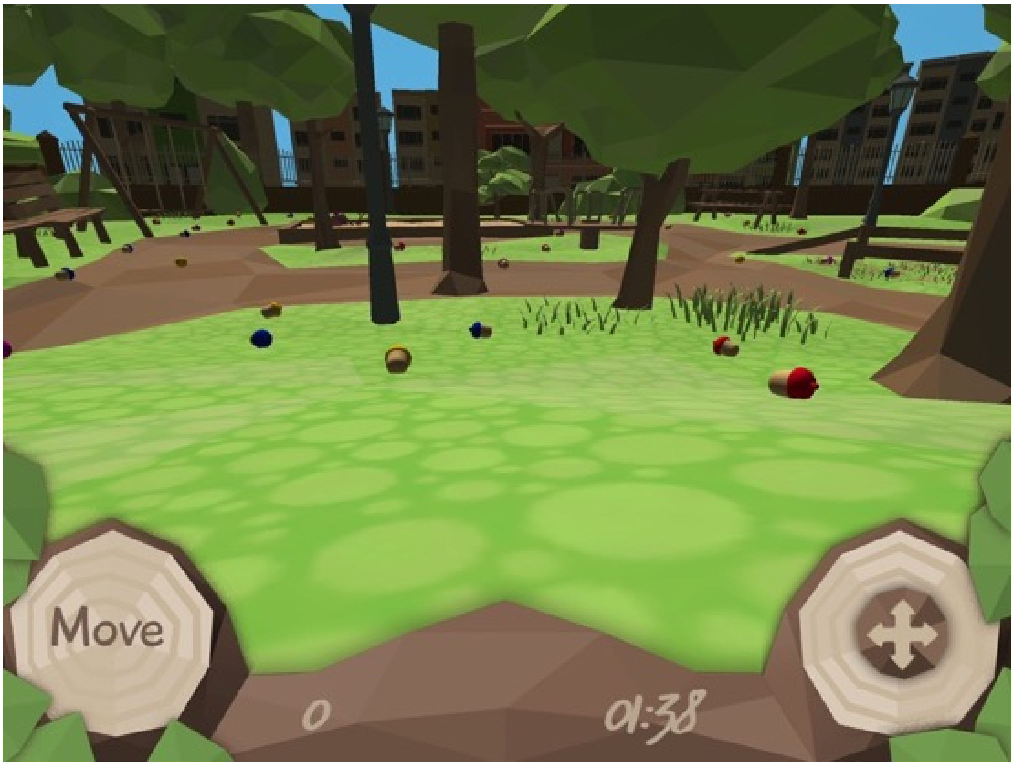

FIGURE 2. App settings menu.

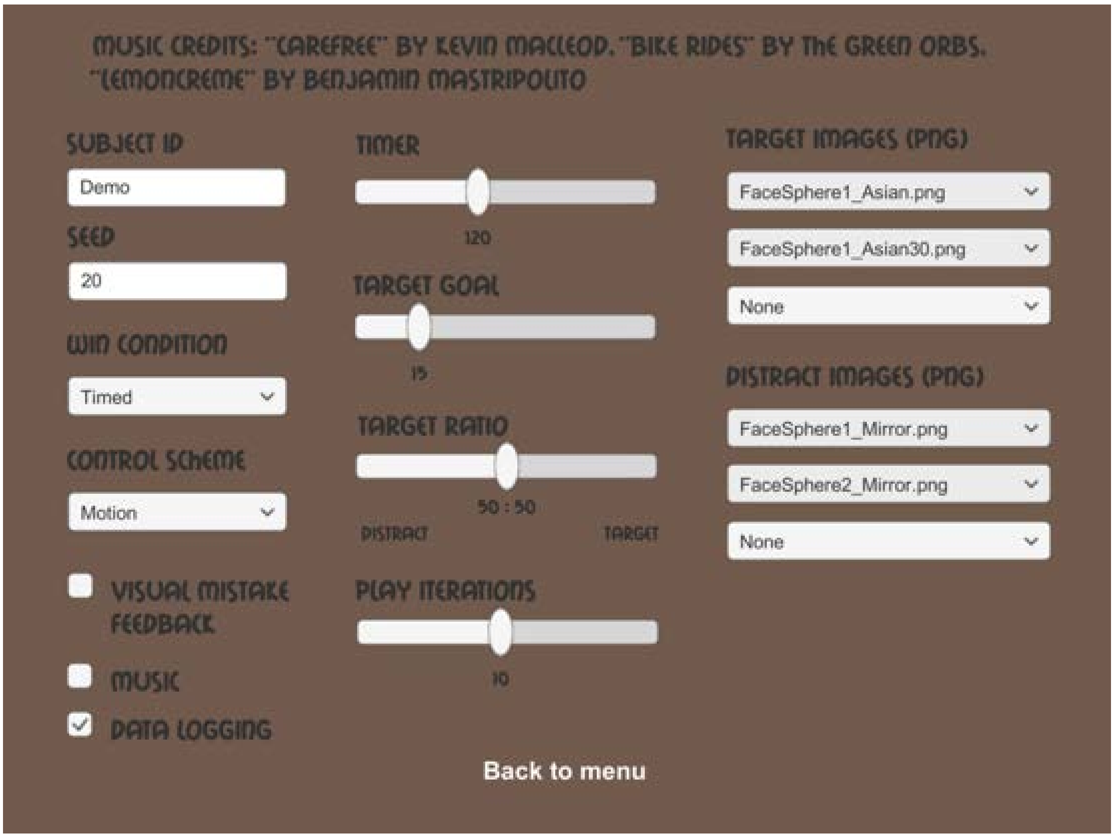

FIGURE 3A-B – Example displays from 2D foraging tasks

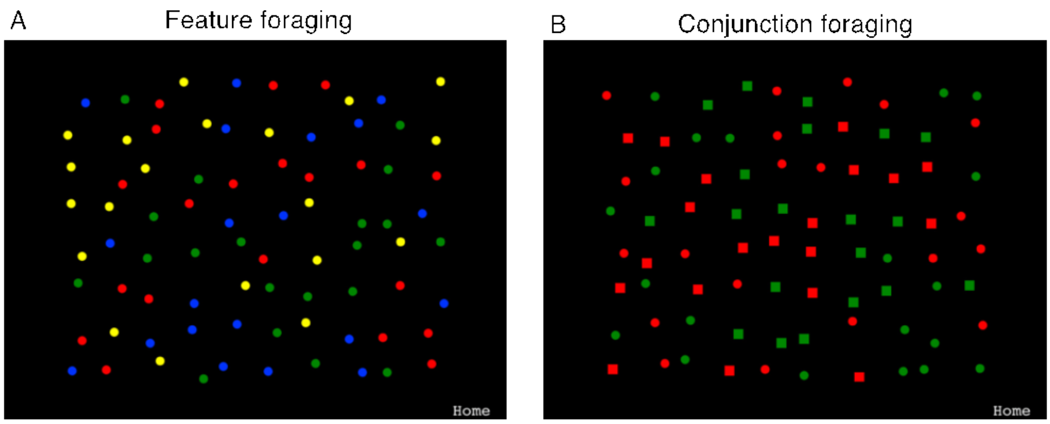

FIGURE 3C – Results from Á. Kristjánsson, Jóhannesson, & Thornton (2014)

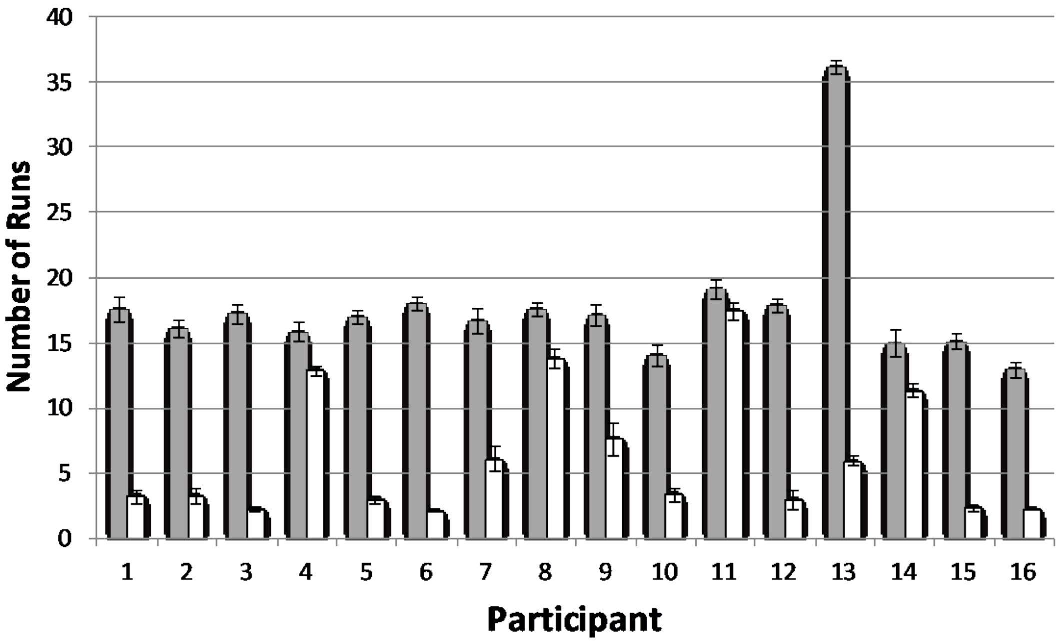

FIGURE 4A – Stimuli

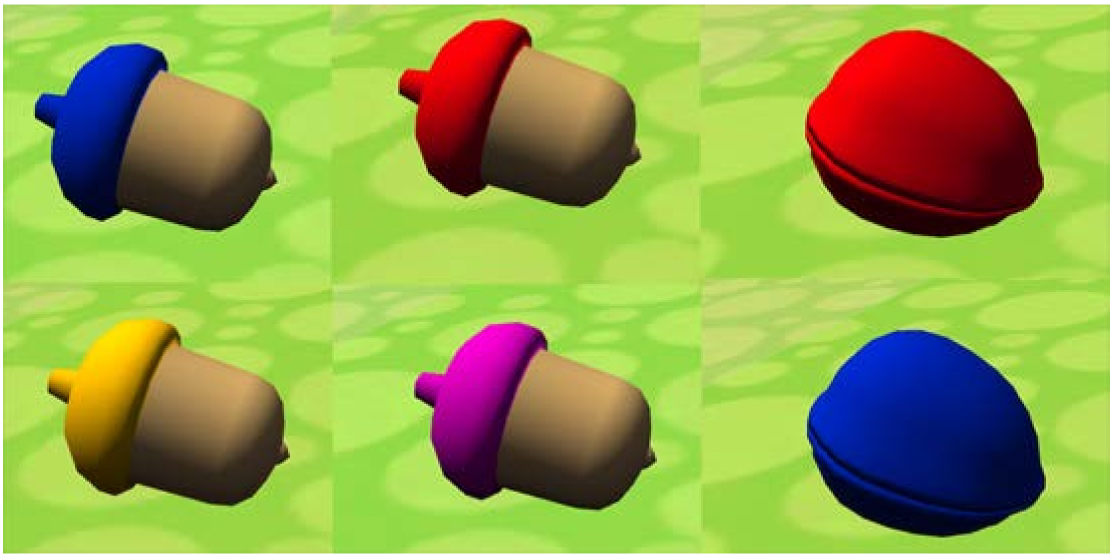

FIGURE 4B – Grid Layout

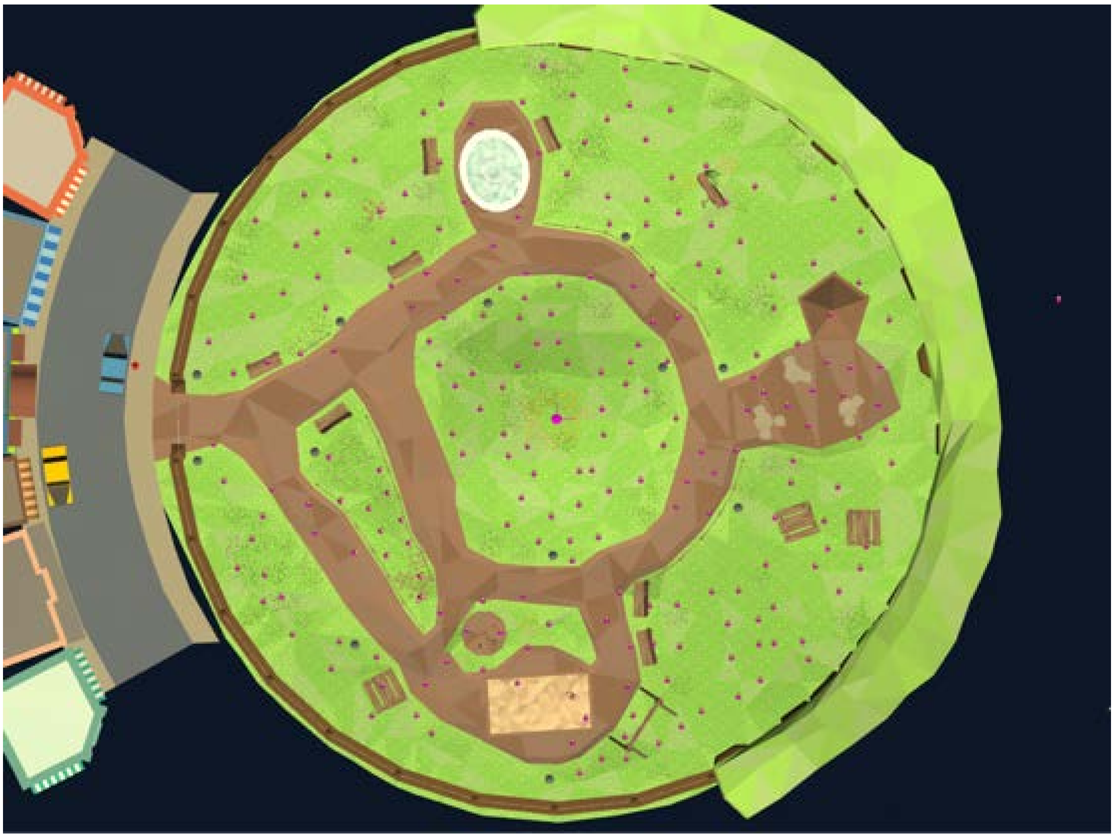

FIGURE 5A – Experiment 1 RUNS

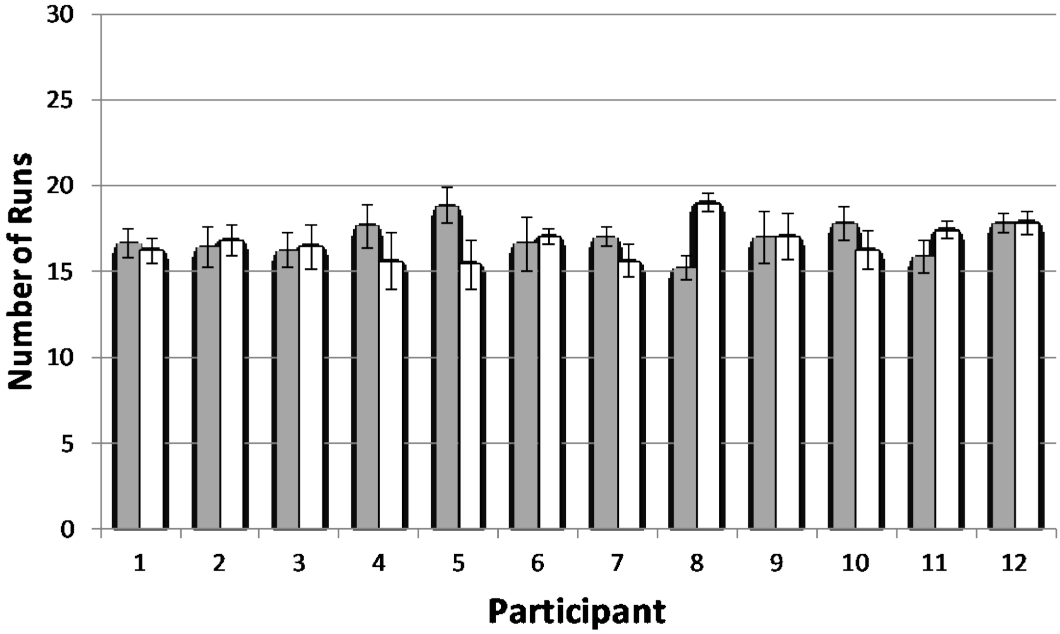

FIGURE 5B – Experiment 2 RUNS

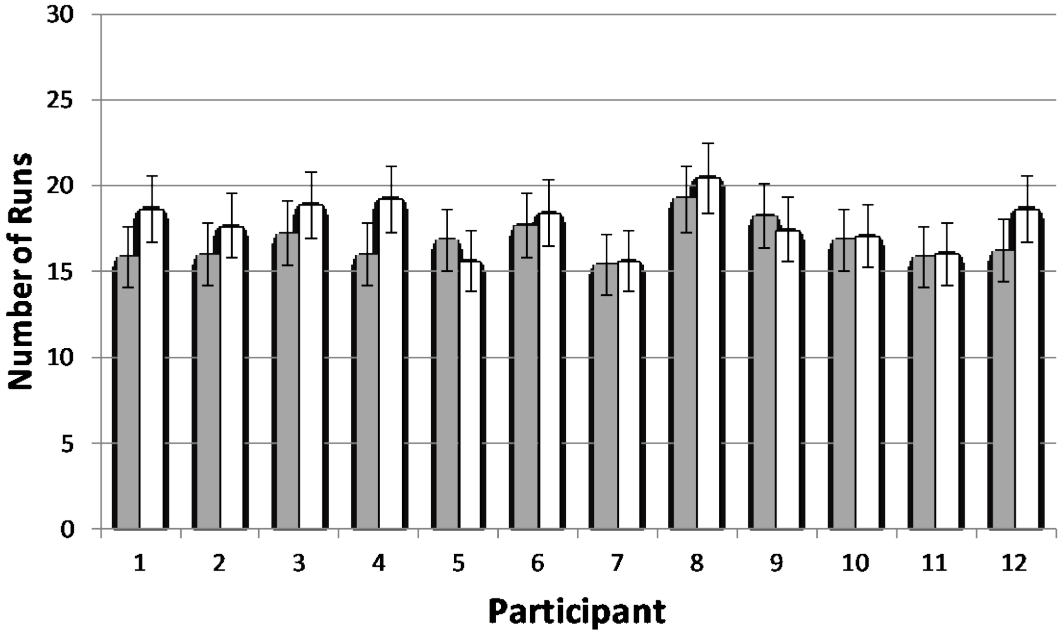

FIGURE 6A – Experiment 2: Summary of ITT

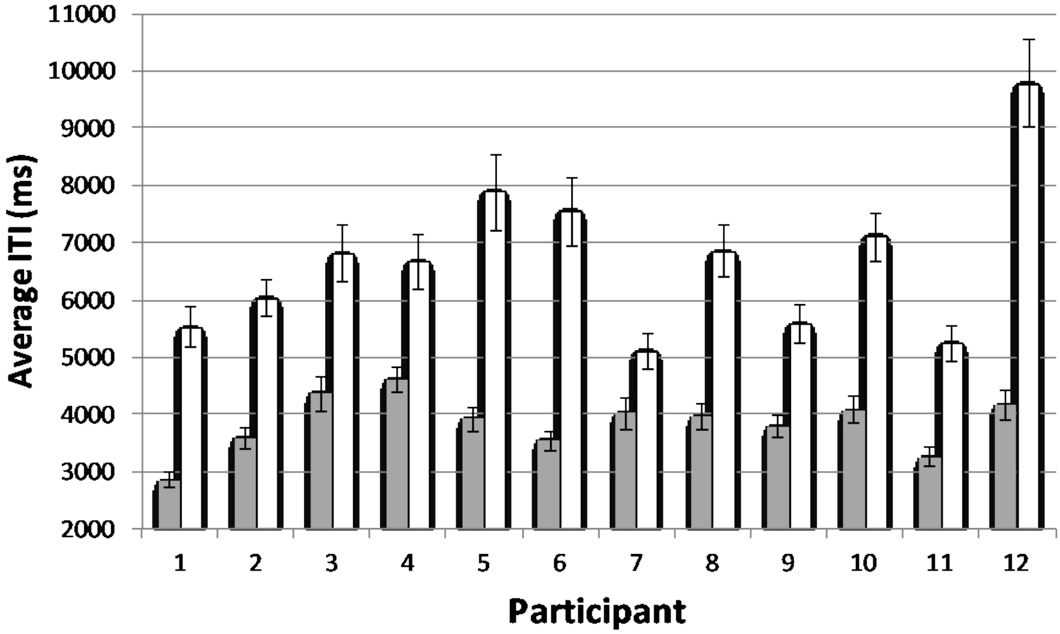

FIGURE 6B Experiment 2 – Summary of ITD