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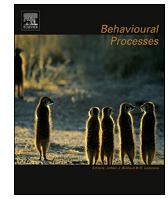

Conditioned anticipatory outcome searching in humans

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ABSTRACT

Two experiments used eye tracking to examine visual searching for expected outcomes in humans during an associative-learning task. In both, participants learned to press keys on a keyboard to activate weapons to repel invading spaceships in the presence of predictive “sensors.” In both experiments, eye tracking showed that participants came to direct their overt visual attention to the portions of the screen where the spaceship would arrive during the presentation of the sensor in a cue-specific manner. Participants also directed attention to the weapon that was used to repel the spaceship. The same results were observed regardless of whether participants were responding on the keyboard, or not (Experiment 2). Pupil dilations occurred to the appearance of the spaceship from the first trial and occurred to the predictive sensor stimuli on later trials in both experiments, suggesting that they might be conditioned responses. In Experiment 2 participants again looked for the expected outcome, but dilations to the predictive stimuli were shown to be an artifact of responding and not due to conditioning. The discussion involves the implications for investigating attention to predictive stimuli using eye trackers, roles of context in behavior, and the utility of outcome searching and pupil dilations as indexes of learning.

1. Introduction

The goal of the present manuscript was to determine how eye behavior in humans changes during the course of learning a simple association between two events. In animals, particularly rats and pigeons, sign-tracking (e.g., Hearst and Jenkins, 1974) is observed where behavior is directed towards conditioned stimuli (CSs) that predict appetitive unconditioned stimuli (USs). Pigeons, for example, come to peck keylights associated with the delivery of food, even under omission schedules where the keylight pecking omits the food delivery (e.g., Williams and Williams, 1969). Rats tend to rear in the presence of lights that predict food (e.g., Holland, 1977). A closer examination of that rearing response, however, reveals that the portions of the behavior that are actually directed toward the light tend to decrease as the association is acquired (Kaye and Pearce, 1984; Ross and LoLordo, 1986).

Apart from tracking signals, animals also demonstrate “Goal” tracking. Boakes (1977) first used the term to describe behavior that is directed towards the place where a US is expected to arrive in the presence of a signal for that US. Rats, for example, increase their investigations of the area where a predicted food stimulus will be delivered and that goal-tracking response is often used as the index of learning (e.g., Nelson, 2002). In addition to sign tracking a predictive cue, pigeons will approach the area where food is delivered in the cue’s presence. It is important to note that goal-tracking responses might interfere with observing responses directed toward the CS (e.g., Kaye and Pearce, 1984; Silva et al., 1992).

The phenomenon was labeled “goal tracking” in animal learning to maintain symmetry with, and the “Tolmanian flavor of,” the term “sign tracking” (Bolles, 1977; p 72). The term was coined from observations of the phenomenon in studies of appetitive conditioning where it could be casually descriptive of the idea that the expected outcome being sought during the signal is a desired objective to be achieved, in the same sense that the term “goal” is applied to humans. Nevertheless, like sign tracking, the goal-tracking behaviors are generally considered conditioned responses as they will persist even under omission schedules (e.g., Harris et al., 2013; Holland, 1979; Williams and Williams, 1969). Moreover, the behavior is not necessarily limited to appetitive stimuli. For example, rats will also defensively bury the source of a predicted shock (e.g., Arnaut and Shettleworth, 1981), indicating advance knowledge of the source of the outcome. Rather than describing the behavior as goal tracking, which might imply that the behavior is voluntarily organized to achieve a desired goal, we will refer to the behavior more generically here as “outcome searching”. Organisms acquire knowledge of where predicted events will occur, regardless of

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whether they are reinforcing or not. Their attention is then directed to that area, prior to the events themselves. Outcome searching is also used here to differentiate the effect from effects described in the human literature on look-ahead fixations and goal anticipation where humans tend to look at objects needed to complete a task or "goal" some milliseconds before manipulating the object. We will briefly discuss those findings later in this introduction.

Several experiments, reviewed below, have shown sign tracking in humans, thus, the main focus of the present experiments was to observe whether human eye behavior will also exhibit outcome searching during associative learning. As an initially secondary interest we also monitored pupillary reactions to events and then determined whether those reactions might be conditioned responses. With respect to simple visual outcome searching in the presence of explicitly predictive stimuli, as described here, we are aware of no studies assessing that phenomenon. How attention is allocated to the area where a predicted event will later appear, when that attention response is unnecessary as it has no impact on events and is not reinforced, has not been assessed.

In several experiments by Hogarth and his colleagues participants were presented with a task where pairs of picture cues on a computer screen signaled the availability of outcomes such as cigarettes (Hogarth et al., 2009, 2006a; Hogarth et al., 2008a, 2007), or money (Hogarth et al., 2007), an aversive noise (Hogarth et al., 2008a, b), or a neutral tone (Hogarth et al., 2009). Participants learned to make a response (e.g., keypress) to obtain the reward, avoid the aversive event, or provide a measure of their expectation of the neutral tone. Trials in these designs are divided up between presentations of cue combinations that are predictive of the presence and absence of the outcomes (e.g., AX+, AY+, BX-, BY-), creating individual cues that are predictive (A and B) and those that are not (X and Y). The routine finding is sign tracking. The time spent looking at the predictive cues is greater than for the other cues. That is, cues that predict the occurrence or availability of an outcome command more overt visual attention than non-predictive cues. Similar results have been reported by Kruschke et al. (2005); Wills et al. (2007); Beesley and Le Pelley (2011); Le Pelley et al. (2011); Mitchell et al. (2012), and Beesley et al. (2015), using predictive learning tasks where cues and outcomes are presented on a computer screen, independently of the participant's behavior.

In the methods of the research cited above, the presence of outcome searching might be indirectly inferred by a decrease in orienting to the predictive stimuli over trials. Despite that more attention should be devoted to cues that are predictive over unpredictive ones, overall attention to cues could decline over trials. As participants come to expect an outcome they may begin to look for that outcome in the presence of the stimuli that predict it, directing attention away from cues. However, even such an indirect evaluation is not possible in many of the studies as they have used self-paced trials which would artificially reduce dwell times per trial (Beesley and Le Pelley, 2011; Le Pelley et al., 2011; Wills et al., 2007); collapsed over trials precluding an analysis of trial-by-trial changes (Hogarth et al., 2008b; Kruschke et al., 2005; Le Pelley et al., 2011); or used relative measures comparing dwell times to the predictive stimuli as a function of dwell times to un-predictive stimuli (Hogarth et al., 2006a, b; Kruschke et al., 2005).

In the studies that have reported data trial by trial and used both fixed-cue durations and absolute dwell times (Hogarth et al., 2006a, a; Hogarth et al., 2007; Hogarth et al., 2009), or have corrected for cue duration (Beesley et al., 2015), some have shown such a decline in attention to the predictive cues over trials (Beesley et al., 2015), while those from the Hogarth research team have not. The task used by the Hogarth team may not lend itself to outcome searching, particularly the 2006 report cited above, as the outcomes were sounds played through headphones. In the remaining reports from the Hogarth lab the rewards were money or cigarettes, stimuli which could be clearly oriented to, but these rewards were delayed in time from the stimulus presentation. Moreover, the tasks were instrumental where rewards were dependent upon the participant's response. Thus, a strong expectation of the reward may not be present until the response has been made, at which time the predictive stimuli have been absent for some seconds and gaze was no longer being monitored. Other reports have shown an absolute increase in attention to predictive cues, and the outcomes used stimuli which were unlikely to support orienting, such as a shock delivered by electrodes attached to the participants foot (Hopkins et al., 2016, 2015) or white noise bursts in headphones (Madipakkam et al., 2016).

The method of Beesley et al. (2015) might be particularly suited to induce participants to orient towards the outcome. In their research, the participants were presented with predictive cues on a screen, along with 2 possible outcomes. Participants then selected the outcome that they believed was predicted by the cues by clicking on it. Next, they were informed on the screen as to whether they were correct or not. Their findings show that participants attend more to cues that were predictive rather than to cues that had unreliable relationships with outcomes. But, over trials they also show that attention decreases. Dwell times decreased both in absolute terms, and when expressed as a proportion of the duration of the self-paced trial. Those reductions in dwell times might be the result of outcome searching. Participants must orient to the outcome to be designated correct and select it. As the correct outcome becomes expected, that orienting could come to be elicited sooner, leading to the choice and ending the trial. However, a similar method used by Mitchell et al. (2012) showed a consistent increase in dwell time to a predictive cue when expressed as a proportion of the total time viewing the screen. As in Beesley et al. (2015) the possible "correct" outcomes were also present on the screen and the participant had to choose the one that was expected to be designated as correct.

Other indicators that humans will search for the occurrence of predicted events comes from the literature on goal anticipation and look-ahead fixations in humans. This literature shows that when humans are engaged in a task that has a subjective point of completion (i.e., a goal), their vision is directed to the objects that are involved in the completion of the task immediately before they are used. For example, in an early study, Land et al. (1999) showed that, when preparing tea, participants fixated on the object to be used an average of 56 ms prior to being manipulated. Such look-ahead fixations are assumed to be used in subsequent coordination of visual input with motor movements (Mennie et al., 2007).

Not only does this immediate anticipatory gaze occur in the individual performing the task, but it also occurs in individuals who are viewing the task being completed by others (e.g., Flanagan and Johansson, 2003). In these studies participants typically follow the trajectory of an object and slightly anticipate its destination. For example, Falck-Ytter et al. (2006) showed participants a video of a person moving balls from the right side of a table (relative to the participants viewpoint) into a bucket on the left. Adult's vision anticipated the arrival of the ball at the bucket along its trajectory by approximately 350 ms. The effect is frequently used as a developmental indicator in infant research to deduce at what age infants are able to infer that the actions of others are goal directed (e.g., Falck-Ytter et al., 2006; Gredebäck and Kochukhova, 2010; Kochukhova and Gredebäck, 2010; Kanakogi & Shoji, 2010). For instance, anticipatory gaze at the bucket in the research described above only occurred in adults and 12-month old infants, but not 6-month old infants.

The anticipatory goal tracking literature in humans uses a similar language as that used to describe searching for predicted outcomes by animals, but the constructs used to explain the effect are considerably different, and, thus the nature of what can be concluded from the investigations is, likewise, different. Anticipating the actions of others is said to occur due to action understanding which, along with goal anticipation, has been suggested to be mediated by a direct matching process that maps an observed action onto motor representations of that action (Falck-Ytter et al., 2006; Flanagan and Johansson, 2003; Kanakogi and Itakura, 2011). Eshuis et al. (2009) suggest that the tendency to anticipate the goal of others' actions might instead be derived from an expectation that humans behave in a goal-directed and rational manner. They directly state that "Proactive eye movements occur as a function of the combination of the intention of an agent to achieve a goal and the desirability of the goal state." In this view, anticipatory gaze, when it occurs, may be the result of a learning process that allows individuals to infer intention. At the time of observing the anticipatory gaze, learning would be assumed to have already been established earlier. Along a teleological line, interpreting actions as goal directed has been described as involving the physical constraints of the situation. The action being observed is "goal directed" if it can be assumed to be the most efficient means to achieve the outcome (Gergely and Csibra, 2003). Once a behavior is recognized as goal-directed, that realization automatically directs attention to the goal ahead of ongoing actions. Research in this area is largely directed towards understanding the function of these anticipatory movements and the effect is used as a dependent variable to differentiate the above accounts of the conditions that are required for the inference of goals.

Pavlovian processes are undoubtedly involved in these tasks. Considering the achievement of the goal or subgoal as the outcome, which is evidenced by some change in stimulation, there are likely to be a variety of stimuli, stimulus combinations, or events, that reliably precede that outcome. These can serve as Pavlovian cues that could elicit an anticipatory search for the next expected stimulus in the required sequence. The necessary associations would be acquired through experience with similar stimuli and manifest in the task through generalization, or through learning that takes place within the task itself (e.g., "learning to learn", Balea et al., 2018). As the explanations that are used in this field might suggest, the research in this area is not designed to reveal Pavlovian processes, nevertheless, there are some results that suggest that searching for expected outcomes in humans may be elicited by signals. For example, Paulus et al. (2011) showed infant and adult participants cartoon videos of a cow walking a path to encounter a sheep at the other end. The path split early, with long and short branches leading to the sheep. The short branch, however, was broken so that the cow could not reach the sheep by way of the more direct route. That is, the efficient route to complete the goal was the long path. The choice point, where the paths divided, was hidden from the viewer by an object. The cow approached the choice point, then was hidden from view as it moved under the occluding object, and next it emerged on the long path and proceeded. On a test trial, the short path was restored. That is, on test the short path was the most efficient means to get to the sheep. If inferred goals drive the behavior in this task, then anticipatory gaze should be directed to the now-efficient short path. Yet, both adults and infants continued to look for the cow to emerge along the long path, as had been done in the practice trials. On the test trial, the cow ultimately emerged on the short path, and adult vision was perhaps counterconditioned and shifted to the short path on subsequent trials. Infants persisted in looking to the long path, at least for the duration of the test trials used.

In Pavlovian conditioning the salience or intensity of the outcome affects conditioning. For instance, Kamin and Schaub (1963) have shown that conditioning with a shock US proceeds more rapidly with an intense shock rather than a weak shock. Likewise, they showed that the intensity of the CS also matters, with more intense CSs conditioning more rapidly than less intense ones. Salience of the goal, which is typically the final destination of an object that has been placed in motion by various agents, has been shown to matter in the types of gaze studies described above. For example, Biro (2013) showed participants a cartoon-type video of a red circle presented in a way to induce the observer to believe it moves under its own volition. The ball traveled and bounced over an obstacle and into a square goal area where the circle rested. As expected, participants gaze fell to the goal area an average of approximately .7 s ahead of the arrival of the ball. However, in a separate experiment the salience of the goal area was ostensibly reduced by coloring it black so that it obscured the presence of the ball within it. In this experiment the anticipatory gaze was reduced to approximately .1 s.

Henrichs et al. (2012) manipulated salience within experiments. Between groups, infants watched a hand reaching for a either a small or large rectangular blue object, with the assumption that the large object was perceived as more salient. Participants in the large-object condition looked at it, prior to the arrival of the hand, significantly sooner than did those in the small-object condition. This latter condition showed no significant anticipatory gaze toward the to-be-picked-up object. An interesting facet of this study is that, unlike the other studies cited here, they report trial-by-trial data as opposed to an average. Thus, the extent to which the behavior is acquired over trials can be examined. The results matched a classic negatively-accelerated learning curve. In the high-salience condition gaze arrived at the object approximately 100 ms prior to the hand on the first trial, and increased in a negatively accelerated fashion to the last trial where the gaze arrived on the object approximately 500 ms prior to the hand (gaze arrival = 197.59 x Log_e (trial) + 181.39; Henrichs et al., 2012).

In the present research we sought evidence of outcome searching in a conditioning method, where one stimulus simply predicted the other, by monitoring not only looking at the predictive cues but also monitoring gaze at the portions of the screen where the outcome would later appear. The method was relatively simple and straightforward. Participants played a visually rich 3-d video game (Nelson et al., 2014; see also Balea et al., 2018) where they first learned to repel four different attacking spaceships. Each ship appeared separately and participants had to rapidly press a key on a keyboard to activate a particular weapon to repel a corresponding ship. After these responses had been attached to the spaceships over several trials the ships were then used as "unconditioned stimuli" (US) outcomes in an experimental phase of the game (see Arcediano et al., 1996; Franssen et al., 2010; Ivanov-Smolensky, 1927, for similar procedures and rationale). In the experimental phase a visual flashing-light sensor was used as a conditioned stimulus (CS) cue that signaled the appearance of a particular spaceship outcome. As participants associated the sensor with the appearance of the attacking spaceship, they began to emit the keyboard response associated with the spaceship (ostensibly to prepare the weapon for its arrival) prior to the arrival of the ship. While participants were playing this game, we monitored their gaze using an eye tracker.

2. Experiment 1

Experiment 1 consisted of 10 trials where a red sensor cue was presented for 20-s and paired with the appearance of a spaceship during its final 15 s on each trial. Only one cue was used, thus, there was only one predictive stimulus. While relative attention to that stimulus would be expected to be higher than to one that was not predictive (see Le Pelley et al., 2016, for review), we expected overt attention to that stimulus to decline over trials. As the cue is associated with the arrival of the spaceship, we expected that participants would begin anticipatory outcome searching and direct their attention to the area of the screen where the spaceship *will* appear, prior to its actual appearance. We expected participants to learn where the outcome will appear and direct attention to that area when the spaceship is anticipated, even though the spaceship itself is absent.

The expectation described above was based on a pilot project, unrelated to the current experiments, where we noticed that participants did exhibit behavior indicative of anticipatory outcome searching. When the sensor cue was illuminated, participants came to direct their attention to the upper right area of the screen where the spaceship outcome would appear. The way the game was programed at that time could produce such a tracking behavior for an uninteresting reason, or two interesting ones.

A rather uninteresting reason that participants could have tracked the area of the screen where the weapon was located, in that version of the game, was that participants' keypressing to activate the weapon caused animations on the weapon to increase in speed in proportion to the key-pressing rate. Thus, participants could have simply been attending to those visual changes which were concomitant with their behavior. The more interesting interpretation would be that participants were expecting the spaceship to appear, and were orienting to that area in anticipation of its appearance. Finally, during the sensor participants come to press the key associated with activating the weapon, but the weapon does not fire *until* the spaceship arrives. Even in the cases where a participant never presses the key, the weapon will fire once on its own at the end of the trial and drive away the spaceship. Thus, there were two expected outcomes associated with that area which the participants could be anticipating. One was the arrival of the spaceship, which was contingent only on the presence of the sensor, and the other the firing of the weapon whose rate of fire was contingent on the arrival of the spaceship and the participant's rate of keypressing.

In the present experiment we removed the response-correlated changes in the animations on the weapon so that they would not command attention. We also modified where the spaceship outcome arrived. For half of the participants the outcome arrived from the right side of the screen, the side where the weapon was located, and for the other half the outcome arrived from the left. In both, the outcome arrived predominately from the center (top to bottom) of the screen.

2.1. Method

2.1.1. Participants

We planned for 60 participants, but no scheduled volunteer who showed up was turned away resulting in a total of 64 college-aged volunteers, assigned randomly to conditions producing groups of 32.

2.1.2. Apparatus

Participants played a video game. The game and all stimuli used therein are thoroughly described in Nelson, Navarro, and Sanjuan (2014), and also shown in the video located at: https://www.youtube.com/watch?v=Yl9Q8ThMN40. The game was first person as if the participant was setting inside of a vessel viewing the game environmental context through a view screen (see Fig. 4a and b). Through the screen participants viewed three-dimensional colored and animated space environments with slowly spinning space stations. The environment used in "response training," described below and shown in the background of Fig. 4a and b, was the inside of a green wireframe-gridded box-shaped chamber and contained no station. "Boutonia," used in the experimental phase, contained blue nebula and a blue ringed planet along with a spinning sphinx-like space station. All environments were viewed though a view screen that had four different gun-like weapons attached to each corner and a crescent-shaped panel containing 8 round sensors at the bottom center of the screen (see Fig. 4a & b).

Four spaceships were used that could appear in any environment, and attack the space stations. The "Learian" was blue and saucer-shaped and was used as the outcome in the experimental phases. It was programmed to appear either from the left or right of the screen, by group. In the experimental phases a space environment could be seen through the viewscreen, and the viewscreen camera was constantly panning in slow, semi-random, trajectories, over this environment such that elements of the environment did not have a fixed relationship to positions of the viewscreen. The entry of the Learian was correlated with the positions of elements of the fixed viewscreen and did not bear a relationship to any element of the background environment viewed through the viewscreen except that it appeared to the far left or right of the station.

The camera constantly panned around the space station until the spaceship entered, then the camera oriented to keep the ship in the screen but did not track it exactly such that the ship would maintain a fixed position relative to the elements of the viewscreen (e.g., it did not keep the ship centered in the screen). To make the spaceship appear on a side of the screen the ship was programmed to appear from a point off screen to the far left of the space station, or from an offscreen point to the far right of the station when appearing from the right. Once the ship was to appear, the camera rapidly oriented so that the ship would be in the view screen. The exact point in the view screen where the ship began to appear depended on where the viewscreen had been last pointing prior to the spaceship, which was random. The precise point of entry into the view screen could not be controlled without a significant re-writing of the program, thus the *exact* entry point to the left or right was random. The ship was in constant motion, rapidly entering the environment as if approaching with great speed from a great distance, flying generally toward the view screen. Then, the ship slowed and turned in a random path toward the station (when outside the response-training context) and began attacking. Thus, the ship did not suddenly and immediately appear in a determined place. Rather, it flew abruptly into the scene with its position being generally within the middle left or right of the view screen for a period of approximately 1 s before it travelled into other areas of the screen.

The screen resolution was set to 1280 × 800. The ship generally appeared in the screen within an elliptical area (approximately 250 × 300 pixels, X by Y). The center of the entry zone was slightly elevated, being approximately 20 pixels above the horizontal midline of the screen. When appearing from the left, the center of the entry zone was approximately 300 pixels from the left of the viewscreen center, and when appearing from the right the entry zone was approximately 300 pixels to the right of the viewscreen center. The ship remained in or near these areas elliptical areas for approximately 1 s before traveling randomly to other areas, and it remained on the determined entry-side of the screen for approximately 1.75 s in total before ever being present fully in the other side of the screen. It was repelled by the weapon located in the top right corner of the screen activated by the backspace key.

The other three ships appeared from corners of the screen and were repelled by activating the weapons located in those corners. The "Juk Destoyer" was a longer red spaceship appearing from the bottom right and repelled by pressing the number-pad zero key. The "Luckonian" was a seahorse-shaped ship appearing from the bottom-left of the screen and repelled by pressing the left shift key. The fourth ship was the "Stellarian", a white airplane-like ship that appeared from the top left of the screen and was repelled by pressing the left tab key.

The cue was illumination of the third sensor oval along the top row of the panel for 20 s with the color red. The illumination began with no red and increased to its maximal value (255 in the RGB system) and then decreased back to zero with that cycle repeating at a rate of 3 cycles per second.

The game was played on a desktop computer with a 22-inch monitor set to a resolution of 1280 × 800. Below the monitor a SensoMotorics Instruments RED 250 eye tracker was placed to monitor the participant's gaze. The monitor and eye tracker were surrounded by a white 1-m square box, with the front side removed. The illumination of the box averaged 450 lumens. Participants were seated approximately 60 cm from the monitor though that distance was modified on a per-participant basis as required for the eye tracker to acquire his/her eyes. The researcher was positioned behind a desk and two computer monitors, approximately 1 m to the right of the participant.

2.1.3. Procedure

2.1.3.1. Calibration. After obtaining informed consent, participants were seated at the computer and headphones were placed on them. The attending researcher then positioned the tracking device so that it was able to reliably detect the participants' pupils. Next, the attending researcher initiated the calibration routine, which was built in as part of the game. Once initiated, all instructions were subsequently delivered by the game. The participant was viewing the game in the "response training" context, described above. A female voice came through the headphones telling the participants that the system must now adapt itself to their eyes and that a circular apparatus with a flashing center would be presented and that the participant should focus on the flashing center and try to discern which colors were flashing. They were instructed to follow it with their eyes if it moved. The target stimulus then appeared which was a mechanical-looking torus-shaped circular apparatus (20-pixel diameter) with a small ball in the center. The ball was covered in a multi-colored spiral pattern texture that spun at such a speed that the ball appeared to flash random colors. Once the subject fixated on the ball the 9-point calibration began where the target moved to 9 different points on the screen, with each change in position triggered by a fixation on its current position. The placement of the 9 points and determination of a fixation were determined by SensoMotorics Instruments IView software.

2.1.3.2. Accuracy checks. Immediately following calibration, the focus point was again put on the screen (centered at 640 pixels from the left and 540 from the top) and the voice on the headphones repeated the instruction "focus on the dot", over and over, for 12 s. After the first 2 s, the eye tracker began recording the participant's gaze. These data were used to determine the accuracy of the calibration. While the participant was focusing on the dot the attending researcher could see the location of the participant's gaze, as determined by the eye tracker, on a separate monitor. If the tracker was not showing the gaze to be on the target for the majority of the period (subjectively determined) the calibration was repeated until the researcher subjectively determined that a better calibration could not be achieved. At the very end of the game another accuracy check was conducted (without any recalibration) to determine if any drift in the tracking had occurred.

2.1.3.3. Response training. After calibration, the game began and all instructions were, again, subsequently delivered by the software. Participants were instructed that they must learn to activate weapons by pressing keys on the keyboard to repel invading spaceships, and received practice trials with four different ships. On the first trial with a particular ship the instruction informed the participant of the name of the ship, the weapon used to repel the ship, and the key to press to activate the weapon. They were instructed that the key must be pressed rapidly and repeatedly. The participant was then left to begin pressing the key on his or her own until he or she discovered the level of responding necessary to activate the weapon. The weapon activation required the accumulation of 5 s of keypresses at a rate of 3 per second. If charged, the weapon began to fire when the spaceship was present and continued to fire with every other keypress so long as a rate of .75 presses per second was maintained. The ship was repelled after 8 shots had been fired. On subsequent appearances of a ship, no further instructions were provided. Participants were trained to respond to the four different ships described earlier (five trials each) in the manner described in the "response training" phase of Experiment 2 in Nelson et al. (2014). At the end of the phase they were informed that they were ready for "patrol" and transported to the Boutonia galaxy for the experimental phases.

2.1.3.4. Experimental phase. After arriving to the Boutonia galaxy participants received 10 trials where the red sensor was illuminated for 20 s. After 5 s of illumination the Learian spaceship appeared (from the left or right of the screen, by group) and attacked the station for 15 s before exiting with the offset of the cue. If participants had accumulated enough rapid responses during the initial 5 s of the cue the weapon began firing when the Learian appeared. If not, the weapon began firing when those responses had been accumulated. If the responses had not been accumulated by the end of the trial, the weapon fired one time at the end of the cue, regardless of whether the participant had responded at all. In all cases the ship was not destroyed, it simply fled the scene at the end of the trial. There were 10 trials with a variable inter-trial interval (ITI) of 20 s.

2.1.4. Data analysis

2.1.4.1. Screening

2.1.4.1.1. Keyboard responses. The computer collected the number of responses per second emitted on the backspace key during each second of the cue and 5 s before the cue (pre-CS). Subjects who failed to learn to respond to the cue were removed from the analysis of the keyboard response data.

2.1.4.1.2. Eye data. 60 data points for each second of recording were obtained for each eye of each participant, representing the X/Y coordinates of where the participant was looking. The data were scanned for missing values and these were replaced by linear interpolation based on the time between the last and next valid recording. In cases where data were missing at the beginning or ending of a recording period interpolation between two points was not possible. In those cases, the change in gaze direction was recorded between every pair of neighboring points in time for the period and an average "change vector" was obtained for the participant. The closest valid data point was found (i.e., the first when data were missing at the beginning of a period, and the last when data were missing at the end of a period) and the missing data were filled in by adding or subtracting the change vector to that point. For example, three missing data points would be filled in at the end of a time period by last_point + change_vector, last_point + 2 x change_vector, last_point + 3 x change_vector. The left and right eye data were then averaged to determine the final gaze position.

At the start of both accuracy checks participants could be looking elsewhere on the screen, despite the 2 s delay between the appearance of the target and the onset of recording. Thus, some of the gaze points might represent both where the participant was looking immediately prior to the check and the path of their eyes as they located the focus point. The accuracy checks were used to correct for any systematic inaccuracy in the eyetracking, thus we eliminated those miscellaneous points in the calculation of the center of the participant's gaze on the accuracy checks. Because of the explicit instructions, "focus on the dot", we assumed that the majority of each participant's gaze points should be at that point. For each accuracy check independently, we counted the number of looks at each pixel of the screen. Then, these totals were smoothed by adding to each pixel containing hits the sum of its neighbors (20-pixel radius) weighted by a Gaussian falloff function (S = 6). The pixel containing the largest value was obtained, and each pixel count was then expressed as a percentage of that maximum. Pixels that were looked at 50% of the maximum or higher, what we shall call a "fixation group", were used to calculate the center (average X coordinate, average Y coordinate) of the gaze points on the accuracy check. For each participant, the center of his or her fixation group for each accuracy check was expressed as a deviation vector from the true center of each on-screen focus point (true center – gaze focus point coordinates).

Each deviation vector (from each accuracy check) was negated to create a correction vector; a vector that when added to each point would adjust the center of the participant's fixation groups to the true centers of the onscreen focus points. Every point in the participant's data was then adjusted by a vector that was itself a linear interpolation between the two correction vectors based on the point's placement in time between the first and second accuracy checks.

Fixations are typically defined by points that are within a particular radius of space within a given period of time. As these values can contain varying degrees or arbitrariness, we made no attempt at computing and analyzing fixations. Rather we simply worked with the number of points observed within an area of interest within specified periods of time (i.e., seconds). We analyzed the amount of time gaze was recorded in the various areas of interest (defined below). As each point represents a $1/60^{th}$ s time sample, the number of observations represents the seconds spent looking in an area when divided by 60.

Areas of interest were defined as the Sensor, Outcome Zone Shallow, Outcome Zone Deep, Other Zone Shallow, and Other Zone Deep and are outlined in orange in Fig. 4a and b. The Sensor was a circular area with a liberal diameter of 67 pixels centered around the middle most top sensor (see the orange outlined sections in Fig. 4a and b). The Outcome Zone refers to the left side of the screen for participants that received the spaceship from the left and the right side of the screen for participants receiving the spaceship from the right. The "Other" zones were simply the sides of the screen opposite to where the outcome appeared. The Outcome and Other zones were divided into Shallow and Deep areas. Each area ran from the top of the screen to the bottom. Shallow areas extended 320 pixels out from the screen center and Deep areas began at the edge of the Shallow area farthest from screen center and extended to the screen edge. The shallow areas were constructed in a manner to exclude the area occupied by the Sensor area.

Pupil diameters were also recorded at a rate of 60 hz. They were averaged across eyes and across each second for presentation and analysis. Missing data were excluded from the averages.

2.1.4.2. Analysis. Keyboard responses, eye-gaze duration data, and pupil diameters were analyzed with mixed (between-within) factorial analysis of variance (ANOVA). Follow-up analyses were conducted with ANOVA using error terms appropriately derived from the overall ANOVA (see Howell, 1987).

2.2. Results

2.2.1. Keyboard data

Screening of the keyboard responses resulted in the removal of seven participants from the Outcome Left condition and 2 from the Outcome Right condition ($X^2 = 1.76, p = .19$). Recording errors by the computer (i.e., game crashes) led to incomplete keyboard-response data from 1 subject in the Outcome Left condition and 2 in the Outcome Right. Thus, in the analysis of the keyboard responses there were 24 participants in the Outcome Left condition and 28 in the Outcome Right condition.

Keyboard responses to the sensor cue are shown in Fig. 1 which shows responses per second during each of the first five seconds of the cue, prior to the outcome. Responding was acquired more slowly when the outcome appeared on the Left side of the screen, opposite the weapon. An Outcome Direction x Trials x Seconds ANOVA confirmed that description. The analysis showed effects of Trials and Seconds that were superseded by Outcome Direction x Trials, $F(9,441) = 2.31$, $p = .015$, $\eta_p^2 = .05$, and Outcome Direction x Seconds interactions, $F(36,1764) = 11.52$, $p = 1.5^{-58}$, $\eta_p^2 = .19$. Participants learned to respond to the cue faster when ship appeared on the same side of the screen as the weapon the participants used to repel it.

2.2.2. Gaze data

Participants that had 10% or more of their eye data interpolated were excluded, resulting in the exclusion of 7 participants. The average and standard deviations of the deviation vector lengths were calculated. Participants with deviations over 2 standard deviations from the average on either the first or second accuracy check were excluded. The average deviation for the remaining subjects was 23 and 34 pixels on the first and second accuracy checks, respectively (s = 17 & 23, respectively). For those excluded as outliers (n = 6), the averages were 228 (s = 23) and 260 (s = 136). Two of the outliers were also participants with excessive missing data, resulting in a total of 11 participants being excluded, four from the Outcome Left and seven from the Outcome Right conditions.

As described above, there were 9 subjects who did not respond during training, however, that does not mean that their eye-behavior did not change as a function of training. All eye-based data were initially analyzed with a grouping variable as to whether or not participants were responders or not. Outcome Direction was excluded in these analyses because the number of non-responders broken down by that variable was too small to make its inclusion. There were no effects involving whether or not participants responded during the Cue prior to the arrival of the US and those participants' data were included in all of the following analyses. In the analysis of the eye data, there were 28 participants in the Outcome Left group and 25 in the Outcome Right group. In the analysis of the pre-CS gaze data 3 more participants were excluded because of missing data during one or more entire pre-CS periods, one in the Outcome Right condition and two in the Outcome Left condition.

2.2.2.1. Gazing at the CS. Gaze hits in the Sensor area are shown in Fig. 2 during the first 5 s of the cue presentation, prior to the outcome. The figure collapses across the Outcome Direction variable as it had no impact. The data were analyzed with an Outcome Direction x Trials x Seconds ANOVA. There was a Trials x Seconds interaction, $F(36,1836) = 2.33$, $p < .0001$, $\eta_p^2 = .04$. No other effects were reliable, $Fs < 1$. On each trial, subjects directed their gaze to the cue, and that attention decreased over seconds. Overall, more attention was devoted to the cue on the first trial than the remaining trials. Excluding the first trial, a Trials x Seconds analysis produced only an effect of Seconds $F(4,204) = 56.06$, $p < .0001$, $\eta_p^2 = .52$, and no other effects, Fs ≤ 1.1, $ps \geq .36$.

2.2.2.2. Gazing at the screen. Data from the pre-CS period, when no cues or outcomes were present, are shown in Fig. 3, top. An Outcome Direction (left or right) x Zone (Outcome zone or Other) x Depth (Shallow, near the center of the screen or Deep, near the edges of the screen) x Trials ANOVA of looking at the screen zones during the pre-CS revealed an Outcome Direction x Zone x Depth interaction, $F(1,48) = 4.75$, $p = .03$, $\eta_p^2 = .09$. Because the left side of the screen was *logically* coded as the Outcome zone for the Outcome Left group, and the right side of the screen was coded as the Outcome zone for the

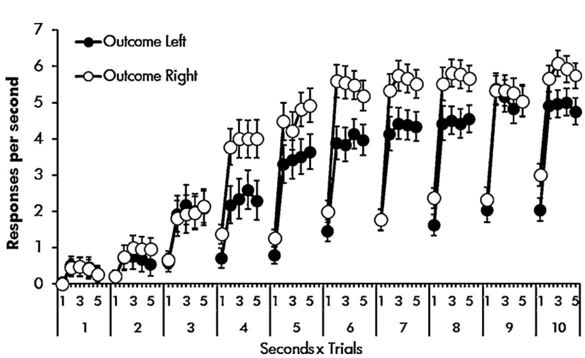

Fig. 1. Responding on the keyboard during conditioning in groups where the Outcome arrived from either the Left or Right of the screen in Experiment 1. Bars represent the standard error of the mean.

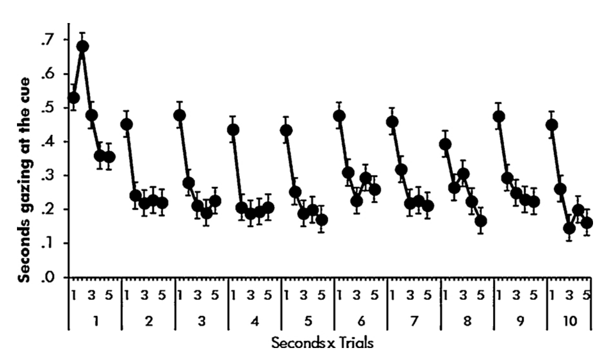

Fig. 2. Seconds spent with gaze recorded on the sensor on each second during the Cue, prior to the arrival of the Outcome on each trial of conditioning. Bars represent the standard error of the mean with between-subject differences removed to facilitate comparisons across seconds and trials.

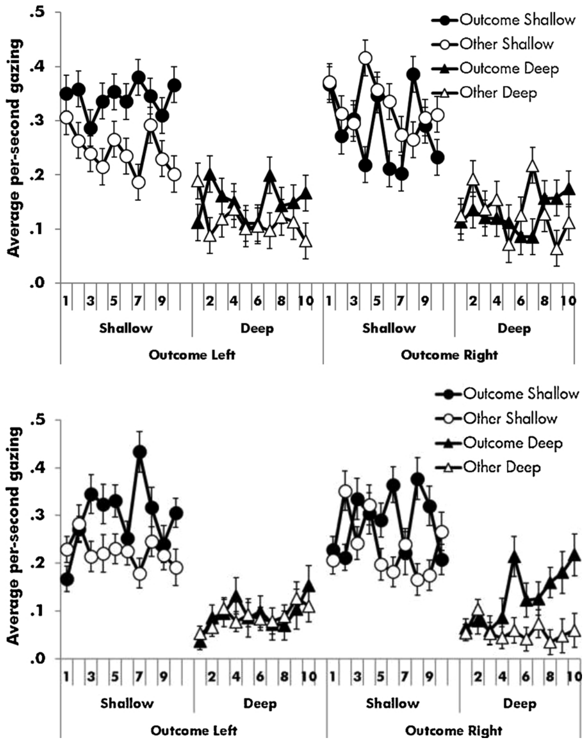

Fig. 3. Both panels show average seconds spent gazing at the shallow and deep areas of the screen in participants receiving the outcome from the Left or Right of the screen. Top panel shows gazing during the 5-s prior to the cue. Bottom panel shows gazing during the 5-s during the cue, prior to the spaceship outcome. Bars represent the standard error of the mean with between-subject differences removed to facilitate comparisons across zones, seconds, and trials.

Outcome Right condition, any Outcome Direction x Zone effects reflects main effects of the *physical* side of the screen. That is, the participants had a bias to look slightly toward the left side of the screen in both groups. There were no other effects. The Outcome Direction x Zone x Trials interaction approached significance, $F(9,432) = 1.77$, $p = .07$, $\eta_p^2 = .036$, though there was no Zone x Trials interaction in either Outcome direction group, $Fs < 1$.

In the shallow zone there was an effect of screen side (left or right), $F(1,48) = 5.90$, $p = .01$, $\eta_p^2 = .11$, with more looks to the left than right, and that did not interact with whether the outcome came from the left or right, $F(1,48) = 1.36$, p .25. In the deep zones there was no effect of screen side, $F(1,48) = 2.18$, $p = .15$ and no interaction with the origin of the outcome, $F < 1$.

Data from the cue period, when the cue was present and the outcome absent, are presented in the bottom of Fig. 3. As the previous analysis of the sensor indicates, participants initially looked at the sensor, and that gazing declined over seconds. When not looking at the sensor cue, participants are necessarily looking at the other parts of the screen. That is, the total sum of gaze time equals gazing at the screen plus gazing at the sensor. Therefore, any effects of seconds when gazing at the screen are simply the inverse of what was observed with gazing at the sensor. Because gazing at the screen will increase as gazing at the sensor decreases, there would clearly be effects involving interactions with seconds when gazing at the rest of the screen. For simplicity, we collapsed across seconds for presentation and analysis as the same conclusions regarding the main effects would be reached.

The data were analyzed with an Outcome Direction x Zone x Depth x Trials ANOVA. There were effects of Zone and Depth, $Fs(1,51) \geq 9.42$, $p < .003$, $\eta_p^2 \geq .16$. More looks were distributed overall to the Outcome zones, and more looks were distributed overall to the Shallow zones. There was also a Depth x Trials interaction, $F(9,459) = 2$, $p = .037$, $\eta_p^2 = .038$. There was a Zone x Depth x Outcome direction interaction, $F(1,51) = 21.05$, $p < .0001$, $\eta_p^2 = .29$, as well as a Zone x Outcome direction x Trials interaction, $F(9,459) = 3.76$, p = .0001, $\eta_p^2 = .069$. The four way interaction approached reliability, $F(9,459) = 1.68$, p = .090, $\eta_p^2 = .032$.

Follow up analyses investigated the effects of Zone and Trials within the Shallow and Deep areas within each group. In the Outcome Left condition, looking to the Shallow areas of the screen produced a clear Zone x Trials interaction, $F(9,243) = 2.57$, p = .008, $\eta_p^2 = .069$. Looks towards the Outcome side of the screen increased over trials over looking to the other side, with notable differences on trials 3,4,7, and 10, $Fs(1,371)_{range} = 4.03$–24.22, $p_{range} = < .0001$ - .045, $d_{range} = .48$–1.28 When looking at the deep areas, there was only an effect of Trials, $F(9,243) = 2.96$, p = .002, $\eta_p^2 = .099$, with no effects of Zone or interaction, $ps \geq .36$. Interestingly, looking at the deep areas of the screen increased for both the Outcome and Other sides of the screen when the spaceship came from the left.

In the Outcome Right condition there were Zone x Trials interactions in both the Shallow, $F(9,216) = 2.78$, $p = .004$, $\eta_p^2 = .104$, and Deep area, $F(9,216) = 3.15$, $p = .001$, $\eta_p^2 = .12$, with the effect being more pronounced in the deep area. Unlike the Shallow area in the Outcome Left group, the effect of Zone in the Shallow area of the Outcome Right condition appeared slightly inconsistent, though looks in the anticipated outcome direction generally increased over looks to the other side over trials. Simple effects of Zone on each trial confirmed that inconsistency showing more looks to the Other side on trial 2, $F(1,372) = 7.57$, $p = .006$, $d = .7$ and more looks to the Outcome side on trials 6 and 8, $Fs(1,371) \geq 5.89$, $ps \geq .016$, $ds \geq .64$. In the Deep area looking was more consistently towards the Outcome Zone, with notable differences on trials 4, 5, 6 and 8, 9, 10, $Fs(1,269)_{range} = 3.9$–16.45, $p_{range} = < .0001$–$.049$, $d_{range} = .5$–1.16.

In summary, both groups came to favor the Outcome side over the Other side across trials, with the preference being stronger in the shallow area for the Outcome Left condition, and the preference being stronger in the deeper area for the Outcome Right condition. Nevertheless, when looking to the deep areas, the Outcome Left condition's gaze increased over trials in *both* the Outcome and Other direction. Fig. 4a and b show the distribution of gaze in the Outcome Left and Right groups, respectively, summed over the last two trials. Brighter and "hotter" colors represent more looks. Inspection of these figures shows that when looking at the deep right, both groups were looking predominately at the weapon in the top right corner. Both the area where the outcome was expected and the weapon whose activation was correlated with the appearance of the outcome, commanded attention. Thus, there was conflict in the Outcome Left group. In the Outcome Left group, where the outcome came from the side of the screen opposite the weapon, participants distributed their *far* gaze more or less equally between looking for the spaceship outcome and glancing at the weapon (Fig. 4a). When the outcome came from the right, the same side of the screen as the weapon, participants predominately focused on the weapon on that side of the screen (Fig. 4b).

During the pre-CS, in the absence of any cues or outcomes, participants had a slight bias to look to the shallow left of the screen. Because the camera was in motion following semi-random trajectories the salient background visuals in the game appear on both sides of the screen. Thus, the visuals alone probably cannot account for the bias. The attending researcher was positioned approximately 1 m to the right of participants during the experiment, which might bias participants casual glances to be to the left, keeping the attending investigator out of their peripheral vision.

Despite that the participants had some preference for looking at the left side of the screen, the pattern observed during the cue, in the absence of the outcome, was different. In the Outcome Right condition, gazing at the screen during the cue overcame the bias to look to the left, and participants looked to the right where the outcomes would appear. As mentioned above, that looking likely reflected that participants were anticipating both the weapon firing and the appearance of the

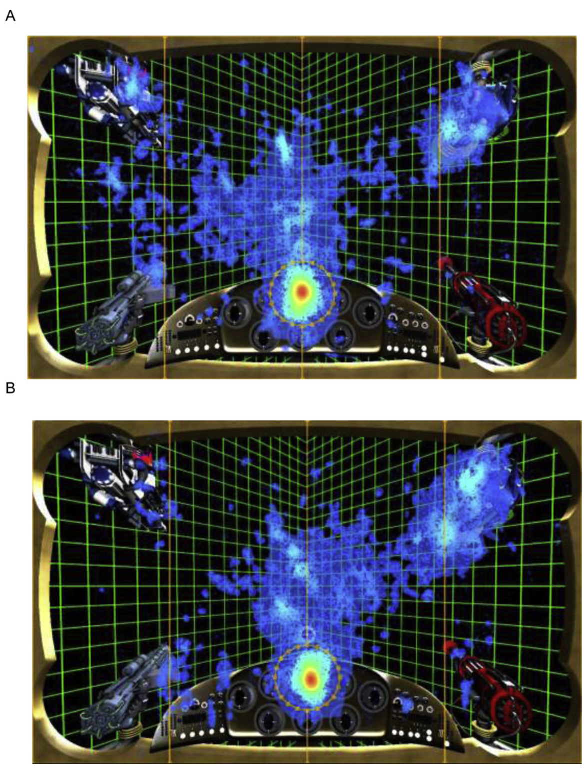

Fig. 4. Heatmaps of gaze distributed during the first 5-s of the Cue on the last two trials of conditioning. The orange lines delineate the different areas of interest defined in the text. Warmer and brighter colors indicate more looks. Panel A shows gaze in the Outcome Left group, and panel B shows gaze in the Outcome Right group. Reds and oranges received the most looks with other shades depending on their proportion relative to the maximum red areas. Shades of yellow received approximately 80% as much gaze, greens received approximately 50% as much gaze, cyan received approximately 20% as much gaze, and darker shades of blue less than 20% as much as red.

spaceship.

In the Outcome left condition, participants looked mostly to the left of the screen during the pre-CS period. Given that there was a bias to look that direction, the results during the cue might appear ambiguous as to whether this group was showing anticipatory outcome searching at all, and that the result in the Outcome Right condition was simply tracking of the weapon in expectation of it firing. If that were the case, however, then the behavior in both groups should be the same. In the absence of outcome searching the only thing countering any urge to look at the weapon on the right in the Outcome Left condition would be the bias to look to the left, which was the same in both conditions, thus their performance would be identical. Rather, the poorer performance in looking to the right in the Outcome Left condition reflects their searching for the spaceship on the left. In the Outcome Left condition looks to the far sides of the screen increased over trials and were distributed between looking for the spaceship on the left and the associated weapon on the right, while looking to the far sides of the screen in the Outcome Right condition were mainly to the right, where both the spaceship and weapon firing would occur. During the cue presentations in the Outcome Left condition, as opposed to the pre-CS, looking was initially equally distributed between both sides in the shallow areas, and the preference for the left during the cue emerged over trials. Those patterns indicate that both groups were looking for the expected spaceship in the sides of the screen where its appearance was expected during the cue.

The Outcome Right condition did not develop a preference for looking to the right during the pre-CS when the cue was absent. Thus, while participants did learn where the outcome would appear, they did not simply attend to that area in the absence of a strong expectation of the outcome provided by the cue.

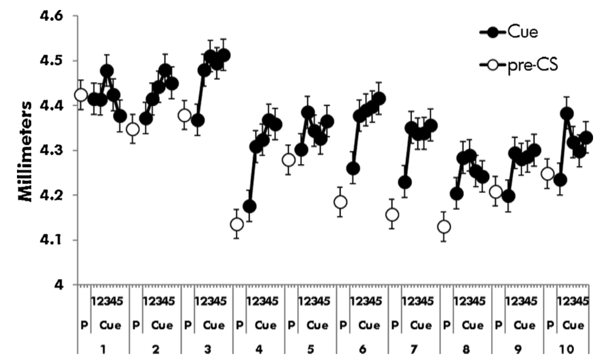

Fig. 5. Pupil diameters measured in millimeters during the 5-s of the Cue prior to the arrival of the Outcome in Experiment 1 during conditioning. Bars represent the standard error of the mean with between-subject differences removed to facilitate comparisons across seconds and trials.

2.2.3. Pupil dilation response

We observed that participants' pupil diameters changed along the course of the cue and outcome presentations, and over trials where they were paired. Below we present a summary of those observations.

2.2.3.1. Response to the cue. Pupil dilations during each second of the first five seconds of cue presentation, prior to the outcome, are shown in Fig. 5. The figure collapses across the insignificant Outcome Direction variable. Open symbols, above "P" on the axis labels, represent the average diameter during the 5 s prior to the cue onset. An Outcome direction x Trials ANOVA of the pre-CS diameters showed that they decreased along trials, $F(9,441) = 9.90$, $p < .0001$, $\eta_p^2 = .17$, with no effects of, or involving, Outcome direction, $Fs < 1$.

During the cue, pupils dilated within trials, but the overall size decreased across trials with the decreases in pre-CS diameters. An Outcome direction x Trials x Seconds ANOVA revealed effects of Trials and Seconds that were superseded by the Trials x Seconds interaction, $F(36,1836) = 1.77$, $p = .003$, $\eta_p^2 = .03$. There were no effects of, or involving, Outcome Direction, $Fs < 1$. There were effects of seconds, with pupil diameters changing during the cue, on all trials except 1,5, and 8, $Fs(4,285) \geq 2.61$, $p_{range} = < .0001 - .036$, $\eta^2_{prange} = = .05\text{-}.199$.

2.2.3.2. Response to the outcome. The outcome elicited a response as well. All effects in a Trials by Seconds ANOVA of the 15 s that the outcome was present were reliable, $Fs \geq 5.42$, $ps < .0001$, $\eta_p^2 \geq .095$. The data are shown in Fig. 6, which shows that the outcome produced a substantial initial increase in dilation that decreased along the outcome

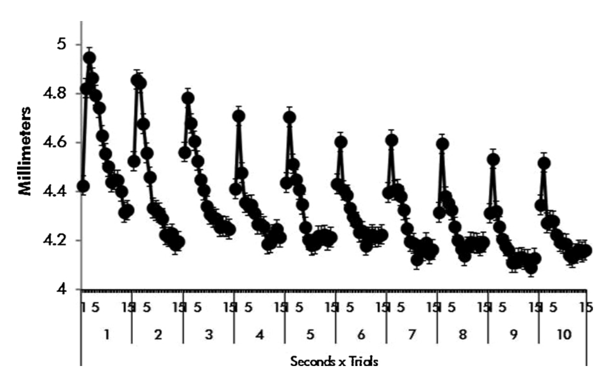

Fig. 6. Pupil diameters measured in millimeters during the 15-s of the Cue and the Outcome in Experiment 1 during conditioning. Bars represent the standard error of the mean with between-subject differences removed to facilitate comparisons across seconds and trials.

presentation, with that overall pattern decreasing over trials.

2.3. Discussion

Participants were trained to activate a weapon in the upper right corner of a computer screen to repel an attacking spaceship which arrived either from the right side of the screen or the left, between subjects. The spaceship was signaled by a red sensor appearing in the middle bottom portion of the screen. Participants came to respond on the keyboard in the presence of the sensor, prior to the spaceship arrival. Interestingly, this response was greater when the spaceship arrived from the same side of the screen as the weapon, showing some effect of the spatial contiguity between where the outcome of their behavior was produced, and the object to which that behavioral outcome was directed, in acquiring the response (c.f. Christie, 1996; Rescorla, 1979).

The experiment provides evidence that participants' eye behavior exhibits outcome searching. Attention to the cue appeared to decline over trials as it became predictive of the outcome and participants looked towards areas where events were predicted to appear. These events were those predicted by both stimuli (e.g., the cue predicting the arrival of the spaceship) and participant's behavior (firing of the weapon). Participants' pupils also dilated to both the cue and, particularly, the outcome. The large dilation produced by the outcome suggests that the dilation observed to the cue might be a conditioned response (e.g., Reinhard, and Lachnit, 2002; Reinhard et al., 2006). But it is unclear here whether the dilation is a function of some arousal or processing produced by expectation of the outcome, or simply the keyboard motor responding elicited by the cue as such responding does produce dilations (Richer and Beatty, 1985).

3. Experiment 2

3.1. Introduction

The previous experiment shows that participants' eye gaze is influenced by the expectation of generally localizable predicted events. As an event comes to be predicted, participants direct their gaze towards the area where it will later occur. The experiment also showed changes in the diameter of participant's pupils. When the outcome arrived, participants' pupils showed a large and rapid dilation that decreased during the outcome and along trials. A similar response was observed to the cue, but not on the first trial. Those results could indicate that the pupil-dilation response observed to the sensor cue here is a conditioned response (e.g., Reinhard, and Lachnit, 2002; Reinhard et al., 2006). However, the response could simply be due to motor responding (Richer and Beatty, 1985). Participants' respond on the keyboard to the outcome, and their pupils dilated. Participants did not respond on the keyboard to the cue on the first trial, and their pupils did not dilate. On later trials where keyboard-responding to the cue was evident, pupillary dilation responses were also evident.

The second experiment investigated whether the pupil response was an artifact of responding, and it also examined the outcome-search response. The design was simple. All participants received 10 trials where the outcome was predicted by a sensor and appeared from the right of the screen exactly as with the Outcome Right condition in the previous experiment, where the strongest outcome searching was observed. We assumed that the pupil data would be the cleanest in this condition where participants' attention is not divided between different outcome locations. Half of the participants received the same instructions as in the previous experiment. The other half were treated identically up to the final instruction in the *response-training* phase. Then, they were instructed to not fire on the spaceships, and given no further explanation. Thus, they observed the same events as the Firing group, but did so simply waiting on the experiment to end without responding. On a conditioning trial in this "waiting" condition, the spaceship would appear and attack the station for 15 s exactly as in the Firing condition. At the end of the trial the weapon would fire once, without participant input, and the spaceship would flee the scene.

The diminution of the dilation response to the outcome over trials observed in the previous experiment could reflect simple habituation, or that the outcome is less arousing as it comes to be predicted. To assess those possibilities, we further divided the Firing and Waiting groups each into three groups for a final test trial. One group (Same) received conditioning with the red sensor and the final trial was with the red sensor, just as the previous 10 trials. Another group (Different) received conditioning with a yellow sensor, located in the far right of the sensor panel, and was tested with the red sensor in the middle position. The third group (None) received conditioning with either the red or yellow sensor, and on the final trial the outcome appeared unsignaled. If the pupillary response to the outcome is due to its surprisingness, as opposed to the responding it provokes, then it is possible that there could be a reduction in the dilation response to the outcome when it is predicted. If so, then we should observe a smaller dilation response to the outcome in the Same condition, where it is predicted, than in the Different or None conditions where it is not.

We also examined gazing at the sensor and the outcome-search response on the pupil-response test trial. The comparison between the Same and Different conditions, where cues were present on test but only one was predictive of the outcome, allows us to determine whether the outcome search response was cue specific.

As the experiment progressed it occurred to us (somewhat late) to simply ask whether pressing a key on the keyboard would produce the pupil dilation response as was observed by Richer and Beatty (1985). Thus, with the final 15 participants we conducted a simple test after the experiment was over. Participants were asked to respond on the key for 5 s, then stop for 5 s, and that sequence was repeated. Participants were tested with the order of responding or not alternated between subjects. During that test, we measured pupil diameters.

3.2. Method

3.2.1. Participants

We again planned for 60 participants, but no volunteer who appeared for their appointment was rejected resulting in 71 college-aged volunteers randomly assigned to conditions.

3.2.2. Apparatus

The same apparatus as was used in the first experiment was used here.

3.2.3. Procedure

Participants were randomly divided into 2 main groups. Following the calibration all groups received the response training. In the "Firing" groups, the phase and instructions were exactly the same as in Experiment 1. In the "Waiting" groups, an additional instruction was appended to the final screen that told the participants to no longer use the keyboard and to not fire at the spaceships. No motive or rationale for that instruction was provided. Participants were simply told not to fire at the spaceships. Each main group was divided into groups Same, Different, and None for testing. Group Same and half of group None received conditioning with the red sensor exactly as in Experiment 1, with the outcome arriving from the right side of the screen. Group Different and the other half of group None received conditioning with a yellow sensor (flashing) in the right-most position of the top row in the sensor panel. All other parameters were the same as in Experiment 1. Following conditioning, participants received a single test trial. Groups Same and Different were tested with a pairing of the Red sensor with the US, while Group None simply received the outcome unsignaled. When the test was over for the final 15 participants and the computer informed the participant that the task was over, the attending researcher spoke to them through the headphones using a microphone and asked them to start pressing the key rapidly. After 5 s they were asked to stop. After 5 s, they were asked to respond again, and then to stop 5 s later. Pupil diameters were recorded during this time. The order of responding (R) or not (N) was counterbalanced between participants (RNRN or NRNR). During this brief test the participants viewed the background galaxy context of the game through the viewscreen.

3.3. Results

3.3.1. Screening

Data were treated as in Experiment 1. Among the 71 subjects, 3 participants were removed from the keyboard data for failing to learn to respond to the CS. As the eye data were to be split between the Firing and the Waiting groups, these non-responding participants in the Firing group were removed from the eye data as well. One subject in the Waiting group was removed from both datasets because he/she responded on the keyboard. Fourteen were removed from the eye data by the screening use in Experiment 1. For the keyboard response data, the final ns were Firing- Same 9, Different 15, None 11; Waiting- Same 12, Different 10, None 10. For the eye data the final ns were Firing- Same 8, Different 8, None 9; Waiting- Same 9, Different 10, None 9.

3.3.2. Conditioning

3.3.2.1. Keyboard responding. Fig. 7 shows responding per second on each second of each trial during conditioning, for those being conditioned with the Red or Yellow sensor. There were no differences due to sensor color. A Sensor Color x Trials x Seconds ANOVA showed effects of Trials, $F(9,297) = 56.31$, $p < .001$ $\eta_p^2 = .63$, Seconds, $F(4,112) = 106.96$, $p < .0001$, $\eta_p^2 = .76$, and Trials x Seconds, $F(36,1188) = 11.39$, $p < .0001$, $\eta_p^2 = .26$. No other effects were reliable, $Fs < 1$. The same analysis grouped by Test Stimulus (Same, Different, None) showed no pre-existing differences, $Fs \leq 1.08$, $ps \geq .36$.

3.3.2.2. Gazing at the sensor. Gazing at the sensor was unaffected by whether the sensor was Red and in the middle of the panel or Yellow and to the right of the panel, or by whether the participants were Firing or Waiting. The time spent gazing in each main group is shown in Fig. 8. A Firing or Waiting x CS Color x Trials x Seconds ANOVA revealed effects of Trials $F(9,441) = 11.14$, $p < .0001$, $\eta_p^2 = .19$, Seconds, $F(4,196) = 49.67$, $p < .0001$, $\eta_p^2 = .50$, and Trials x Seconds, $F(36,1764) = 1.66$, $p = .008$, $\eta_p^2 = .03$. There were no effects involving the grouping variables, $ps \geq .18$. The analysis with Test Stimulus (Same, Different, None) as a factor revealed no effects involving that variable, $ps \geq .29$. As in the previous experiment, gazing at the sensor decreased between and within trials.

3.3.2.3. Outcome searching. The red sensor was centered in the screen, as in the previous experiment, while the yellow sensor was located in

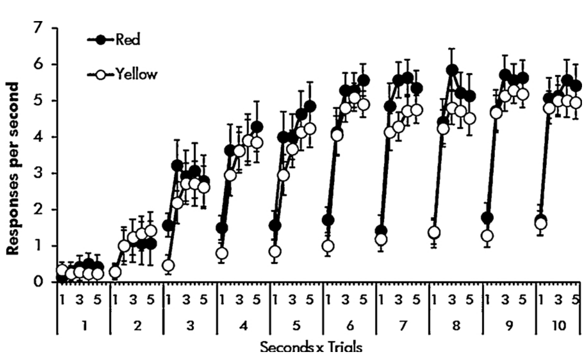

Fig. 7. Responding on the keyboard during the 5-s of either a Red or Yellow Cue prior to the arrival of the Outcome in Experiment 2 during conditioning. Bars represent the standard error of the mean.

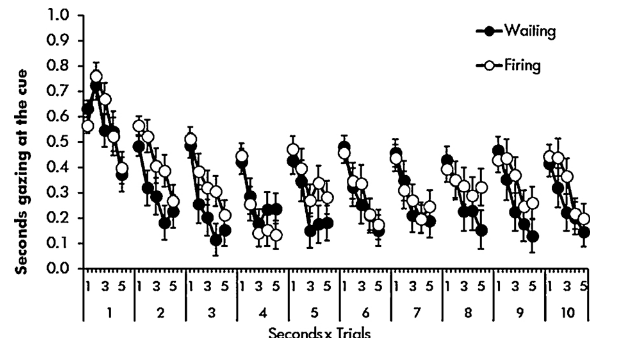

Fig. 8. Seconds spent gazing at the Cue, per second, during the 5-s of the Cue prior to the arrival of the Outcome in groups that respond to the Cue (Firing) or were instructed to simply observe events (Waiting) during conditioning in Experiment 2. Bars represent the standard error of the mean with between-subject differences removed to facilitate comparisons across seconds and trials.

the side of the screen where the outcome would arrive. Any gaze towards or away from the yellow sensor area would involve the gaze passing through the Outcome zones, thus the data from that group would be biased toward the Outcome zone. To avoid that bias, only the data from the groups receiving conditioning with the red sensor (ns = 13) are presented and analyzed here. The data are shown in Fig. 9. The top panel shows the data from the pre-CS period where participants, again, had a preference for looking at the left side of the screen. Despite that preference, during the cue a preference for the Outcome Zone emerged over trials predominately in the deep area in both the Firing and Waiting groups (Fig. 9, bottom).

A Firing or Waiting x Zone (Outcome vs Other) x Depth (shallow vs Deep) x Trials ANOVA of the pre-CS screen gazing revealed a Depth, F

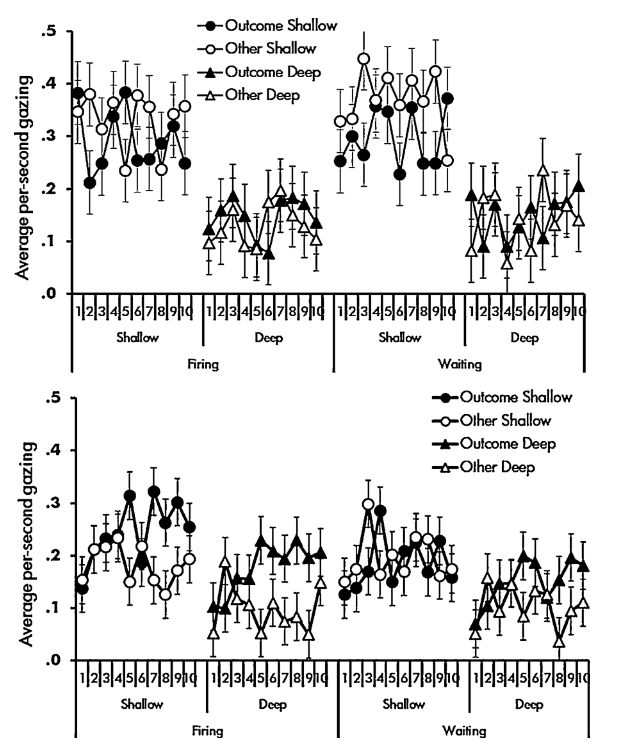

Fig. 9. Both panels show average seconds spent gazing at the shallow and deep areas of the screen in participants responding to the Cues (Firing) or instructed to simply observe events (Waiting). Top panel shows gazing during the 5-s prior to the cue. Bottom panel shows gazing during the 5-s during the cue, prior to the spaceship outcome. Bars represent the standard error of the mean with between-subject differences removed to facilitate comparisons across zones, seconds, and trials.

(1,24) = 71.93, $p < .0001$, $\eta_p^2 = .74$, and a Zone x Depth interaction, $F(1,24) = 7.04$, $p = .01$, $\eta_p^2 = .23$. There were no other effects, $ps \geq .102$. In the shallow area participants showed a bias to look left over the right, $F(6,27) = 6.27$, p = .016, $\eta_p^2 = .12$, and showed no differences in the deep area, $F < 1$.

A Firing or Waiting x Zone x Depth x Trials ANOVA during the cue, prior to the spaceship outcome, revealed effects of Zone, $F(1,24) = 6.12$, p = .02, $\eta_p^2 = .20$, with more looks into the Outcome zone than the other side of the screen, Depth, $F(1,24) = 14.46$, p = .0009, $\eta_p^2 = .38$, with more looks to the shallow than deep area, and Trials, $F(9,216) = 6.03$, $p < .0001$, $\eta_p^2 = .20$, showing that looking to the screen (away from the sensor) increased over trials. The Zone x Depth interaction approached significance, $F(1,24) = 3.84$, p = .06, $\eta_p^2 = .14$, as did the Zone x Trials interaction, $F(9,216) = 1.70$, p = .09, $\eta_p^2 = .07$. No other effects were notable, $ps > .15$.

The overall analysis does not appear to necessarily support what is shown in the figure, which suggests a Firing or Waiting x Depth x Zone interaction. The figure shows what appears to be a clear zone effect in both the Shallow and Deep areas in the Firing condition, while the Waiting group appears to show a clear zone effect only in the deep area.

Nevertheless, follow up analyses of Firing or Waiting x Zone x Trials in each depth showed only an effect of trials in the shallow area, $F(9,216) = 2.15$, p = .03, $\eta_p^2 = .08$, and no other effects, $ps \geq .13$. The shallow depth is where the figure suggests a Zone by Firing or Waiting interaction, but none was present, $F(1,24) = 2.42$, $p = .13$. Simpler Zone x Trials analyses in each group failed to find effects in either group, $ps \geq .14$, despite the seemingly larger difference between the Zones in the shallow area of the Firing group.

A Firing or Waiting x Zone x Trials analysis of the deep area showed clear effects of Zone, $F(1,24) = 14.83$, p = .0008, $\eta_p^2 = .38$, Trials, $F(9,216) = 2.05$, p = .035, $\eta_p^2 = .08$, and Zone x Trials, $F(9,216) = 1.96$, p = .04, $\eta_p^2 = .08$. There were no effects of, or involving, Firing or Waiting, $ps \geq .33$. There was an effect of Zone in both groups, $Fs(1,12) \geq .5.46$, $ps \leq .038$, $\eta_p^2 \geq .31$.

The patterns of significance were not anticipated by the figure, as the difference between the deep-area zones in the Waiting group, which was significant, was smaller than the difference between the shallow-area zones in the Firing group, which was repeatedly found to be unreliable despite a modest amount of "data mining." The error bars in the figure reflect the average within-subject variation around each mean, but the effect of Zone depends further on the variance produced by the consistency of the differences between the Outcome and Other zones within each group. In the shallow area, with the Firing group, the differences were inconsistent; some participants produced large differences, some small, and four of the 13 participants produced more looks in the Other zone than in the Outcome zone, producing twice the within-subject variation ($S_{-} = .04$) than did looking to the deep areas in the Waiting group, $S_{-} = .02$. In any case, the results in both groups generally reproduce those from the Outcome Right group from the previous experiment where looking to the Outcome zone increased in the deep area more consistently than in the shallow area. The outcomes appearing on the right at the end of the cue reversed the bias to look to the left seen in the pre-CS data and established that those looks were a function of the outcome being predicted by the cue.

3.3.2.4. Pupil responses. Inter-subject variability in the pupil data produced many situations where there were interactions of the grouping variables with within-subject variables, yet simple effect tests could not detect group differences at any level of the within-subjects variable. To reduce the variability, we expressed the data as a function of the pre-CS data which was measured for 5 s prior to the onset of each of the 11 (10 training, 1 test) trials. A Firing or Waiting x Trials x Seconds ANOVA of the pre-CS data themselves showed only an effect of trials, $F(10,470) = 8.53$, $p < .0001$, $\eta_p^2 = .15$. As in Experiment 1, the pre-CS pupil diameters evidenced habituation, decreasing from 3.83 mm to 3.63 mm across the 10 trials of training and the test trial. There were no effects involving the Firing or Waiting variable, $Fs \leq 1.25$, $ps \geq .22$.

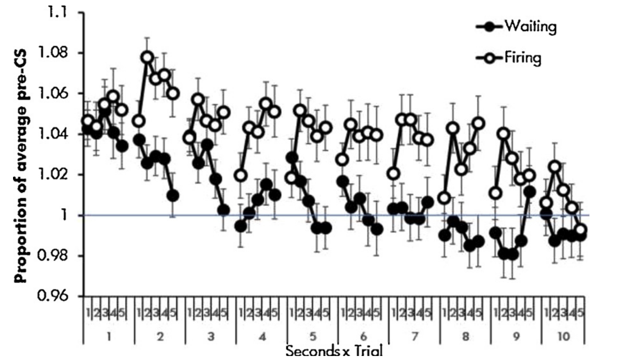

Fig. 10. Pupil diameters measured in millimeters during the 5-s of the Cue prior to the arrival of the Outcome during conditioning of Experiment 2 expressed as a proportion of the average pre-CS diameter by subject. Bars represent the standard error of the mean with between-subject differences removed to facilitate comparisons across seconds and trials.

The pre-CS diameters were highly correlated across trials, r's $\geq .83$. We averaged across the 11 trials to form a single pre-CS score for each participant. This average pre-CS was highly correlated with every subsequent measure of the pupil diameters taken during the cue (r's $\geq .75$). We then expressed each measure of each participant's pupil diameter during the cue as a proportion of his or her average pre-CS diameter (cue / pre-CS). Expressing each participant's diameter during the cue as a function of a constant pre-CS average reduced the inter-subject variability within each group while preserving the form of the within-subject effects across trials. The data are shown in Fig. 10.

The color of the training cue was irrelevant as there were no systematic differences in pupil diameters as a function of whether the cue was Red or Yellow and the variable was ignored. A Firing or Waiting by Trials by Seconds ANOVA of the transformed diameters showed effects of Firing or Waiting, $F(1,51) = 21.39$, $p < .0001$, $\eta_p^2 = .3$, Trials, $F(9, 459) = 6.17$, $p < .0001$, $\eta_p^2 = .11$, Trials x Seconds, $F(36, 1836) = 1.44$, p = .04, $\eta_p^2 = .03$, and Firing or Waiting by Seconds, $F(4,204) = 8.03$, $p < .0001$, $\eta_p^2 = .14$. The effect of seconds was reliable in the Firing condition, $F(4, 204) = 7.71$, $p < .0001$, $\eta_p^2 = .13$, but fell short in the Waiting condition, $F(4, 204) = 2.31$, $p = .06$, despite the trend to decrease produced by 4 of the 10 trials (i.e., trials 2,3,5, & 6).

As the figure shows, pupil diameters generally decreased to the average pre-CS size over training. The presentation of the cue led to a slight initial dilation which was maintained during the cue in the Firing group. Notice that in both groups any changes in the diameter during the cue largely cease by the end of training where they reach the average pre-CS level. The dilation caused by responding habituated over trials to the pre-CS level and there is no clear evidence that the predictive relationship with the spaceship outcome, which was consistent across the phase and between groups, had any impact.

We also examined the pupil response to the appearance of the outcome, and those are shown in Fig. 11. Both the Firing and Waiting participants showed a substantial response to the appearance of the outcome. Over trials, that response declined in both groups, with the decline being most evident in the waiting groups as the process of firing served to maintain the response better, particularly in the early seconds. A Firing or Waiting by Trials by Seconds ANOVA revealed a significant three-way interaction, $F(126,6426) = 1.39$, p = .003, $\eta_p^2 = .027$, that superseded all other effects and is what is expected from the description above.

3.3.3. Pupil response test

3.3.3.1. Keyboard responding. Keyboard responses during the first 5 s of

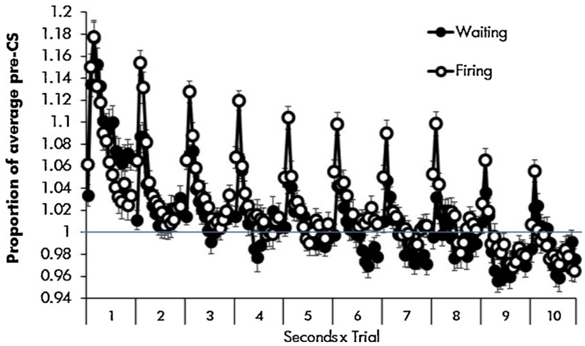

Fig. 11. Pupil diameters measured in millimeters during the 15-s of the Cue and Outcome in Experiment 2 expressed as a proportion of the average pre-CS diameter by subject. Bars represent the standard error of the mean with between-subject differences removed to facilitate comparisons across seconds, and trials.

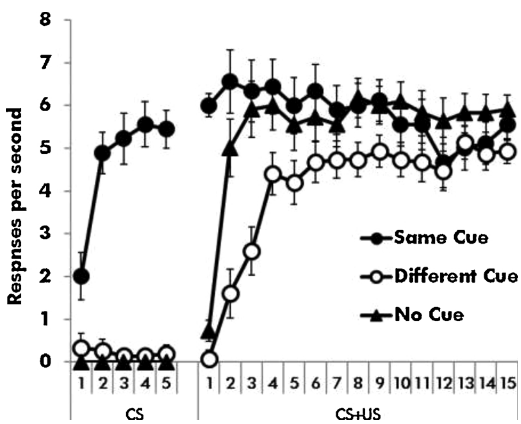

Fig. 12. Responses per second on the keyboard, by group, during the 5-s of the Cue prior to the Outcome, and during the Outcome on test in Experiment 2. Bars represent the standard error of the mean.

the cue and during the 15 s of the cue + outcome are shown in Fig. 12. At left, it is clear without further analysis that the Firing group receiving the same cue showed strong anticipatory responding while those that received a Different cue or no cue showed no response. When the Outcome was present there was a Test Cue by Seconds interaction, $F(28,448) = 5.77$, $p < .0001$, $\eta_p^2 = .27$. Responding to the US continued at a high level in the Same Cue group. The other groups began responding to the unexpected US, with responding increasing faster in the group for which there was no cue over the group for which it was signaled with a new cue. The presence of a novel cue produced some disruption of responding to the spaceship.

3.3.3.2. Pupil responses. The responses to the Same Cue, Different Cue, or No Cue in the Firing and Waiting groups are shown in Fig. 13. The five data points at left in each half show the response during the Cue period and those at right in each half show the response to the outcome in Group None and the cue + outcome in the other groups. The figure suggests that both the Firing and Waiting conditions showed a response to the new cue (Group Different), but none to the old cue (Group Same). A new stimulus produced some dilation, whether or not responding was present.

A Firing or Waiting by Test Cue (Same, Different, None) by Seconds ANOVA of the first five seconds where the US was absent showed effects of Test CS $F(2, 47) = 12.15$, $p < .0001$, $\eta_p^2 = .34$, and a Seconds x Test Cue interaction, $F(8,188) = 3.99$, $p = .0002$, $\eta_p^2 = .145$, as responding to the Different cue clearly rose above that of the other groups both when responding on the keyboard and not. There were no effects involving Firing or Waiting, $Fs \leq 1.38$, $ps \geq .24$.

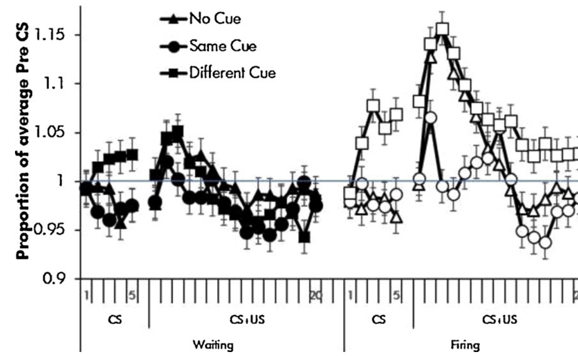

Fig. 13. Pupil diameters measured in millimeters during the 5-s of the Cue prior to the Outcome, and during the 15-s of the Cue and Outcome on test in Experiment 2, expressed as a proportion of the average pre-CS diameter by subject. Bars represent the standard error of the mean.

In the Firing conditions, the groups for which the outcome was unsignaled, or signaled by a different cue, showed a substantial response to the outcome. The response was much less for the group for which the outcome was signaled. As groups Different and None were just beginning their responding to the outcome (group same had already been responding for 5 s) these data suggest that the dilation response may be due to initiating action rather than maintaining it.

In the Waiting group, there were no group differences. Thus, the decline in dilation to the outcome over trials in training was not the result of the outcome being signaled. Rather, the decline represented simple habituation as both an unsignalled outcome and one signaled by a new cue, failed to elicit a greater response than one signaled by the same cue as used in training. Analyses confirmed the descriptions above.

A Firing or Waiting by Test Cue (Same, Different, None) by Seconds ANOVA of the 15 s where the US was present showed that the main effects of Firing or Waiting and Test Cue were significant, $Fs \geq 4.12$, $ps \leq .02$, $\eta_p^2 \geq .14$, but not their interaction, $F(2,47) = 2.66$, $p = .08$. All effects involving seconds were significant, including the interactions with the between-subjects variables leading to a three way Firing or Waiting x Test Cue x Seconds interaction, $F(28,658) = 1.51$, $p = .0455$, $\eta_p^2 = .06$.

A Test Cue x Seconds ANOVA within the Firing group showed an effect of Test Cue, $F(2,22) = 4.47$, $p = .02$, $\eta_p^2 = .29$ and that it interacted with Seconds, $F(28,308) = 3.47$, $p < .0001$, $\eta_p^2 = .24$. The figure shows rather clearly that both the No Cue and Different Cue conditions obtained a greater dilation than did the Same Cue group in the early seconds of the outcome. The same analysis within the Waiting group showed only an effect of Seconds, $F(14,350) = 9.25$, $p < .0001$, $\eta_p^2 = .27$, but no effects of, or involving, Test Cue, $Fs \leq 1.18$, $ps \geq .23$.

3.3.3.3. Outcome searching. A second by second analysis of the data supported the same general conclusions as did the main effects collapsed over seconds in analysis of both gazing at the sensor and the rest of the screen. For simplicity, we report the latter here. In the presence of the cue, participants that were receiving a different cue than that used in training looked at the cue, on average, longer in each second (mean = .56) than those receiving the familiar cue (mean = .23), $F(1,31) = 20.29$, $p < 0.0001$, $\eta_p^2 = .4$. There were no effects involving whether the participants were firing or waiting, $ps > .05$.

Analysis of looking at the rest of the screen, divided into shallow and deep areas by zone type (outcome or other) supported the same conclusions as collapsing over the depth variable, so we report the latter analysis here for brevity. During the pre-CS, prior to the cue, a Test cue (same or different) x Firing or Waiting x Zone ANOVA of the time spent gazing at the rest of the screen showed no effects, $ps \geq .14$. There was no tendency to look to the outcome zone, or prefer any

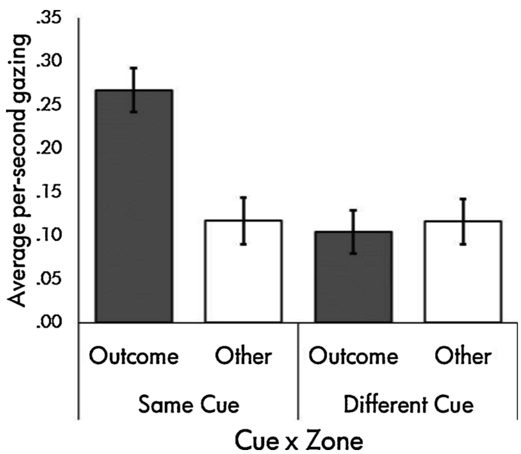

Fig. 14. Average time per second spent gazing at the Outcome and Other zones during testing with either the Same cue as used in training, or a Different cue. Bars represent the standard error of the mean.

particular part of the screen in either group, at the time of test. In the presence of the cues, the same analysis showed effects of Zone, $F(1,31) = 4.89$, $p = .035$, $\eta_p^2 = .14$, and a Test cue x Zone interaction, $F(1,31) = 6.66$, $p = .015$, $\eta_p^2 = .18$. No other effects were reliable, $ps > .05$. The data are shown in Fig. 14. As the figure suggests, the effect of zone was reliable with same cue, $F(1,31) = 5.61$, $p = .02$, $\eta_p^2 = .27$, with more looking to the outcome side of the screen, and there was no effect of Zone with the different cue, $F < 1$.

3.3.4. Response test

Our manual timing of the intervals during the four trials of the response test was not exact, resulting in intervals shorter than 5 s on some trials for some individuals. For that reason, we analyzed the average of only the first four seconds collapsed over trials with a Pressing or Not by Trial by Test Order (R-N-R-N or N-R-N-R where R and N refer to responding and not responding, respectively) ANOVA. The analysis showed a clear effect of Pressing, $F(1,13) = 9.88$, $p = .008$, $\eta_p^2 = .43$, and no other effects, $ps \geq .09$. Pupil diameters averaged 4.27 mm while pressing and 4.16 while resting.

3.4. Discussion

The experiment, again, demonstrated outcome searching in that participants came to direct their attention to the portion of the screen where the expected outcomes would appear over trials. Interestingly, this direction of attention did not depend on participants producing any overt responding. Participants instructed to simply observe the events and not respond also demonstrated outcome searching. Simply observing events was sufficient for their eye-gaze to be controlled by the covariations of the stimuli in the game. Any other active participation/interaction was not necessary. Analysis of the data from the final test between those tested with the same training cue and those tested with a new, novel, cue showed that the outcome search response was specific to the trained cue. In the absence of an evoked expectation of the spaceship, participants attention remained devoted to the novel sensor, and did not vary between zones when looking elsewhere.

The appearance of the spaceship produced a substantial dilation of the pupils in both groups, though it was more substantial in the Firing group, and that declined over trials. In the presence of the cue, changes in pupil dilations were only observed in the group that was Firing, and those also decreased over trials. Though the outcome produced a dilation, pairing it with a cue did not condition any pupillary change to the cue. The pupil responses observed in the previous experiment, and in the Firing condition here, were due to the motor responses on the keyboard.

On the test, in the Waiting group, there was no notable dilation response to the Same cue as was used in training, though the novel cue in group Different did elicit a response. The cue in the Waiting group never elicited a response during training, but the overall size of the pupils decreased along training. Once the overall pupil size had habituated, there was perhaps room to see a response to a novel stimulus which was not observable on the first trial when the training cue was also novel. The presence of the outcome elicited a small dilation response, but it did not vary between groups. Thus, the presence of a signal for the outcome was not what was responsible for the reduced pupil response to the outcome observed over trials. Rather, that reduction was simple habituation to the stimulus.

On the final test with the US in the Firing group there was no notable response to the signaling cue when it was the Same cue as used in training and there was very little response to the outcome. The dilation response to these stimuli and actions had habituated over trials. In the groups where the outcome was unexpected because it was signaled by a Different cue or unsignalled, there was a substantial dishabituation of the response to the outcome. That overall pattern suggests that the unexpected initiation of responding supports a dilation of the pupils. In the Same group participants were already responding at the time the outcome arrived, and any effect that the appearance of the outcome had on pupil responses had habituated over conditioning so little response was observed in that group. The Different group showed a pupil response to the novel cue, and an increase in that response in the presence of the outcome. As the keyboard data show, the Different group did not respond on the keyboard to the novel cue, thus their keyboard responses, along with the unsignaled group, were initiated with the arrival of the outcome.

4. Conclusions and general discussion

The present experiment produced evidence for outcome searching in simple conditioning. As participants associated the appearance of spaceships with the illumination of predictive sensors in a video game, two clear changes occurred. Overt visual attention to the sensor declined and attention to the area of the screen where the spaceship was scheduled to appear increased. On the first trial participants devoted substantial attention to the novel sensor, and that declined rapidly both within and between trials, showing no further change between trials after the second trial. On subsequent trials participants spent about .5 s looking at the sensor on the first second of its presentation, and that attention declined within each trial. As the participants only needed to detect and identify the stimulus, which was physically simple and easily recognizable, very little attention was perhaps needed for it to direct behavior (see also Hogarth et al., 2009).

As the participants associated the sensor with the spaceship, their anticipatory keyboard responding increased over trials. In a largely parallel fashion, their gaze towards the area of the screen where the outcome would appear also increased. Interestingly, participants gaze toward the weapon, which minimally fired at the end of the trial, also increased whether they were required to respond, or not. That increase in gaze could be due to expecting the weapon to fire, or perhaps due to some type of within-compound association between the weapon and the spaceship.

There was a further effect of the spatial contiguity between the weapon and the spaceship on associating the cue with the outcome (c.f. Christie, 1996; Rescorla, 1979). Anticipatory keyboard responding to activate the weapon in the presence of the cue was acquired more rapidly when the spaceship's appearance and the weapon were both on the right side of the screen as compared to the spaceship appearing from the left.

Similar results were obtained in a report by Thorwart, Uengoer, Livesey, and Harris (2017). In a computer task, participants earned points by catching fish (1 point per fish) by clicking on fish when they appeared in a stream to the left of the screen. They were also tasked with “feeding a pig” by clicking on the entrance to a cave where the pig’s eye would appear for one second. There was a limited hold on the response. If participants made the correct response in the second when the eyes were visible, they were awarded 100 points, otherwise they were punished by losing 100 points. Both the reward and punishment far outweighed what the would earn or lose by catching or missing fish, respectively.

The appearance of the eyes was signaled by compound stimuli formed by changing the color of the river accompanied by an auditory cue. The compound lasted between 3.66 and 4.66 s. The eyes appeared during the last second of the compound cue. Participants came to direct their mouse to the cave during the cues, prior to the occurrence of the eyes. That is, as they learned to anticipate the eyes given the cues, they directed their mouse, and ostensibly their attention, to the location where the eyes would appear. The present results compliment these in that participants came to direct overt visual attention to the area where an expected event was predicted to occur, while differing in several respects. In the feed-the-pig task, the window of time in which a response can be rewarded, or a punishment avoided, is very small and not very well predicted by the variable-duration compound CS. Thus, moving the mouse to the target zone undoubtedly allows the subject to avoid missing the click window, and thus, is reinforced by both positive and negative reinforcement.

In the present task the anticipatory eye gaze appeared to be driven only by the correlation between the sensor and the outcome. The gaze was wholly incidental in that none of the events or outcomes in the procedure were contingent upon it, or affected by it. Neither did gaze seem be affected by whether participants were required to respond to the spaceship or not. When the spaceship appears, it appears rapidly and is accompanied by a unique and somewhat aversive sound. It is visible and substantially large enough that it is identifiable regardless of where the participant’s eyes are focused at the moment of arrival. The exact point of entry is not predictable, thus, regardless of whether participants were looking in the general area or not, they would still need 200 or so milliseconds to initiate a saccade to focus on the ship when it appears. It does not seem likely that the spaceship appearance simply provides operant reinforcement for searching in the area of its initial arrival. For example, on trial 1 the data show that participants were mostly looking to the sensor when the spaceship arrived, with other looks divided between the Outcome and Other Zones. Nevertheless, looking at the sensor, the predominant behavior occurring immediately prior to the ship’s appearance, decreased subsequently as did looking at the other side of the screen.

All the information that the participant needs to learn the task and respond appropriately is present when the spaceship arrives. In Experiment 2, the search response was observed even though no responding or action of the participant was required. Attending to the arrival area ahead of time confers no additional knowledge than that provided by the arrival, and has no effect upon any of the events. As participants became more certain that the outcome was forthcoming given the signal, as evidenced by their keypressing, they devoted more time searching for the outcome in its absence. When participant uncertainty appeared to be at a minimum, their outcome searching was at its strongest.

The results show that participants learn not only what cues predict, but also where those events will occur. Such knowledge is clearly useful in guiding appropriate responses to anticipated events in real-world settings. Moreover, it is knowledge that is largely taken for granted in studies of associative learning. Understanding that aspect of conditioning has important implications for how conditioning occurs and what is learned. For example, in the present study the tonic contextual elements of the scene indicated where the outcome would arrive (e.g., on the right side between weapons). The “what and when” (e.g., Bouton, 1997) aspects of the outcome appear controlled by the CS, while the “where” requires contextual cues to localize the event. Moreover, there was no evidence in the pre-CS data of participants attending to the outcome areas in the absence of the CS. Thus, a presumably simple CS could have multiple roles, signaling what event will occur, as well as when it will occur, while “occasion setting” (see Fraser and Holland, 2019, for review) the context’s ability to indicate where the event will occur. Changes of context sometimes produce losses of conditioned responding (e.g., Honey & Hall, 1989; Honey et al., 1990) that are thought to reflect retrieval failure on the part of the CS (e.g., Bouton, 1993). Rather, the knowledge controlled by the CS might be intact, while the knowledge of “where” the event occurs is disrupted by the context change, disrupting performance.

Knowledge of where events occur should also be considered in studies of attention devoted to predictive stimuli. As shown in the present work, when predicted outcomes are localizable in space and time, particularly in a space separate from the signal, attention devoted to these upcoming events could interfere with measurements of what are assumed to be attentional changes to the cues. The results also suggest that visual anticipatory outcome searching can be used as an index of associative learning. To the extent that gaze behavior reflects unconscious processes (e.g., Hopkins et al., 2015, 2016; Madipakkam et al., 2016), visual anticipatory outcome searching might also be useful in distinguishing the operation of supposed lower-level associative processes from reasoning-accounts of conditioning.

The present work shows that a simple contingency between events can lead to searching for the predicted event in the presence of the predictive cue. An application of this finding to the literature on goal inference/anticipation in adults and infants is beyond the scope of this manuscript, but the findings indicate that such processes should be considered. Pavlovian conditioning has been assumed to be a process underlying and co-existing with cognition (McLaren et al., 2019). It could also underly goal inference, or at least interfere with that process, in some cases, and produce results that are more consistent with practice trials producing Pavlovian learning rather than reasoning about goals (e.g., Paulus et al., 2011). Many well documented and understood phenomena associated with classical conditioning, such as the finding that not all stimuli are equally associable (e.g., Garcia et al., 1972; Ohman and Mineka, 2001) and factors that dictate when prior experiences with stimuli can attenuate (e.g., Lubow, 1973; Nelson and Sanjuan, 2006) or facilitate (e.g., Balea et al., 2018; Kehoe et al., 1995) subsequent learning, can improve our understanding of the factors that contribute to the attribution of goal directedness to other’s behavior.

In the present method, we observed a pupil-dilation response to the spaceship outcomes both when participants were firing and when they were not, though the effect was larger in the former condition. Participants’ pupils also dilated in response to the cue, but only when they were firing and not when they were simply observing events. Thus, there was no evidence that the pupillary response evoked by the outcome was conditioned to the cue. Neither was there evidence that the pupil response to the outcome was modulated by the cue other than by the cue’s effects on initiating keyboard responding.

Pupils dilate in many situations (see Einhäuser, 2017, for review), particularly as a function of cognitive load (e.g., Beatty, 1982), arousal (e.g., Bradley et al., 2008), and responding (Richer and Beatty, 1985). The changes in dilation observed here appeared to simply be the sum of these processes being affected by habituation over trials. The initial levels of dilation observed were likely due to arousal and cognitive load as participants were observing and learning about all the elements of the game. Initiating responding, or the presence of novel stimuli also led to dilation. As the participants became more familiar with the game and responding, pupil dilations produced by these processes habituated over trials. Unlike other methods where pupil diameters have been shown to be valuable indexes of associative learning (Reinhard, and Lachnit, 2002; Reinhard et al., 2006), they are not in the present method, and are not universal in that regard. There is little in the present pupil data to suggest anything other than that, with this method, they are simple orienting-type responses that habituate with experience.

Declarations of interest

None.

Acknowledgments

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References

Arcediano, F., Ortega, N., Matute, H., 1996. A behavioural preparation for the study of human pavlovian conditioning. Q. J. Exp. Psychol. 49B, 270–283.
Arnaut, L., Shettleworth, S.J., 1981. The role of spatial and temporal contiguity in defensive burying in rats. Anim. Learn. Behav. 9, 275–280.
Balea, P., del Carmen Sanjuan, M., Nelson, J.B., 2018. Learning to learn in conditioning and extinction in humans. Behav. Processes 157, 148–160.
Beatty, J., 1982. Task-evoked pupillary responses, processing load, and the structure of processing resources. Psychol. Bull. 91, 276–292.
Beesley, T., Le Pelley, M.E., 2011. The influence of blocking on overt attention and associability in human learning. J. Exp. Psychol. Anim. Behav. Process. 37, 114–120.
Beesley, T., Nguyen, K.P., Pearson, D., Le Pelley, M.E., 2015. Uncertainty and predictiveness determine attention to cues during human associative learning. Q. J. Exp. Psychol. 68, 2175–2199.
Biro, S., 2013. The role of the efficiency of novel actions in infants' goal anticipation. J. Exp. Child Psychol. 116 (2), 415–427.
Boakes, R.A., 1977. Performance on learning to associate a stimulus with positive reinforcement. In: Davis, H., Hurwitz, M.B. (Eds.), Operant-Pavlovian Interactions. Lawrence Erlbaum Associates, Hillsdale, New Jersey, pp. 67–101.
Bouton, M.E., 1997. Signals for whether versus when an event will occur. In: Fanselow, M.S., Bouton, M.E. (Eds.), Learning, Motivation, and Cognition: The Functional Behaviorism of Robert C. Bolles. American Psychological Association, Washington, DC, pp. 385–409.
Bradley, M.M., Miccoli, L., Escrig, M.A., Lang, P.J., 2008. The pupil as a measure of emotional arousal and autonomic activation. Psychophysiology 45, 602–607.
Christie, J., 1996. Spatial contiguity facilitates Pavlovian conditioning. Psychon. Bull. Rev. 3, 357–359.
Einhäuser, W., 2017. The pupil as marker of cognitive processes. Computational and Cognitive Neuroscience of Vision. Springer, Singapore, pp. 141–169.
Eshuis, R., Coventry, K.R., Vulchanova, M., 2009. Predictive eye movements are driven by goals, not by the mirror neuron system. Psychol. Sci. 20 (4), 438–440.
Falck-Ytter, T., Gredebäck, G., von Hofsten, C., 2006. Infants predict other people's action goals. Nat. Neurosci. 9 (7), 878.
Flanagan, J.R., Johansson, R.S., 2003. Action plans used in action observation. Nature 424 (6950), 769–771.
Franssen, M., Clarysse, J., Beckers, T., van Vooren, P.R., Baeyens, F., 2010. A free software package for a human online-conditioned suppression preparation. Behav. Res. Methods 42 (1), 311–317.
Fraser, K.M., Holland, P.C., 2019. Occasion setting. Behav. Neurosci. 133 (2), 145–175.
Garcia, J., McGowan, B.K., Green, K.F., 1972. Biological constraints on conditioning. In: Black, A.H., Prokasy, W.F. (Eds.), Classical Conditioning II: Current Research and Theory. Appleton-Century-Crofts, New York, pp. 3–27.
Gergely, G., Csibra, G., 2003. Teleological reasoning in infancy: the naïve theory of rational action. Trends Cogn. Sci. 7 (7), 287–292.
Gredebäck, G., Kochukhova, O., 2010. Goal anticipation during action observation is influenced by synonymous action capabilities, a puzzling developmental study. Exp. Brain Res. 202 (2), 493–497.
Harris, J.A., Andrew, B.J., Kwok, D.W., 2013. Magazine approach during a signal for food depends on Pavlovian, not instrumental, conditioning. J. Exp. Psychol. Anim. Behav. Process. 39, 107–116.
Hearst, E., Jenkins, H.M., 1974. Sign-tracking: the Stimulus-reinforcer Relation and Direction Action. Psychonomic Society, Austin, Texas.
Henrichs, I., Elsner, C., Elsner, B., Gredebäck, G., 2012. Goal salience affects infants' goal-directed gaze shifts. Front. Psychol. 3, 391.
Hogarth, L., Dickinson, A., Hutton, S.B., Bamborough, H., Duka, T., 2006a. Contingency knowledge is necessary for learned motivated behaviour in humans: relevance for addictive behaviour. Addiction 101, 1153–1166.
Hogarth, L., Dickinson, A., Hutton, S.B., Elbers, N., Duka, T., 2006b. Drug expectancy is necessary for stimulus control of human attention, instrumental drug-seeking behaviour and subjective pleasure. Psychopharmacology 185, 495–504.
Hogarth, L., Dickinson, A., Wright, A., Kouvaraki, M., Duka, T., 2007. The role of drug expectancy in the control of human drug seeking. J. Exp. Psychol. Anim. Behav. Process. 33, 484–496.
Hogarth, L., Dickinson, A., Austin, A., Brown, C., Duka, T., 2008a. Attention and expectation in human predictive learning: the role of uncertainty. Q. J. Exp. Psychol. 61, 1658–1668.
Hogarth, L., Dickinson, A., Janowski, M., Nikitina, A., Duka, T., 2008b. The role of attentional bias in mediating human drug-seeking behaviour. Psychopharmacology 201, 29–41.
Hogarth, L., Dickinson, A., Duka, T., 2009. Detection versus sustained attention to drug cues have dissociable roles in mediating drug seeking behavior. Exp. Clin. Psychopharmacol. 17, 21.
Holland, P.C., 1977. Conditioned stimulus as a determinant of the form of the Pavlovian conditioned response. J. Exp. Psychol. Anim. Behav. Process. 3, 77–104.
Holland, P.C., 1979. Differential effects of omission contingencies on various components of Pavlovian appetitive conditioned responding in rats. J. Exp. Psychol. Anim. Behav. Process. 5, 178–193.
Honey, R.C., Willis, A., Hall, G., 1990. Context specificity in pigeon autoshaping. Learn. Motiv. 21, 125–136.
Hopkins, L.S., Schultz, D.H., Hannula, D.E., Helmstetter, F.J., 2015. Eye movements index implicit memory expression in fear conditioning. PLoS One 10 (11), e0141949. https://doi.org/10.1371/journal.pone.0141949.
Hopkins, L.S., Helmstetter, F.J., Hannula, D.E., 2016. Eye movements are captured by a perceptually simple conditioned stimulus in the absence of explicit contingency knowledge. Emotion 16, 1157.
Howell, D.C., 1987. Statistical methods for psychology PWS-Kent. Boston, MA.
Ivanov-Smolensky, A.G., 1927. On the methods of examining the conditioned food reflexes in children and in mental disorders. Brain 50 (2), 138–141.
Kamin, L.J., Schaub, R.E., 1963. Effects of conditioned stimulus intensity on the conditioned emotional response. J. Comp. Physiol. Psychol. 56 (3), 502.
Kanakogi, Y., Itakura, S., 2011. Developmental correspondence between action prediction and motor ability in early infancy. Nat. Commun. 2, 341.
Kaye, H., Pearce, J.M., 1984. The strength of the orienting response during conditioning. J. Exp. Psychol. Anim. Behav. Process. 10, 90–109.
Kehoe, E.J., Horne, A.J., Macrae, M., 1995. Learning to learn: real-time features and a connectionist model. Adapt. Behav. 3, 235–271.
Kochukhova, O., Gredebäck, G., 2010. Preverbal infants anticipate that food will be brought to the mouth: an eye tracking study of manual feeding and flying spoons. Child Dev. 81 (6), 1729–1738.
Kruschke, J.K., Kappenman, E.S., Hetrick, W.P., 2005. Eye gaze and individual differences consistent with learned attention in associative blocking and highlighting. J. Exp. Psychol. Learn. Mem. Cogn. 31, 830–845.
Land, M., Mennie, N., Rusted, J., 1999. The roles of vision and eye movements in the control of activities of daily living. Perception 28 (11), 1311–1328.
Le Pelley, M.E., Beesley, T., Griffiths, O., 2011. Overt attention and predictiveness in human contingency learning. J. Exp. Psychol. Anim. Behav. Process. 37 (2), 220–229.
Le Pelley, M.E., Mitchell, C.J., Beesley, T., George, D.N., Wills, A.J., 2016. Attention and associative learning in humans: an integrative review. Psychol. Bull. 142, 1111–1140.
Lubow, R.E., 1973. Latent inhibition. Psychol. Bull. 79 (6), 398–407.
Madipakkam, A.R., Rothkirch, M., Wilbertz, G., Sterzer, P., 2016. Probing the influence of unconscious fear-conditioned visual stimuli on eye movements. Conscious. Cogn. 46, 60–70.
McLaren, I.P.L., McAndrew, A., Angerer, K., McLaren, R., Forrest, C., Bowditch, W., et al., 2019. Mackintosh lecture: Association and cognition: Two processes, one system. Q. J. Exp. Psychol. 72, 98–117.
Mennie, N., Hayhoe, M., Sullivan, B., 2007. Look-ahead fixations: anticipatory eye movements in natural tasks. Exp. Brain Res. 179, 427–442.
Mitchell, C.J., Griffiths, O., Seetoo, J., Lovibond, P.F., 2012. Attentional mechanisms in learned predictiveness. J. Exp. Psychol. Anim. Behav. Process. 38, 191–202.
Nelson, J.B., 2002. Context specificity of excitation and inhibition in ambiguous stimuli. Learn. Motiv. 33, 284–310.
Nelson, J.B., Sanjuan, M., 2006. A context-specific latent inhibition effect in a human conditioned suppression task. Q. J. Exp. Psychol. 59 (6), 1003–1020.
Nelson, J.B., Navarro, A., Sanjuan, M., 2014. Presentation and validation of "the Learning Game", a tool to study associative learning in humans. Behav. Res. Methods 46, 1068–1078.
Ohman, A., Mineka, S., 2001. Fears, phobias, and preparedness: toward an evolved module of fear and fear learning. Psychol. Rev. 108, 483–522.
Paulus, M., Hunnius, S., van Wijngaarden, C., Vrins, S., van Rooij, I., Bekkering, H., 2011. The role of frequency information and teleological reasoning in infants' and adults' action prediction. Dev. Psychol. 47 (4), 976.
Reinhard, G., Lachnit, H., 2002. Differential conditioning of anticipatory pupillary dilation responses in humans. Biol. Psychol. 60, 51–68.
Reinhard, G., Lachnit, H., König, S., 2006. Tracking stimulus processing in Pavlovian pupillary conditioning. Psychophysiology 43, 73–83.
Rescorla, R.A., 1979. Spatial contiguity facilitates Pavlovian second-order conditioning. J. Exp. Psychol. Anim. Behav. Process. 5, 152–161.
Richer, F., Beatty, J., 1985. Pupillary dilations in movement preparation and execution. Psychophysiology 22, 204–207.
Ross, R.R., LoLordo, V.M., 1986. Rearing in response to a visual conditioned stimulus: an index of associative strength or of associabiity? Learn. Motiv. 17, 335–346.
Silva, F.J., Silva, K.M., Pear, J.J., 1992. Sign-versus goal-tracking: effects of conditioned-stimulus-to-unconditioned-stimulus distance. J. Exp. Anal. Behav. 57, 17–31.
Williams, D.R., Williams, H., 1969. Auto-maintenance in the pigeon: sustained pecking despite contingent non-reinforcement. J. Exp. Anal. Behav. 12, 511–520.
Wills, A.J., Lavric, A., Croft, G.S., Hodgson, T.L., 2007. Predictive learning, prediction errors, and attention: evidence from event-related potentials and eye tracking. J. Cogn. Neurosci. 19, 843–854.