The Role of Prediction in Learned Predictiveness.

Carla J. Eatherington¹

Mark Haselgrove²

¹The University of Lincoln

²The University of Nottingham

Correspondence Address:

Mark Haselgrove

School of Psychology

University Park

The University of Nottingham

Nottingham

NG7 2RD, UK

Email: Mark.Haselgrove@Nottingham.ac.uk

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Abstract

Learning permits even relatively uninteresting stimuli to capture attention if they are established as predictors of important outcomes. Associative theories explain this “learned predictiveness” effect by positing that attention is a function of the relative strength of the association between stimuli and outcomes. In three experiments we show that this explanation is incomplete: learned overt visual-attention is not a function of the relative strength of the association between stimuli and an outcome. In three experiments, human participants were exposed to triplets of stimuli that comprised (i) a target (which defined correct responding), (ii) a stimulus which was perfectly correlated with the presentation of the target and (iii) a stimulus which was uncorrelated with the presentation of the target. Participants’ knowledge of the associative relationship between the correlated/uncorrelated stimuli and the target was always good. However, eye-tracking revealed that an attentional bias towards the correlated stimulus only developed when it AND target-relevant responding preceded the target stimulus. We propose a framework in which attentional changes are modulated during learning as a function the relative strength of the association between stimuli and the task-relevant response, rather than an association between stimuli and the task-relevant outcome.

Keywords: Learning; Attention; Association; Eye-tracking; Learned Predictiveness

Introduction.

The study of the relationship between learning and attention has a long history. Pavlov (1927) noted that a novel stimulus presented to an organism would elicit an “investigatory reflex” (p.12) - something that would today be referred to as an orienting response, and Lashley (1929) soon after, noted that only stimuli, or components of stimuli, that are organised by the principles of attention will become associated with one another. In the intervening 90 or so years there has been much discussion about the relationship between learning and attention (for reviews see: Le Pelley, 2004; Le Pelley, Mitchell, Beesley, George & Wills, 2016; Mackintosh, 1975; Pearce & Hall, 1980), but one feature of this relationship that has sustained interest is the extent to which a stimulus will come to attract attention if it is *predictive* of a subsequent event. In his influential theory of attention, for example, Mackintosh (1975) proposed that “subjects learn to attend to and ignore stimuli to the extent that those stimuli successfully predict the outcome of a trial”, and more recent theoretical analyses of learning and attention make similar claims (e.g. Esber & Haselgrove, 2011; George and Pearce, 2012; Le Pelley, 2004). This general principle has become known as the predictiveness principle, which refers to the idea that “*cues become more psychologically salient as a result of their predictiveness with respect to important outcomes; more attention will be allocated to predictive cues than to nonpredictive cues,*” (Le Pelley et al., 2016, p. 8).

There seems to be good reason for advocating a general predictiveness-principle too. So called “learned predictiveness” tasks reliably show that stimuli which are good predictors of an outcome come to attract more overt visual attention than stimuli which are not. For example, in a study by Le Pelley, Beesley, and Griffiths (2011) participants’ eye movements were recorded while they were presented with pairs of stimuli (nonsense words) on a computer screen, and on each trial asked to predict which of two different outcomes (sounds) would follow each pair. Across the experimental design, half of the stimuli were perfectly

predictive of the identity of the outcome, whilst the remainder of the stimuli were irrelevant. The specifics of the design of the training can be seen in Table 1, where the nonsense words are represented as letters A to D, and V to Y. As can be seen, stimuli A and D were predictive of Outcome 1, and stimuli B and C were predictive of Outcome 2 thus permitting the solution of this task. Stimuli V to Y, however, were presented on trials that terminated with Outcome 1 and Outcome 2. These stimuli were therefore predictively redundant and consequently irrelevant to the solution of this task.

Outcome 1	Outcome 2
AV	BV
AW	BW
DX	CX
DY	CY

Table 1. Design of the training received by participants in Le Pelley et al's (2011) study. Letters A to D, and V to Y denote nonsense words presented on screen. Outcomes 1 and 2 denote the sounds participants were required predict based upon the identity of the nonsense words.

The results of Le Pelley et al.'s (2011) study revealed that, as a consequence of this training, participants' visual dwell times were longer to the predictive stimuli than the irrelevant stimuli, a result that has been reproduced on a number of occasions using a variety of stimuli and tasks, in different laboratories (e.g.: Alamia & Zénon, 2016; Aristizabal, Ramos-Álvarez, Callejas-Aguilera & Rosas, 2016; Beesley, Nguyen, Pearson & Le Pelley, 2015; Griffiths & Mitchell, 2008; Haselgrove et al., 2015; Lochmann & Wills, 2003;

Mitchell, Griffiths, Seetoo & Lovibond, 2012). It is also a result that concurs with studies of learning and attention in non-human animals (e.g.: Haselgrove, Esber, Pearce & Jones, 2010; Mackintosh & Little, 1969, Roberts, Robbins, & Everitt, 1988)

Experimental results which conform to the predictiveness principle are often interpreted in terms of the framework provided by associative theories of learning. These theories stipulate that the attention that is paid to a stimulus can change according to some function of its associative strength, or the difference between its associative strength and the magnitude of the outcome: the so-called prediction error. To illustrate this, it is useful to consider the theory proposed by Mackintosh (1975), an influential model of learning in its own right, but one which has also been incorporated into more contemporary, and comprehensive treatments of learning (e.g. Le Pelley, 2004; Pearce & Mackintosh, 2010). According to Mackintosh, the change in the strength of the association between a stimulus (e.g. A) and an outcome (ΔV_A) is determined by Equation 1:

$$\Delta V_A = \alpha \cdot \theta \cdot (\lambda - V_A) \quad (\text{Equation 1})$$

Here, the error term ($\lambda - V_A$) is the discrepancy between the magnitude of the outcome (λ) and the current associative strength of stimulus A. θ is a learning rate parameter, determined by the properties of the outcome. Most important for the Mackintosh model, α is a variable stimulus-attention parameter that may increase or decrease following the consequence of each trial. The rules proposed by Mackintosh for determining these increases and decreases in attention ($\Delta\alpha$) are shown in Equations 2a and 2b respectively:

$$\Delta\alpha_A > 0 \text{ if } |\lambda - V_A| < |\lambda - V_r| \quad (\text{Equation 2a})$$

$$\Delta\alpha_A < 0 \text{ if } |\lambda - V_A| \geq |\lambda - V_r| \quad (\text{Equation 2b})$$

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115   where V_r is the sum of the associative strength of all stimuli present on that trial,
 116 minus V_A (i.e. it is the remainder). The size of the change in $\Delta\alpha_A$ is assumed to be
 117 proportional to the magnitude of the inequalities in Equations 2a or 2b. Using these
 118 equations, it can be seen how Mackintosh's (1975) theory provides a mechanism for
 119 understanding the predictiveness principle. For example, the error terms of the predictive
 120 stimuli (A to D) in Le Pelley et al.'s (2011) study, for example, will on each trial be less than
 121 the error terms of the irrelevant stimuli (V to Y). Consequently, it follows from Equation 2a
 122 that attention to predictive stimuli will increase, and from Equation 2b that attention to
 123 irrelevant stimuli will decrease.

124   One might wish to make the argument, however, that a sleight of hand is being
 125 performed when associative theories of attention, such as Mackintosh's (1975) theory, are
 126 applied to our understanding of the predictiveness principle. Associative theories, rather
 127 paradoxically, say very little about how time is represented during learning (Gallistel &
 128 Gibbon, 2000). According to these theories, when events are paired, an opportunity is
 129 provided for an association to form between them. However, no information about the
 130 temporal relationship between the events themselves forms a part of the association.
 131 Consequently, the notion that a stimulus may be *predictive* of another event rather than
 132 merely *connected* to it, is something that is beyond the explanation of most accounts of
 133 associative learning. Consider Equations 1, 2a and 2b, for example; these analyses of learning
 134 and attention make no explicit statement about the role of time, sequence or (crucially)
 135 prediction in learning. Instead, association and associative error, are employed to drive

learning and attention; and yet conceptual understandings of learning and attention appeals to the role of prediction and prediction error in order to explain attentional phenomena such as the so-called learning-predictiveness effect.

Perhaps, then, we have gone too far in our analysis of the role of prediction in learning and attention. There are at least two reasons for thinking this may be so. The first is historical: William James (1890) in his classic “Principles of Psychology” considered how attention might come to be derived by stimuli, and he noted that under such circumstances stimuli owe their attention to “association with some other immediately interesting thing” (p. 416). Thus for William James, at least, it was through association and not prediction that stimuli may come to acquire attention. The second reason is a hint provided from empirical evidence. Cue competition effects such as overshadowing and blocking, which are typically revealed under circumstances in which a predictive relationship is established between stimuli and outcomes (e.g. Kamin, 1968, Pavlov, 1928), have been demonstrated to be (at least in part) a consequence of an attentional learning mechanism (e.g. Dickinson, Hall & Mackintosh, 1976; Jones & Haselgrove 2011; 2013; Mackintosh, 1976). However, both overshadowing and blocking can also be observed under circumstances in which the experimental stimuli and outcomes are all presented to the organism simultaneously (e.g. Blaisdell, Denniston & Miller, 1998; Dwyer, Jones & Haselgrove 2011) thus robbing the stimuli of their predictive significance. If demonstrations of simultaneous-stimulus blocking and overshadowing are also partly a function of an attentional learning mechanism then it opens up the possibility that the role of prediction in learned changes in attention has been overstated.

The purpose of the experiments reported here was to uncouple association and prediction in order to determine their roles in learned changes in attention. To do this we investigated whether overt changes in attention were acquired to stimuli that were

associatively correlated, or uncorrelated, with other events in the world *in the absence of a sequential, predictive, relationship between them*. To anticipate our results, we observed that association between stimuli alone was insufficient to modulate an attentional bias. Instead, a learned attentional bias was only acquired to stimuli when predictive responding was necessitated by the task. We consider the role of the association between stimuli and task-relevant responding in order to explain these results.

Experiment 1

Experiment 1 established a scenario in which stimuli were either correlated or uncorrelated with the presentation of a target stimulus, in the absence of any predictive relationship. The question of interest was whether, under these circumstances, visual dwell time would be longer to stimuli that were correlated with the target than stimuli which were uncorrelated with it. To achieve this, participants were trained with triplets of stimuli, each of which comprised a target stimulus (that participants were required to respond to), a correlated stimulus (that was presented with the target stimulus on 100% of the training trials) and an uncorrelated stimulus (that was presented with the target stimulus on only 50% of the training trials). The specifics of the design are shown in Table 2. It can be seen that during the training trials, stimuli U and V were perfectly correlated with the presentation of the targets Y and Z respectively. However, stimuli W and X were uncorrelated with the target stimuli as they are presented equally frequently with Y and Z and thus provide no information about the identity of the target stimulus. Occasional test trials were presented that comprised only the correlated and uncorrelated stimuli.

Training trials	Correct response (Target)	Test trials
U W Y	Y	U W
U X Y	Y	U X
V W Z	Z	V X
V X Z	Z	V W

Table 2. Example Design of Experiment 1. Triplets of letters comprising correlated, uncorrelated and target stimuli were presented on screen. Responses to the presentation of either of two target stimuli (e.g. Y and Z) were required. Test trials with the correlated and uncorrelated stimuli alone were interspersed throughout training with the training trials.

The duration of participants eye gaze towards the correlated and uncorrelated stimuli was measured to determine whether participants acquired an attentional bias towards the correlated stimuli on the basis of their perfect association with the target stimulus, relative to the uncorrelated stimulus. According to analyses that emphasise the importance of association in the acquisition of attention, such as that proposed by James (1890), and which is modelled in more contemporary associative formalisations (e.g. Esber & Haselgrove, 2011; Mackintosh, 1975) a stimulus that is correlated with the occurrence of the target will acquire more attention than a stimulus that is uncorrelated with the occurrence of the target. The same prediction does not necessarily hold if it is thought that prediction is an important determinant of learned changes in attention (e.g. Le Pelley et al., 2016).

Methods

Participants. Eighteen participants (14 females; 4 males) were recruited from the University of Nottingham's School of Psychology. Participants had a mean age of 19.6 yrs ($SD = 0.61$).

All participants had normal or corrected-to-normal vision, and were excluded if they reported a history of visual disturbances triggered by flashing lights. Participants received course credit for their participation or a £3 inconvenience allowance. This experiment, as well as Experiments 2 and 3, received ethical approval from the institution's local ethics committee.

Apparatus and stimuli. The experiment was designed and run using Experiment Builder version 1.10.1630. An SR (Mississauga, Canada) Research Eyelink 1000 Plus eye-tracker sampled participant's right eye at a rate of 1000 Hz. Gaze location was determined by monitoring the location of the pupil using an infrared camera mounted on the desk in front of the display monitor. Thresholds used to define fixations and saccades were: 15° displacement, 30°/s velocity and 8,000°/s² acceleration. Participants viewed stimuli binocularly from a distance of 67 cm, and head movements were minimised using a chin and forehead rest. Stimuli were presented upon a BenQ XL2420T LED monitor (33 x 57 cm) with a resolution set to 1920 x 1080 at 114 Hz. Stimuli consisted of the letters U, V, W, X, Y and Z, presented in the colour black, font size 60, Times New Roman. Stimuli were presented 5 cm apart from each other, at the apexes of a notional upright equilateral triangle the centre of which coincided with the centre of the monitor screen. All stimuli were presented on a white background and subtended a visual angle of 25.4°. Regions of interest were set to 2.7 x 2.7 cm squares centred on each letter. Stimuli were counterbalanced as either the target, correlated or uncorrelated stimuli.

Procedure. Eye movement data were recorded from each participant's right eye. The eye-tracker was calibrated for each participant at the outset of the experimental session using a nine-point calibration, except for two participants who could only be calibrated using a

five-point procedure. A brief health questionnaire was administered to screen for exclusion criteria, written instructions were given, and informed consent was gained. At the start of each experimental session, the experimenter checked that both pupil and corneal reflections were present whilst participants read the on-screen instructions before performing a calibration. The written instructions for the calibration task were: *“Thank you for participating in this study. Your first task is to focus on the dot and follow it with your eyes. Press the space bar to begin the experiment.”* After performing the calibration, participants read further on-screen instructions: *“Each trial will begin with a fixation cross in the centre of the screen. You need to look directly at the cross. Following this, your task is to indicate whether the letter (Y or Z) is present in the array. Try to remember which letters are paired together because at the end of the experiment you will have a memory test. (Y = left, Z = right). Press any key to start the experiment.”*. Non-italicised text in brackets indicates example text that was counterbalanced for each participant.

Each trial began with the presentation of a 1 cm² fixation cross located in the centre of the screen for 1000ms. This was then replaced with either the triplets of stimuli (on training trials) or pairs of stimuli (test trials). The triplet stimuli remained on the screen until a response was made; the test trials stimuli remained on screen for 5000 ms. Each trial was separated by an inter-stimulus interval of 1000 ms, during which the screen was blank. Each of the four compounds of three stimuli shown in table 2 was presented on 72 occasions across the experiment, providing 288 training trials in total. In addition, there were 24 test trials with the correlated and uncorrelated stimuli presented in the absence of the target stimulus (which may reasonably be expected to command most of the visual attention). Trial order was randomised over the whole experiment (312 trials in total). Stimulus position was varied across the experiment to ensure that target, correlated and uncorrelated stimuli were presented equally frequently in all three positions on both training and test trials.

After participants completed the experiment they were given two paper-based questionnaires each of which tested their understanding of the relationship between the correlated and uncorrelated stimuli with each target stimuli. At the top of the page was written, for example “*How likely was the letter “TARGET STIMULUS ” to be paired with the following letters?(please circle)*”. Presented underneath this question were the two correlated and two uncorrelated stimuli, next to each of which was a 10 point Likert scale that was anchored with the word “Unlikely” adjacent to the number 1, and the word “Likely” adjacent to the number 10. Upon completion of the questionnaires participants were thanked for their time and debriefed.

Results

Occasionally the eye-tracker lost track of pupil and corneal reflections, resulting in missing eye-movement data. Participants were excluded from further analysis if the percentage of missing data were greater than 20% (zero participants were excluded on this basis). Furthermore, if participants were excluded if they achieved less than 60% correct responses across all trial blocks (zero participants were excluded on this basis). For statistical analyses in this and subsequent experiments, Greenhouse-Geisser corrections were applied where sphericity was violated, however, degrees of freedom are rounded to the nearest whole number for the sake of clarity.

Behavioural data. Panel A of Figure 1 shows the mean proportion of correct responses over 16 blocks of 18 trials and reveals that participants performed the task accurately from trial block 1, and by block 16 had a mean accuracy of almost 96%, which a one-sample t-test revealed to be significantly above chance ($.5$), $t(17) = 69.28$, $p < .001$. A one-way repeated

measures Analysis of Variance (ANOVA) of mean proportion correct with the factor of block (1-16) revealed a non-significant main effect, $F(5, 87) = .73$, $\eta p^2 = .04$, $p = .605$, reflecting the lack of change over training. Similarly, the mean response time, measured from the termination of the fixation cross, varied very little across training (Figure 1, Panel B). A one-way repeated measures ANOVA of response time (RT) with the factor of block (1-16) also revealed a non-significant main effect, $F(4,60) = .66$, $\eta p^2 = .04$, $p = .606$].

INSERT FIGURE 1 HERE

Eye gaze analysis. Mean proportions of dwell time were calculated by dividing the total dwell time each participant spent within an ROI on each trial by the RT for that trial. These dwell times for the correlated, uncorrelated and target stimuli during the training trials are shown in the Panel C of Figure 1. This reveals that the target stimuli attracted the largest proportion of dwell time, and very little was directed either towards the correlated or the uncorrelated stimuli. A two-way repeated measures ANOVA of proportion of dwell time with the factors of stimulus type (target vs. correlated vs. uncorrelated) and trial block (1- 16) revealed a significant main effect of stimulus type, $F(1,19) = 58.02$, $\eta p^2 = .77$, $p < .001$, trial block, $F(4,73) = 4.43$, $\eta p^2 = .21$, $p = .002$, and a significant interaction, $F(22,374) = 1.86$, $\eta p^2 = .10$, $p = .050$. Simple main effects analysis of this interaction revealed a significant difference between the proportion of dwell time directed towards target stimuli and the correlated or uncorrelated stimuli from block 1 onwards, smallest, $F(1,19) = 26.03$, $\eta p^2 = .51$, $p < .001$, with the target stimuli always attracting a higher proportion of dwell time than the correlated and uncorrelated stimuli, which did not differ.

It was important to ascertain whether this non-significant difference between correlated and uncorrelated stimuli supported the null hypothesis (there was no difference between the proportion of dwell time directed towards correlated and uncorrelated stimuli), or supported no conclusion at all (Dienes, 2011). To decide between these two possibilities, a Bayes factor analysis was conducted. A Bayes factor of less than .33 would support the null hypothesis, above 3 would provide support for the alternative hypothesis, and in between the two values provides inconclusive evidence for either the null or the alternative hypothesis. In order to calculate the Bayes factor, a plausible effect size needed to be provided. To do this, we calculated the mean difference in proportion of dwell time directed towards predictive and irrelevant stimuli from an unpublished, standard, learned-predictiveness experiment conducted in our laboratory which had revealed a significant difference in dwell time between these stimuli. This mean difference was .1 s across participants. For the current experiment, we observed a mean difference of -.001 between the proportion of dwell time directed towards correlated and uncorrelated stimuli for all participants. Following Dienes (2011: see: http://www.lifesci.sussex.ac.uk/home/Zoltan_Dienes/inference/Bayes.htm), the data were modelled using a two-tailed distribution with a mean of 0 (indicating no difference between the proportion of dwell time directed towards correlated and uncorrelated stimuli) and standard error (SE) was set to .005. This yielded a Bayes factor of .05, which provides support for the null hypothesis - there was no difference between the proportion of dwell time directed towards correlated and uncorrelated stimuli.

One possible explanation for the absence of a difference between the proportion of dwell time directed towards correlated and uncorrelated stimuli is that participants were directing so much attention towards the task relevant target stimulus, that attention to the remaining stimuli on the screen was at floor levels. To examine this possibility, the 24 test trials where the target stimulus was absent were examined. Figure 1, Panel D shows that on

the target-absent test trials, the mean proportion of dwell time directed towards correlated and uncorrelated stimuli was moderately longer than it was during the training trials that included the target (Figure 1, Panel C) but there was still no difference in dwell time between these stimuli. A two-way repeated measures ANOVA of proportion of dwell time with the factors of stimulus type (correlated vs. uncorrelated) and trial block (1-4) revealed a no effect of stimulus type, $F(1,17) = .04$, $\eta^2 = .002$, $p = .850$, trial number, $F(7,112) = 1.76$, $\eta^2 = .09$, $p = .107$, and no interaction between these factors, $F(8,133) = .73$, $\eta^2 = .04$. A Bayes factor was again calculated for the difference between correlated and uncorrelated stimuli using an observed mean difference of .0001ms, and a SE set to .005. This yielded a Bayes factor of .05, which again provides support for the null hypothesis.

Questionnaire data. Participants were given a questionnaire which tested their understanding of the associative relationship between the correlated/uncorrelated stimuli with the target stimuli. A difference score was calculated to determine the specificity of the stimulus-target relationship. For the correlated stimulus, this was computed by subtracting the rating of the relationship between the correlated stimulus and the target stimulus it *was not paired with* from the rating of the relationship between the same correlated stimulus and the target stimulus that *it was paired with* (e.g. the rating of the relationship between U and Z was subtracted from the rating of the relationship between U and Y). For the uncorrelated stimulus, this was computed by subtracting the rating of the relationship between the uncorrelated stimulus and a target stimulus from the rating of the relationship between the same uncorrelated stimulus and the other target stimulus that it was paired with (e.g. the rating of the relationship between W and Y was subtracted from the rating of the relationship between W and Z): UY-UZ, VY-VZ, WY-WZ, XY-XZ. Panel E of Figure 1 reveals that the

difference score was higher for correlated stimuli compared to uncorrelated stimuli, $t(34) = 6.69$, $p < .001$.

Discussion.

Participants received trials in which stimuli were either strongly positively-correlated or entirely uncorrelated with the presentation of a task-relevant target. Participants engaged quickly and accurately with this task (Figure 1, Panels A and B), and showed clear knowledge about the associative relationship between the correlated stimuli and the target (Figure 1, Panel E). According to theories of learning that emphasise the role of changes in attention to stimuli as consequence of association, these conditions should be sufficient for the acquisition of a bias in attention towards the correlated stimuli and away from the uncorrelated stimuli (e.g. Esber & Haselgrove, 2011; Le Pelley, 2004; Mackintosh, 1975). However, neither during training trials that included the target stimulus, nor during the test trials that included only the correlated and uncorrelated stimuli could we find any differences in the duration of visual dwell times, using either traditional frequentist statistics, nor with a calculation of Bayes factors (Figure 1, Panels C and D). These results imply that mere association, or differences in associative error, alone, are not sufficient for the establishment of differences in learned variations in attention.

Experiment 2

In Experiment 1, we arranged for one set of visual stimuli to be positively correlated with a target stimulus whilst another set of stimuli were not. Despite the presence of appropriate associative knowledge about the relationship between the correlated/uncorrelated stimuli and the target, there was no difference in the extent to which participants' overt visual

attention was directed towards these stimuli. As we have noted, these results imply that mere association with a task relevant stimulus *alone* is not sufficient for the acquisition of an attentional bias to other stimuli (e.g. Esber & Haselgrove, 2011; James, 1890; Le Pelley, 2004; Mackintosh, 1975). Instead, these results are consistent with the idea that a predictive relationship must be arranged between stimuli in order for associations to be translated into changes in attention – an idea that is implied by the predictiveness principle (Le Pelley et al., 2016). However, whilst real and nonsense words are regularly used as visual stimuli in studies of the relationship between learning and attention (e.g. Le Pelley et al., 2011) it is relatively rare for single letters to be employed in the same role. It is possible, then, that the stimuli employed in Experiment 1 were, in and of themselves, unable to support learned variations in attention, irrespective of whether a predictive relationship was arranged between them or otherwise. The aim of Experiment 2, therefore, was to employ single-letter stimuli as in Experiment 1, with the same degrees of correlation or non-correlation between themselves and the target but under circumstances in which a predictive relationship is also embedded into the trial structure to explore whether, now, a bias in learned attention would develop. In order to do this, three groups of participants were included in Experiment 2. First, we included a group (Group Simultaneous) which closely replicated the conditions of Experiment 1 in order to examine whether the outcome of this study would reproduce. A second group (Group Serial-Target) received identical instructions to participants in Group Simultaneous, but for this group the correlated and uncorrelated stimuli were presented simultaneously, as a pair, and then followed immediately afterwards with the target stimulus – thus reproducing the temporal arrangement of cues and outcomes more commonly employed in studies of learned predictiveness. Finally, a third group (Group Serial-Stimuli) received an identical trial structure to Group Serial-Target, however for this group the instructions were subtly changed. For Group Serial-Stimuli, participants were again informed

that they could respond when the target appeared, however, they were also informed that they could make a response earlier – prior to the presentation of the target during the preceding stimuli - if they thought they were able to predict its arrival. The purpose of including Group Serial-Target and Group Serial-Stimuli was to explore whether it was sufficient for just a predictive *temporal* relationship to be established between the correlated and target stimuli for an attentional bias to develop towards these stimuli; or, instead, whether in addition it was necessary for a predictive *response* to be made about the identity of a forthcoming, future event.

On the basis of the results of Experiment 1, we expected to see no difference in dwell times towards the correlated and uncorrelated stimuli in Group Simultaneous. What remained to be determined, however, was whether the two groups that had a serial relationship established between the correlated/uncorrelated stimuli and the target (Group Serial-Target and Group Serial-Stimuli) would show evidence of differences in attention to the correlated and uncorrelated stimuli; and perhaps most interestingly whether these two groups would differ themselves. Finally, and in keeping with the design of Experiment 1, at the end of the Experiment 2, all groups received a questionnaire to determine their knowledge of the relationship between the correlated, uncorrelated and target stimuli.

Methods

Participants. 52 participants were recruited from the University of Nottingham's School of Psychology and randomly assigned to either Group Simultaneous, Group Serial-Stimuli or Group Serial-Target. Group Simultaneous consisted of 18 females with a mean age of $18.5 \pm .86$ (Mean $\pm$ SD) years; Group Serial-Target consisted of 18 females with a mean age of $18.33 \pm .49$ years and Group Serial-Stimuli consisted of 16 females with a mean age of 19 ± 1.27

years. Exclusion criteria for all groups were the same as in Experiment 1, and like in Experiment 1, all participants had normal or corrected-to-normal vision and received course credit for their participation or a £3 inconvenience allowance.

Apparatus and stimuli. The apparatus employed in Experiment 2 was identical to that used in Experiment 1. Stimuli consisted of the letters J, P, Q, V, W and Z, which are better matched in terms of frequency in the English language than the letters used in Experiment 1. In keeping with Experiment 1, letters were presented in black, font size 60, Times New Roman. Letters Q and P always served as the target stimuli, whilst letters J, V, W and Z were randomly assigned to serve as either the correlated or uncorrelated stimuli for each participant. For Group Simultaneous the target appeared simultaneously with the correlated and uncorrelated stimuli at a random apex of the notional triangle described in Experiment 1. For Group Serial-Target and Serial-Stimuli, the target appeared alone at a random location within the notional triangle on the subsequent screen following the presentation of the compound of the correlated and uncorrelated stimuli.

Each of the four training trials was presented 36 times thus making 144 trials overall. Eight probe trials were randomly distributed throughout the experiment in which the four trials with each compound stimulus were presented twice in the absence of a target stimulus, and participants predicted what they thought the target stimulus would have been. On these trials, the correlated and uncorrelated stimuli were presented in the same manner as in Experiment 1.

Procedure. The same calibration, informed consent and health-screening procedure was employed at the start of Experiment 2 as in Experiment 1. After this, participants read the

following on-screen instructions: “*Each trial will begin with a fixation cross in the centre of the screen. This will be followed by a series of letters. Your task is to indicate whether the letter ‘Q’ or ‘P’ is present in the array. Q = left arrow, P = right arrow. Pay attention to which stimuli are paired together because at the end you will have a memory test. Press any key to start the experiment.*”. For Group Serial-Stimuli, participants were additionally told, “*You can press early if you think you know which letter will appear*”. Each training trial began with the presentation of a fixation cross that was located in the centre of the screen for 1000 ms. This fixation cross was then removed and for Group Simultaneous replaced with the triplet of the correlated, uncorrelated and target letters, simultaneously, for 2000ms. For Groups Serial-Stimuli and Serial-Target, the fixation cross was replaced with the presentation of the correlated and uncorrelated stimuli for 2000 ms, which were then removed from the screen and followed immediately by the target stimulus, also for 2000 ms. For all groups the trial then recycled, following a 1000ms blank screen, to the fixation cross.

After participants completed this stage of the experiment, they were given a questionnaire to complete which tested their understanding of the relationship between the correlated and uncorrelated stimuli with target stimuli. With the exception of the identities of the letters employed in Experiment 2, the questionnaire was the same as that used in Experiment 1.

Results

The exclusion criteria were identical to those used in Experiment 1. Again zero participants were excluded.

Behavioural data. In keeping with the results of Experiment 1 participants responded with high accuracy from trial-block 1 onwards, in all groups. In Groups Simultaneous, Serial-

Target and Serial-Stimuli the mean proportions of correct responses during the final trial block were 98%, 95% and 89% respectively. One sample t-tests revealed that each of these means was significantly greater than chance (.5), smallest $t(17) = 773.98$, $p < .001$. The mean RT was again measured from the termination of the fixation cross, and remained relatively constant for Group Serial Target (Overall Mean: 2570 ms) and group Simultaneous (Overall Mean: 872 ms), implying that participants in these groups were responding solely on the basis of the target stimulus. For participants in Group Serial Stimuli, however, response times during the first block of trials had a mean of 2097 ms, before dropping quickly, and then terminating in the final block of training at a mean of 1000 ms, implying that participants acquired a predictive response to the target stimulus. A two-way mixed ANOVA of mean RT with the within factor of trial block (1-8) and the between-subjects factor of group (Group Simultaneous vs. Group Serial-Stimuli vs. Group Serial-Target), revealed a main effect of group, $F(2, 49) = 250.64$, $\eta^2 = .91$, $p < .001$, of trial block, $F(7,343) = 17.85$, $\eta^2 = .27$, $p < .001$, and an interaction between these factors, $F(14,343) = 7.32$, $\eta^2 = .23$, $p < .001$. Bonferroni adjusted post-hoc tests revealed that each group differed from each other group on each block (smallest mean difference = 305 ms, SE = 95.88, $p = .008$).

Eye gaze analysis. Panel A of Figure 2 show that there was no difference in the mean proportion of dwell time directed towards the correlated and uncorrelated stimuli on the training trials in Group Simultaneous – a result which reproduces the effect observed in Experiment 1. Panel B of Figure 2 shows the proportion of dwell time for group Serial-Stimuli. Interestingly, for this group, a clear bias established as training progressed, with longer dwell time being spent towards the correlated stimuli relative to the uncorrelated stimuli. Finally panel C of Figure 2 shows the dwell time to the correlated and uncorrelated stimuli in Group Serial-Target was comparable. A three-way repeated measures ANOVA of mean proportions of dwell time with the factors of stimulus type (correlated vs. uncorrelated),

495 trial block (1-8), and the between factor of group (Group Simultaneous vs. Group Serial-
 496 Stimuli vs. Group Serial-Target) confirmed these impressions. This revealed a significant
 497 main effect of group, $F(2,26) = 27.84$, $\eta^2 = .68$, $p < .001$, a main effect of trial block,
 498 $F(3,42) = 3.18$, $\eta^2 = .20$, $p = .031$, but no main effect of stimulus type, $F(1,13) = 3.47$, η^2
 499 $= .21$, $p = .085$. There was, however, a significant three-way interaction between these
 500 factors, $F(14,182) = 1.83$, $\eta^2 = .12$, $p = .037$, but no other interactions were significant, $F_s <$
 501 2.58 , $p_s > .095$. To further investigate the interaction between stimulus type (correlated vs.
 502 uncorrelated) and trial block (1-8) within each group, three two-way repeated measures
 503 ANOVAs were conducted. The first of these, conducted on the data from Group
 504 Simultaneous, revealed no effect of stimulus type, $F(1,17) = .00$, $\eta^2 = .00$, $p = 1.00$, a
 505 significant effect of trial block, $F(7,119) = 8.95$, $\eta^2 = .35$, $p < .001$, and a significant
 506 interaction, $F(7,119) = 1073.30$, $\eta^2 = .98$, $p < .001$. Simple main effects analysis of the
 507 interaction revealed a significant effect of stimulus type on blocks 4 and 7, smallest, $F(1,17)$
 508 $= 5.41$, $\eta^2 = .24$, $p = .033$, with firstly uncorrelated and then correlated stimuli receiving
 509 longer dwell times. A Bayes factor was calculated for the difference between correlated and
 510 uncorrelated stimuli using an observed mean difference of .001ms, and a SE which was set to
 511 .001. This yielded a Bayes factor of .04, which provides evidence for the null hypothesis. The
 512 same analysis conducted on the data from Group Serial-Target revealed no main effect of
 513 stimulus type, $F(1,17) = 2.52$, $\eta^2 = .13$, $p = .131$, trial block, $F(7,119) = .75$, $\eta^2 = .04$, $p =$
 514 $.631$, and no interaction, $F(7,119) = .55$, $\eta^2 = .03$, $p = .798$. Again, a Bayes factor was
 515 calculated for the difference between correlated and uncorrelated stimuli using an observed
 516 mean difference of .051 ms, and a SE set to .032. This yielded a Bayes factor of 2.14, which
 517 was inconclusive. The same analysis performed on the data from Group Serial-Stimuli,
 518 however, revealed a significant effect of stimulus type, $F(1,15) = 5.83$, $\eta^2 = .28$, $p = .029$,

95% CI [.02, .51], trial block, $F(3.8, 56.99) = 2.17$, $\eta p^2 = .13$, $p = .088$, but no interaction, $F(3.43, 51.53) = .68$, $\eta p^2 = .04$, $p = .588$.

Insert Figure 2 here

Probe trials. Panel D of Figure 2 show dwell times to the correlated and uncorrelated stimuli from the test trials. These results largely confirm the observations from the training trials, with dwell times being longer to the correlated stimuli than the uncorrelated stimuli in Group Serial-Stimuli ($t(17) = 3.73$, $p = .002$), but not in Group Simultaneous ($t(17) = 1.30$, $p = .221$) or Group Serial-Target ($t(17) = 1.50$, $p = .153$).

Questionnaire data. Panel E of Figure 2 shows that the mean difference rating for the correlated stimuli was higher than that for the uncorrelated stimuli in all three groups. A two-way repeated measures ANOVA of mean difference rating with the factors of stimulus type (correlated vs. uncorrelated), and the between-subjects factor of group (Group Simultaneous vs. Group Serial-Stimuli vs. Group Serial-Target), revealed a main effect of stimulus type, $F(1, 35) = 238.99$, $\eta p^2 = .87$, $p < .001$, no effect of group, $F(2, 70) = .02$, $\eta p^2 = .001$, $p = .978$, and no interaction, $F(2, 70) = .18$, $\eta p^2 = .005$, $p = .835$.

Discussion.

Experiment 2 reproduced the effect observed in Experiment 1 by demonstrating, again, that an attentional bias did not develop towards stimuli that were positively correlated with a co-present target event, even when participants had clearly learned the associative relationships between these events (Group Simultaneous). The same outcome was also observed when a serial, rather than a simultaneous relationship was arranged between the

correlated/uncorrelated stimuli and the target (Group Serial-Target). An overt attentional bias was *only* established towards stimuli that were correlated with a target when participants were asked to make a predictive response about the identity of the target, *prior* to its presentation (Group Serial-Stimuli). Together, these results provide scant support for the notion that mere association is sufficient to establish an attentional bias to stimuli that are correlated with a task-relevant target (e.g. Esber & Haselgrove, 2011; James, 1890; Mackintosh, 1975). They are, of course, perfectly in keeping with the notion that prediction is a key component for the allocation of learned attentional biases (Le Pelley et al., 2016).

Experiment 3

It is possible that the training given to Group Serial-Target and Group Simultaneous in Experiment 2 was, in fact, sufficient to bias attention towards the correlated stimuli; but, for some reason, the conditions of stimulus training (or exposure) may not have been appropriate to reveal this bias and thus masked its expression. In other words, the conditions of training employed to vary attention, between groups, were confounded with the conditions of testing employed to detect that bias. In order to explore this possibility, in Stage 1 of Experiment 3, participants first received identical training to that given to participants in Group Simultaneous and Group Serial-Target in Experiment 2. On the basis of the results observed in Experiment 2 we expect to observe no difference in the dwell times towards the correlated and uncorrelated stimuli in this stage of the experiment. In order to determine if this training did, however, establish attentional biases to the correlated and uncorrelated stimuli that were, in some way, masked by the conditions of testing, all participants transferred to a second stage of the experiment in which the conditions of stimulus exposure and response instructions were the same as those given to Group Serial-Stimuli in

Experiment 2. Thus, in Stage 2, all participants were tested under the same circumstances and also under circumstances known (from Experiment 2) to permit the detection of a learned bias in overt attention.

A crucial manipulation in Stage 2 permitted us to evaluate whether any attentional bias established to the correlated cues in Stage 1 was unexpressed. For half of the participants within each of the two groups, the stimuli that were correlated with the target in Stage 1 remained correlated with the target in Stage 2 (and similarly the stimuli that were uncorrelated with the target in Stage 1 remained uncorrelated with the target in Stage 2) - generating groups Serial Congruent and Simultaneous Congruent. For the remaining participants within the Serial and Simultaneous groups, the stimuli that were correlated with the target in Stage 1 became uncorrelated with the target in Stage 2 (and similarly, the stimuli that were uncorrelated with the target in Stage 1 became correlated with the target in Stage 2) – generating groups Serial Incongruent and Simultaneous Incongruent (See table 3). The logic behind this manipulation is that if attention was biased towards the correlated stimuli in Stage 1, but unexpressed, then in Stage 2 this bias should be revealed. This should particularly be the case in the two conditions where the contingencies between the stimuli and the targets remained the same between the two stages (that is to say there would be a behavioural saving in groups Serial Congruent and Simultaneous Congruent) relative to the two groups for whom the contingencies between the stimuli and the targets were reversed between Stage 1 and 2. For groups Serial Incongruent and Simultaneous Incongruent, the prior (putatively masked) biases, should hinder the expression of the attentional bias in Stage 2.

Group	Stage 1 (Respond to Target)	Stage 2 (Predict Target)	Test trials
Simultaneous Congruent	<i>JWQ</i>	<i>JW→Q</i>	JW
	<i>JZQ</i>	<i>JZ→Q</i>	JZ
	<i>VWP</i>	<i>VW→P</i>	VW
	<i>VZP</i>	<i>VZ→P</i>	VZ
Simultaneous Incongruent	<i>JWQ</i>	<i>JW→Q</i>	JW
	<i>JZQ</i>	<i>JZ→P</i>	JZ
	<i>VWP</i>	<i>VW→Q</i>	VW
	<i>VZP</i>	<i>VZ→P</i>	VZ
Serial Congruent	<i>JW→Q</i>	<i>JW→Q</i>	JW
	<i>JZ→Q</i>	<i>JZ→Q</i>	JZ
	<i>VW→P</i>	<i>VW→P</i>	VW
	<i>VZ→P</i>	<i>VZ→P</i>	VZ
Serial Incongruent	<i>JW→Q</i>	<i>JW→Q</i>	JW
	<i>JZ→Q</i>	<i>JZ→P</i>	JZ
	<i>VW→P</i>	<i>VW→Q</i>	VW
	<i>VZ→P</i>	<i>VZ→P</i>	VZ

Table 3. Example Design of Experiment 3. Target stimuli are shown in bold. Stimuli

correlated with the target, within a stage, are in italics.

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Methods

Participants. Each group consisted of eighteen participants who were recruited from the University of Nottingham's School of Psychology and were randomly assigned to one of the four experimental groups. Group Serial-Congruent consisted of 11 females (Mean $\pm$ SD age: 19.90 ± 1.51); Group Serial-Incongruent consisted of 12 females (19.83 ± 1.64); Group Simultaneous-Congruent consisted of 12 females (21.08 ± 2.11); and finally Group Simultaneous-Incongruent consisted of 12 females (20.67 ± 3.23). Exclusion criteria for all groups were the same as in Experiment 1, and like in Experiment 1, all participants had

normal or corrected-to-normal vision and received course credit for their participation or a £3 inconvenience allowance.

Apparatus and stimuli. The apparatus and stimuli employed in Experiment 3 were identical to that used in Experiment 2.

In Stage 1, each of the four trial-types was presented 18 times each in a random order. The spatial and temporal arrangement of the stimuli and trials for Groups Serial-Congruent and Serial-Incongruent was identical to that given to Group Serial-Target in Experiment 2. The spatial and temporal arrangement of the stimuli and trials for Groups Simultaneous-Congruent and Simultaneous-Incongruent was identical to that in Group Simultaneous in Experiment 2. There were no probe trials, in which the target was omitted in this stage of the Experiment.

In Stage 2, the spatial and temporal arrangement of the stimuli and trials was the same for all groups, and identical to that given to Group Serial-Stimuli in Experiment 2. At the end of Stage 2 for each group, the four trial types were presented six times in a random order in the absence of a target stimulus, and participants were asked to report which target stimulus they thought accompanied the compound during training .

Procedure. The eye tracker was calibrated and eye movement data were recorded in the same manner as described in Experiment 2.

After performing the calibration, participants read on-screen instructions for Stage 1. For participants in all four groups, the Stage 1 instructions read: *“Each trial will begin with a fixation cross in the centre of the screen. This will be followed by a series of letters. Your task is to indicate whether the letter ‘Q’ or ‘P’ is present in the array. Q = left arrow, P = right arrow. Pay attention to which stimuli are paired together because at the end you will have a memory test. Press any key to start the experiment.”*

Each trial during Stage 1 began with the presentation of a fixation cross in the centre of the screen for 1000 ms. Following this, for Groups Simultaneous Congruent and Simultaneous Incongruent, participants were presented with a triplet of the correlated, uncorrelated and target stimuli for 2000 ms. For Groups Serial Congruent and Serial Incongruent the correlated and uncorrelated stimuli were presented for 2000 ms followed by the target stimulus for 2000 ms. For all groups, these sequences were followed by an inter-stimulus interval of 1000 ms before the trial recycled with the fixation cross on the next trial.

Upon completing Stage 1, participants were presented with the following instructions: *“In the next stage you will see two letters followed by a target letter, but in addition to indicating its identity, this time you can anticipate whether the target will be a ‘P’ or a ‘Q’ by pressing early. Press the space bar to continue.”*

Each trial in Stage 2 began with the presentation of a fixation cross in the centre of the screen for 1000 ms. Participants were then presented with the correlated and uncorrelated stimuli for 2000 ms. This compound was then followed by the target stimulus for 2000 ms. This was followed by an inter-stimulus interval of 1000 ms before the trial recycled to fixation cross for the next trial. Upon completing Stage 2, participants received a final series of test trials: *“In the final stage of the experiment you will be presented with two letters but they will not be followed by a target letter. Based on these you need to guess which letter should have been paired with them. Press the space bar to continue.”*

After participants completed this stage of the experiment, they were given a questionnaire to complete which tested their understanding of the relationship between the correlated and uncorrelated stimuli with target stimuli. The questionnaire was the same as that used in Experiment 1.

Results

Exclusion criteria were identical to those employed in experiment 1, and again zero participants were excluded.

STAGE 1.

Behavioural data. Participants in groups Simultaneous Congruent and Simultaneous Incongruent were treated identically in Stage 1, as were groups Serial Incongruent and Serial Congruent. The data for these two pairs of groups were therefore combined for the analysis in Stage 1. During stage 1 the mean proportion of correct responses was high ($>.9$) from block 1, and increased only slightly over the course of the experiment. A two-way mixed measures ANOVA of individual proportions of correct responses with the within factor of trial block (1-4) and between factor of group (simultaneous vs. serial), revealed a significant main effect of trial block, $F(3,177) = 3.16$, $\eta^2 = .04$, $p = .034$, and group, $F(1,70) = 6.47$, $\eta^2 = .09$, $p = .013$, with the mean proportion correct being higher in the serial groups than in the Simultaneous groups. The interaction between block and group was not significant, $F(3,177) = 2.53$, $\eta^2 = .01$, $p = .657$. The mean RT decreased slightly for the simultaneous and serial groups as training progressed. A two-way mixed measures ANOVA of individual RT with the within factor of trial block (1-4) and between factor of group (simultaneous vs. serial), revealed a significant main effect of trial block, $F(2,170) = 12.42$, $\eta^2 = .15$, $p < .001$, and group, with RTs being faster in the simultaneous group, $F(1,70) = 4.61$, $\eta^2 = .06$, $p = .035$. The interaction between block and group was not significant, $F(2,170) = 2.73$, $\eta^2 = .04$, $p = .057$,

Eye gaze analysis. In keeping with the outcome of Experiment 2, Panels A, B, C and D of Figure 3 demonstrates that there was no difference in the mean proportion of dwell time directed towards the correlated and uncorrelated stimuli for any of the groups over the trial blocks of Stage 1. A four-way mixed measures ANOVA of mean proportion of dwell time

with the within factors of trial block (1-4) and stimulus type (correlated vs. uncorrelated), and between factors of group (simultaneous vs. serial) and congruency (congruent vs. incongruent) revealed a significant main effect of group, $F(1,34) = 68.16$, $\eta^2 = .67$, $p < .001$, all remaining main effects and interactions were non-significant (largest $F(1,34) = 2.23$, $\eta^2 = .06$, $p = .144$).

Insert Figure 3 here

STAGE 2

Behavioural data Panels A and B of Figure 4 show the mean proportion of correct responses for the four groups during Stage 2. Performance improved across the four blocks of training and, across the majority of these blocks, accuracy was superior in the congruent groups, regardless of whether training involved serial or simultaneous training in Stage 1. A three-way mixed measures ANOVA of mean proportion correct responses with the within-group factor of trial block (1-4), and between factors of group (simultaneous vs. serial) and congruency (congruent vs. incongruent), revealed a significant main effects of trial block, congruency and group, smallest $F(1,31) = 6.42$, $\eta^2 = .17$, $p = .017$. There was a significant block x group interaction, $F(3,93) = 3.58$, $\eta^2 = .10$, $p = .017$, and block x congruency interaction, $F(2.41,74.57) = 4.39$, $\eta^2 = .12$, $p = .011$. However, the interaction between congruency and group, and the three-way interaction were not significant, largest $F(3,93) = 1.66$, $\eta^2 = .05$, $p = .182$. Simple main effects analysis of the interaction between block and group revealed that the difference in proportion of correct responses between Group Simultaneous and Group Serial was significant in block 1 and 2, smallest, $F(3,93) = 6.90$, $\eta^2 = .33$, $p = .020$ with Group Simultaneous having a higher proportion of correct

responses. Simple main effects analysis of the interaction between block and congruency revealed that the difference in proportion of correct responses for Group Congruent and Group Incongruent was significant in block 1, 2 and 3 smallest, $F(2.41, 74.57) = 11.01$, $\eta^2 = .44$, $p = .005$ with Group Congruent having a higher proportion of correct responses. This final interaction, as well as the main effect of congruency confirms that our manipulation of congruency between Stage 1 and 2 had a detectable impact upon behaviour.

Panels C and D of Figure 4 show that in Stage 2, the mean RT decreased across training in both the simultaneous and serial groups, but was fastest for the congruent conditions, again confirming that switching the contingency of the correlated and uncorrelated stimuli between experimental stages was effective, and that participants were sensitive to the difference in correlation of the stimuli during Stage 1 of the Experiment. A three-way mixed measures ANOVA of mean RT with the within factor of trial block (1-4), and between factors of group (simultaneous vs. serial) and congruency (congruent vs. incongruent) revealed significant main effects of trial block, group and congruency, smallest $F(2.01, 58.19) = 4.30$, $\eta^2 = .13$, $p = .018$, and a significant block x group interaction, $F(3, 87) = 4.30$, $\eta^2 = .13$, $p = .007$. All remaining interactions were non-significant, largest $F(1, 29) = 1.26$, $\eta^2 = .04$, $p = .270$.

Insert Figure 4 here

Eye gaze Panels A, B, C and D of Figure 5 show that a larger proportion of dwell time was directed towards the correlated stimuli in all groups in Stage 2, irrespective of whether participants were in the congruent or incongruent groups, or whether training in Stage 1 was conducted using a serial or simultaneous procedure. A four-way mixed measures ANOVA of

mean proportion of dwell time with the within factors of trial block (1-4), stimulus type (correlated vs. uncorrelated), and between-group factors of group (simultaneous vs. serial) and congruency (congruent vs. incongruent) revealed significant main effects of block, stimulus type and group, smallest $F(1,34) = 4.62$, $\eta p^2 = .12$, $p = .039$, the remaining main effect of congruency was not significant, $F(1,34) = 3.30$, $\eta p^2 = .09$, $p = .078$. There was a significant block x stimulus type interaction, $F(3,102) = 3.19$, $\eta p^2 = .09$, $p = .027$, but all remaining interactions were non-significant, largest $F(1,34) = 2.61$, $\eta p^2 = .07$, $p = .116$.

Insert Figure 5 here

Panels A and B of Figure 6 show the mean proportion of dwell times directed to the correlated and uncorrelated stimuli during the test trials for all groups in Stage 2. Overall, incongruent trials attracted a higher proportion of dwell time compared to congruent trials, perhaps reflecting the uncertainty associated with their introduction in Stage 2 (Pearce & Hall, 1980). In keeping with the data from the training trials, correlated stimuli attracted the largest proportion of dwell time in groups trained simultaneously or serially in Stage 1. A three-way repeated measures ANOVA of mean proportion of dwell time with the within-subjects factor of stimulus type (correlated vs. uncorrelated) and between-groups factors of group (simultaneous vs. serial) and congruency (congruent vs. incongruent) revealed a significant main effect of stimulus type, $F(1,68) = 22.77$, $\eta p^2 = .25$, $p < .001$, group, $F(1,68) = 4.71$, $\eta p^2 = .07$, $p = .034$, and congruency, $F(1,68) = 14.19$, $\eta p^2 = .17$, $p < .001$. However, all interactions were non-significant, largest, $F(1,68) = 2.64$, $\eta p^2 = .04$, $p = .109$.

Questionnaire data. Difference scores for all four groups were calculated in a manner identical to Experiment 2 and are shown in panels C and D of Figure. A three-way repeated measures ANOVA of mean difference rating with the within factor of stimulus type (correlated vs. uncorrelated) and between factors of group (simultaneous vs. serial) and congruency (congruent vs. incongruent) revealed a significant main effect of stimulus type, $F(1,68) = 149.83$, $\eta p^2 = .688$, $p < .001$, but no effect of group or congruency, largest $F(1,68) = 2.12$, $\eta p^2 = .03$, $p = .145$. Significant interactions were found between stimulus type x congruency ($F(1,68) = 7.13$, $\eta p^2 = .10$, $p = .009$), stimulus type x group ($F(1,68) = 8.01$, $\eta p^2 = .11$, $p = .006$), but the three-way interaction was non-significant ($F(1,68) = .146$, $\eta p^2 = .002$, $p = .704$). Simple main effects analysis of the interaction between stimulus type and congruency revealed that the difference in difference rating between correlated and uncorrelated stimuli was significant in congruent and incongruent groups, smallest, $p < .001$. Simple main effects analysis of the interaction between stimulus type and group revealed that the difference in difference rating between correlated and uncorrelated stimuli was significant in the simultaneous and serial conditions, smallest, $p < .001$. Thus, in keeping with the previous experiments, participants knowledge of the associative relations between the correlated/uncorrelated stimuli and the target was good.

Discussion.

The eye-tracking data from Stage 2 of the current experiment, reproduced the effect observed in Group Serial-Stimuli from Experiment 2: when participants were required to make a predictive response about the identity of a subsequent task-relevant target then their overt attention came to be biased towards the stimuli correlated with the target. The data from Stage 1 reproduce the effects observed in Groups Serial-Target and Simultaneous from Experiment 2: when a simultaneous or sequential relationship between correlated stimuli and target is established - without the requirement of predictive response - then there was no

indication of the acquisition of an attentional bias. Of most interest, the current experiment revealed that when the predictive contingencies of the correlated and uncorrelated stimuli were swapped between Stage 1 and 2 then there was no disruption in the bias in overt attention to the correlated stimuli in Stage 2. In fact, numerically, the difference in dwell times between the correlated and uncorrelated stimuli was most substantial in the Incongruent groups than in the Congruent groups. Thus it does not appear that the simultaneous and sequential training in Stage 1 established an attentional bias that, for whatever reason, went undetected. If this were the case then we would anticipate seeing an attenuation of the difference in dwell time between the correlated and uncorrelated stimuli in the Incongruent groups in Stage 2, which was not observed. It is worth reiterating that the behavioural data (mean proportion correct and response times) and the overall dwell times were different between the incongruent groups and the congruent groups in Stage 2, thus providing a confirmation of the effectiveness of this manipulation. Finally, all groups showed appropriate knowledge about the associative relationships between the correlated stimuli and the targets. The results of the current experiment, together with Experiments 1 and 2, therefore strongly suggest that mere association, or associative error is insufficient to result in learned changes in overt attention.

General Discussion

The purpose of the experiments reported here was to investigate the role of prediction in learned predictiveness. Prior studies of this phenomenon (e.g. Le Pelley et al, 2011) have revealed that a stimulus correlated with a task-relevant event comes to control more overt visual attention than a stimulus that is task irrelevant. These studies have been taken to

support the “predictiveness principle”: the idea that, through learning, stimuli which are “predictive” of events of importance come to control relatively more attention. However, as we have noted, formal models that are used to simulate these effects (e.g. Esber & Haselgrove, 2011; Le Pelley, 2004; Mackintosh, 1975) employ association and associative error to bridge the relationship between learning and attention. Despite this, prediction has no place in these models, despite their application to the problem more broadly.

Experiment 1 revealed that despite participants’ having appropriate associative knowledge about the relationship between stimuli that were correlated or uncorrelated with a target stimulus, no bias in visual dwell time was observed towards the correlated stimulus when all these stimuli were presented simultaneously. This result implies that mere association between stimuli is insufficient to modify learned variations in attention. Experiment 2 reproduced this effect in Group Simultaneous, and also revealed that arranging for the correlated and uncorrelated stimuli to precede the target stimulus was, in and of itself, also insufficient to result in the acquisition of a bias in visual dwell time to the correlated stimuli (Group Serial-Target). This was again, in the presence of appropriate associative knowledge about the relationship between these stimuli and the target. Thus a veridical, predictive, relationship between *stimuli* is insufficient for learning to modify attention. Only when participants were asked to make a predictive *response*, that is to say a response prior to the presentation of the target, were longer dwell times acquired to the correlated stimulus relative to the uncorrelated stimulus. Experiment 3 confirmed these findings, and also provided evidence that the lack of attentional biases in Groups Simultaneous and Serial-Target were not a consequence of a confound between the conditions of training and the conditions of testing.

Together, these results imply a crucial role for predictive responding in the aetiology of the learned predictiveness effect. More specifically they suggest that responding needs to

be contingent with a stimulus at a time when the target is not present in order for learning to change overt visual attention. To make this clear, consider Figure 7, which shows a timeline of one trial for Groups Serial-Stimuli, Group Simultaneous and Group Serial-Target from Experiment 2. Note that the temporal relationships between the correlated stimulus and the Target stimulus was equivalent in Group Serial-Stimuli and Group Serial-Target. Thus, the contiguity between these events *alone* was not sufficient to explain the bias in visual attention evident in Group Serial-Stimuli. Furthermore, relative to the onsets of the correlated and uncorrelated stimuli, responses are produced at comparable times in Groups Serial-Stimuli and Group Simultaneous. Consequently, the contiguity between the correlated stimulus and the response *alone* is not sufficient to explain the bias in visual attention evident in Group Serial-Stimuli but not in Group Simultaneous. In order to explain the attentional bias towards the correlated stimulus observed in Group Serial-Stimuli, but not in the other groups, we postulate that the target-relevant response must be performed contiguously with the correlated stimulus, at a time when the target is not present.

Insert Figure 7 here

It is relatively straightforward to, algorithmically, modify the equations provided by associative models of learning in order to realise the conceptual description provided above. For example, taking Mackintosh's theory as a case in point, we could stipulate that equations 2a and 2b described in the General Introduction only take effect when the task-relevant response occurs at a time before the onset of the task-relevant target (i.e. $t_{CR} < t_\lambda$). In the context of Mackintosh's theory this would mean that associative learning would still take place (as equation 1 is not limited by the temporal relationship between response and target),

however this learning will not be translated into changes in attentional control, unless the task relevant responding preceded the presentation of the target stimulus. Consequently, this modification to Mackintosh's theory would explain why all three groups in Experiment 2 demonstrated good, and equivalent, knowledge of the associative relationships between the correlated/uncorrelated stimuli and the target but why only group Serial-Stimuli translated this knowledge into a change in attention.

There are, however, some problems with this algorithmic fudge. The first is relatively minor as it applies only to the modification as it is applied to the Mackintosh (1975) model. Note that learning, in Equation 1, is driven with an individual error term (e.g. Bush and Mosteller, 1951), rather than the summed error term used more standardly (e.g. Rescorla & Wagner, 1972). The summed error term is only employed, in Mackintosh's theory, to change attention to stimuli in Equations 2a and 2b. Consequently, effects such as blocking (Kamin, 1968), or overshadowing (Pavlov, 1927) are driven by changes in the allocation of attention to stimuli (specifically, a reduction in attention to redundant stimuli). It follows then, that if we restrict attentional change to circumstances in which task-relevant responding precedes presentation of the target then overshadowing and blocking should not be evident under circumstances in which a conditioned, or target-relevant response, coincides with the unconditioned, or target, stimulus; a prediction which is demonstrably false (e.g. Balleine, Espinet & González, 2005; Dwyer, Haselgrove & Jones, 2011). Fortunately this problem can be overcome if we relax the assumption that the summed error term is applied only to the mechanism that changes the allocation of attention. If a summed error term is applied at the level of the learning algorithm too (e.g. Esber and Haselgrove, 2011; Le Pelley, 2004), then more than one source of cue-competition is available and effects such as simultaneous-stimulus blocking and overshadowing can be explained, albeit in a manner that does not permit the stimuli employed in these studies to undergo a change in attention.

The second problem with the modification described above is more fundamental and applies to theories of learning and attention more generally. As we have seen, most models of attentional learning (e.g. Esber & Haselgrove, 2011; Le Pelley, 2004), which can successfully explain a broad range of learning phenomena, do so without taking into account how time is represented within the architecture of the model – they are so called trial-based models. Consequently, before any such algorithmic modification may be applied, one must first begin to tackle the question of precisely how the timing of stimuli and their associated responses will be represented. A common approach to this problem is to acknowledge that rather than discrete trials being the smallest unit of temporal resolution within learning, instead, shorter windows of associability (epochs, or “bins”, e.g. Moore and Stickney; 1980) are assumed to successively open and close as time passes, with experimental events potentially spanning multiple epochs. Applying this assumption may provide a resolution of the experiments that we report here. Consider Figure 8, which for the sake of illustration and simplicity, redraws Figure 7 to exemplify how a single trial may be represented across 6 different windows of associability that open and close during this series of experimental events. We make the assumption that associations between any experimental event (stimuli or responses) will be more successfully acquired when those events occupy the same epoch (e.g. Moore and Stickney; 1980). We also make the assumption (which we will discuss later) that attention to stimuli is modified not on the basis of their association with other stimuli, but on the basis of their association with the task-relevant *response*.

Insert Figure 8 here

On the basis of these assumptions, it can be seen that in each group there is 1 or more epoch in which the correlated stimulus and the target stimulus are both co-active (epoch 4 for the two Serial groups, and epochs 1 to 4 for Group simultaneous). Consequently, associative learning will have the opportunity to take place between these stimuli, and thus a test of associative knowledge (such as the test trials presented at the end of each experiment) has the opportunity to reveal this. Similarly, it can also be seen that the correlated stimulus and the response are also both co-active (in epoch 2 for Groups Serial-Stimuli and Simultaneous, and in epoch 4 for Group Serial-Target). Note, however, that for Groups Simultaneous and Serial-Target the correlated stimulus and the response are both co-active within the same epoch as the target stimulus. On the basis of most learning rules, therefore, the association between the correlated stimulus and the response will be overshadowed by the target stimulus. This will not be the case in Group Serial-Stimuli, however, because for this group the target is not presented during an epoch in which the correlated stimulus and the response are co-active; consequently the influence of overshadowing by the target will be far less. If, as we have postulated above, attentional control by stimuli (in this case the correlated stimulus) is a function of its association with the task-relevant response, then what should be observed is the acquisition of an attentional bias in Group Serial-Stimuli, but not in the remaining two groups, which is of course the result we observed. Our proposed mechanism for this is a combination of standard associative principles (in this case overshadowing) operating at the epoch level – a proposal which is not particularly controversial (McLaren & Mackintosh, 2000; Vogel, Brandon & Wagner, 2003) and an attentional modulation mechanism which is sensitive to the correlation of stimulus and task-relevant responding. It is to this final proposal that we now turn our attention.

Whilst associative models typically emphasise the role of attention to be one that permits organisms to better select stimuli on the basis of their predictive validity of other

subsequent *stimuli* (e.g. an outcome), an alternative view of attention is afforded by a number of cognitive models, which instead emphasise the primary role of attention to be one of controlling action (e.g. Alport, 1989; Norman and Shallice, 1980). By placing the emphasis on the relationship between stimuli and responses, the proposals outlined here can be viewed as consistent with the idea that attention is bound to the intended actions of the participant (e.g. Engel, Maye, Kurthen & Konig, 2013). For example, according to pre-motor theories of attention, the selection of sensory information is determined by current action plans (Rizzolatti, Riggo, Dascola & Umiltá et al, 1987). Notably, Craighero, Fadiga, Rizzolatti and Umiltá (1999) state the general position as one in which “Orienting of attention implies an activation of basic sensory-motor circuits according to the action goal. *Attention results, therefore, from an internal representation of the required response during the interval between cue presentation and target presentation*” (p. 1690). Similarly, so-called late-selection models of attention (e.g. Deutsch & Deutsch, 1963; Duncan, 1980, Kahnemann, 1973) assume that attentional selection, or filtering, occurs at a relatively late stage in information processing (c.f. Broadbent, 1958). According to models of this class, the selection of stimuli for attention involves more complex, “categorical” information than mere physical stimulus properties. As Deutsch & Deutsch note, “all sensory messages which impinge on the organism are perceptually analysed at the highest level” (p.85), and as Quinlan and Dyson (2008) note, in their discussion of late selection models more generally, “It is as if everything is identified but that *the critical constraints relate to responding*” (p. 286). The proposal we suggest here, in which learned changes in attention are a consequence of stimulus-response associations, concords with the idea that the purpose of attention is to guide actions. Perhaps this position has some face validity too. If the organism finds itself engaged in a task in which the constraints require the selection of information, then it may well be a consequence of the limits of processing capacity being either reached, or at least

approached. Under these circumstances, then, a relatively automatic mechanism for determining how attention should be allocation seems necessary. A direct association between stimulus and response fulfils this requirement.

By proposing that learned variations in stimulus attention are a function of the strength of the association between that stimulus and the task-relevant response, we align the current results with a literature that suggests that attentional selection for reward associated stimuli is a consequence of an attentional habit. (e.g. Anderson, 2016; Luque et al, 2017). According to this position, an attentional habit is conceptually similar to the architecture (stimulus-response) of a habit as considered in reinforcement-learning paradigms. For example, lever-press responding for food comes under the control of a particular stimulus (e.g. the sight of the lever) - an association which is reinforced by reward (Dickinson, 1985). When applied to an attentional habit, the notion here is that eye movements can be thought of as the instrumental response which has come under the control of experimental stimuli (e.g. cues predictive of target outcomes). The associative structure of the proposals we describe here concord with this general view; however, our suggestion is that the association between stimuli and task-relevant motor responses (such as key presses) in addition to eye movements, also modifies overt attention.

Our analysis, thus far, has focused on the role of differences in the timing of responding during stimuli in the aetiology of learned predictiveness. However, it is important to also consider that the three groups in Experiment 2, and the conditions of Stage 1 and Stage 2 in Experiment 3 also differed in terms of the instructions that participants were provided with, and that this difference is an equally good predictor of which conditions or groups demonstrated an attentional bias to the correlated stimuli. Specifically, when participants were instructed that they may anticipate the arrival of the target stimulus, and press the response key early, then only under these circumstances did dwell times come to be

longer to the correlated stimuli relative to the uncorrelated stimuli. It is therefore worthwhile considering whether the instructions alone were responsible for the effects observed in the current studies. Evidence for the role of instruction in learned variations in attention has been provided by Mitchell, Griffiths, Seetoo and Lovibond (2012). In their Experiment 2, participants were required to learn to predict the shape that a tree would grow into depending on the sets of cross-pollinating seeds that were used. Their results revealed a standard learned predictiveness effect, in that dwell times were longer to the stimuli (seeds) that were established as predictive of the outcome (tree shape) than to stimuli that were irrelevant to the task. However, this bias in dwell time could be reversed in a second stage of the experiment if participants were given instructions that informed them that it was highly unlikely that the seeds that controlled the shape of the tree previously would influence the shape of the trees from now on. Subsequent studies have also revealed that instructions can influence learned predictiveness, however a residual bias towards previously predictive cues can survive the instructions (Don & Livesey, 2015; Shone, Harris, & Livesey, 2015). Mitchell et al. account for their results by suggesting that the learned predictiveness effect is a consequence of participants' controlled attention being determined (in part) by a "causal model" of the scenario described in the cover story of the task used in their experiment, a model which can be revised on the basis of instruction (see also: Mitchell, De Houwer & Lovibond, 2009). The implications of this literature for the current results are twofold. First, it is clear that the nature of the instructions given to participants can have a substantial influence on how learned variations in overt visual attention are expressed to stimuli that are correlated or uncorrelated with task-relevant goals. Thus the proposal that the current results may be, at least in part, a consequence of explicit experimental instruction is not entirely without merit. Whether the effect of instruction *alone* is sufficient to explain the current results, however, remains unclear. Second, whilst the theoretical analysis of the effects of instruction on

991 learned predictiveness provided by Mitchell et al. (2012) constitutes a reasonably intuitive
992 explanation of this effect when it is embedded within a casual learning scenario it is not
993 entirely clear how easily it could be applied to the results of the current studies. Unlike many
994 demonstrations of learned predictiveness, the current studies provided no cover story
995 motivating participants to form a scenario about the casual relationship between the stimuli
996 and the task-relevant target. Furthermore, it is unclear why instructing participants to respond
997 prior to the onset of the target stimulus should necessarily promote the establishment of a
998 causal model, but requiring participants to respond to the target alone did not. Thus, until a
999 principled reason can be developed for why this might be the case, we remain sceptical about
1000 how appropriate the causal-model explanation can be for the current results.

1001   In any case, the current experiments reveal that in order for learning to modify
1002 attention to a stimulus that is correlated with a target, task-relevant responding must take
1003 place at a time prior to target presentation. Mere “association with some other immediately
1004 interesting thing” (James, 1890) is insufficient for a stimulus to derive attention. It seems,
1005 then, that learned predictiveness is appropriately named – but perhaps for not the reason
1006 suspected by associative theories of learning.

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Footnote to Title Page

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1141 Carla J. Eatherington, School of Life Sciences, University of Lincoln. Mark Haselgrove,
1142 School of Psychology, University of Nottingham.

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1146 Correspondence concerning this article should be addressed to Mark Haselgrove, School of
1147 Psychology, University Park, The University of Nottingham, Nottingham, NG7 2RD United
1148 Kingdom. E-mail: Mark.Haselgrove@Nottingham.ac.uk.

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Figure Captions.

Figure 1. Results of Experiment 1. (A) Mean Proportion Correct Responses during the training trials, (B) Mean Responses times during the training trials, (C) Mean proportion Dwell Times to the Correlated, Uncorrelated and Target Stimuli during training trials, (D) Mean Proportion Dwell Times to the Correlated and Uncorrelated stimuli during the probe trials. (E) Mean Difference Scores to the Correlated and Uncorrelated stimuli during the final test questionnaire. Error bars represent 1 +/- standard error of the mean.

Figure 2. Results of Experiment 2. (A) Mean Proportion Dwell Times to the Correlated, Uncorrelated and Target stimuli during the training trials in Group Simultaneous, (B) Mean Proportion Dwell Times to the Correlated and Uncorrelated stimuli during the training trials in Group Serial-Stimuli, (C) Mean Proportion Dwell Times to the Correlated and Uncorrelated stimuli during the training trials in Group Serial-Target, (D) Mean Proportion Dwell Times to the Correlated and Uncorrelated stimuli during the probe trials in each group, (E) Mean Difference Scores to the Correlated and Uncorrelated stimuli during the final test questionnaire. Error bars represent 1 +/- standard error of the mean.

Figure 3. Results of Experiment 3. Mean proportions of dwell times to the correlated and uncorrelated stimuli during the training trials of Stage 1 of Experiment 3 in Groups (A) Simultaneous Congruent, (B) Simultaneous Incongruent, (C) Serial Congruent and (D) Serial Incongruent. Error bars represent 1 +/- standard error of the mean.

Figure 4. Results of Experiment 3. Panels A and B: Mean Proportion Correct responses during Stage 2 of Experiment 3 - (A) Groups Simultaneous Congruent and Incongruent, (B) Groups Serial Congruent and Incongruent. Panels C and D: Mean Response Times during Stage 2 of Experiment 3 - (C) Groups Simultaneous Congruent and Incongruent, (D) Groups Serial Congruent and Incongruent. Error bars represent 1 +/- standard error of the mean.

Figure 5. Results of Experiment 3. Mean Proportion Dwell Times to the Correlated and Uncorrelated Stimuli during stage 2 of Experiment 3. (A) Group Simultaneous Congruent (B) Group Simultaneous Incongruent (C) Group Serial Congruent (D) Group Serial Incongruent. Error bars represent 1 +/- standard error of the mean.

Figure 6. Results of Experiment 3. Mean Proportion Dwell times to the correlated and uncorrelated stimuli during probe trials in Groups Simultaneous Congruent and Simultaneous Incongruent (Panel A) and Groups Serial Congruent and Serial Incongruent (Panel B). Mean Difference scores to the correlated and uncorrelated stimuli from the final questionnaire in Groups Simultaneous Congruent and Simultaneous Incongruent (Panel C) and Groups Serial Congruent and Serial Incongruent (Panel D). . Error bars represent 1 +/- standard error of the mean.

Figure 7. A time line depicting the relative presentation times of the correlated and uncorrelated stimuli (grey rectangles) participant's response (white rectangle) and the target (black rectangle) during a trial in Groups serial-stimuli, simultaneous and serial-target of Experiment 2.

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1197 Figure 8. A time line depicting the relative presentation times of the correlated and
1198 uncorrelated stimuli (grey rectangles) participants response (white rectangle) and the target
1199 (black rectangle) during a trial in Groups serial-stimuli, simultaneous and serial-target of
1200 Experiment 2. Dotted rectangles represent 6 theoretical windows of associability.

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