# Focused Spatial Attention is Independent of Rapid Resumption of an Interrupted Search

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**Abstract**

Three experiments examined possible relationships between the spatial focus of attention and the rapid resumption of a visual search following a brief interruption. Experiment 1 tested the role of involuntary (exogenous) spatial orienting to one region (quadrant) of a search display, Experiment 2 tested the role of voluntary (endogenous) spatial orienting to the same region, and Experiment 3 tested the role of voluntary orienting to the specific location in which the target item appeared. All three experiments indicated that spatial orienting speeds correct responding and greatly increases the probability of search success in the look immediately following the presentation of a spatial cue. However, these benefits of spatial cues were also shown to be completely independent of the rapid resumption effect, which depends on observer's forming a perceptual hypothesis about a target in one look, but being unable to confirm that hypothesis until a second look is possible (Lleras et al. 2005).

A brief glance at a scene can result in a rich visual experience, one that does not end when the scene vanishes from view. Following even a brief glimpse, humans are able to report many details if probed within 100 milliseconds (ms) (Sperling, 1960), and they are able to detect changes made to a scene after 200 ms if the changes involve objects that were the focus of attention during the initial glimpse (O'Regan, Deubel, Clark & Rensink, 2000). Here we examine the relations between focused spatial attention and the processing that occurs following a brief glimpse at a scene.

In addition to documenting the rich and structured memorial content of the visual information in a brief glance (e.g., Henderson & Hollingsworth 2003), recent studies have focused on an important predictive aspect of the processing that occurs following a brief glimpse. This is highlighted in the phenomenon of *rapid resumption*, which is a pattern of responding that occurs when observers perform a visual search task in which brief glances at a scene (e.g., a look of 100 ms) are interrupted by blank screens (e.g., a wait of 900 ms). Observers are generally quite good at completing interrupted searches of this kind, being able to identify the target within three or four glances at the display and with accuracy levels of 95% or more (Lleras, Rensink & Enns, 2005). The predictive aspect of their processing is revealed in the high proportion of extremely short identification latencies that occur following re-representation of the display.

Detailed analyses reveal two distinct phases in the response time (RT) distributions that occur following interrupted looks. There is an early phase of correct responding that begins around 100 ms and peaks between 200-299 ms. Then there is a later phase of responding that peaks in the range of 500 to 699 ms. Illustrations of these two phases can be seen in the middle panel of the response time distributions from each experiment in the present study (Figures 3, 5, and 7). In contrast to the pattern of responses that occur following a single glance at a scene (< 2% of responses between 0-499 ms; > 98% of responses between 500-999 ms, see top panel of Figures 3, 5 and 7) it is common for subsequent glances to result in 30% -50% of responses occurring in the early phase (0-499 ms). This is the operational definition of rapid resumption used in the present study.

We interpret rapid resumption as evidence for the existence of implicit perceptual predictions made in the context of a *reentrant processing theory* of visual awareness of Di Lollo et al. (2000). According to this theory, perception is an iterative process whereby information is processed at several levels, most notably a higher level associated with object representations and a lower level associated with pre-categorical sensory input. Perceptual awareness is achieved once a prediction about a candidate object is created and confirmed against the current sensory input. Notably, a precondition for awareness is that the reentrant activity in the system matches the sensory input. If there is no match, then perceptual awareness of the object generating the prediction does not occur and the system generates a new prediction regarding the current sensory information.

When this theory is applied to visual search (Lleras & Enns, 2008), it is our view that after only a few trials in a search task (e.g., a looking for a T among Ls) observers form detailed representations of the target in its various orientations and colors. Yet, despite holding these memorial representations, a first glimpse of the display still rarely elicits a response in less than 500 ms. The reason it takes this long is that even when the observers' eye registers the target, it is still necessary to activate and test a hypothesis about it, both in order to distinguish an actual target from its memorial representation (i.e., to see rather than merely imagine it) and to prepare the appropriate motor response. Rapid resumption responses following an interrupted look are able to escape some of these time-consuming steps because the information in the first look has been sufficient to activate a hypothesis and to predict what will be seen next, even though the step of confirming the hypothesis must await the reappearance of the display. The central idea is that merely having to confirm a prediction when the display reappears takes less time than activating a perceptual prediction and then confirming it.

The hypothesis that rapid resumption is an index of prediction has been tested in several ways. First, rapid resumption does not occur if the scene is not re-presented following a single look (Lleras et al., 2005, Experiment 5), suggesting that the phenomenon occurs when a prediction is confirmed, not merely when a correct hypothesis is entertained. Second, rapid resumption fails to occur when the first

look is a view of all the distractor items in a display (minus the target) and the second look includes the target (Lleras et al., 2007, Experiment 1). This finding is consistent with observers making a prediction about a particular object rather than about the task context or the scene as a whole. Third, rapid resumption does not occur when the location of the target is randomly relocated from look to look, consistent with a prediction being made about an object that is expected in a given location (Lleras et al., 2005, Experiment 6). Fourth, rapid resumption still occurs when incidental features of the target item are changed from look to look, but it fails to occur when the changed features are relevant to the identification response that must be made to the target (Lleras et al., 2007, Experiments 3 and 4). This is consistent with the prediction being made quite specifically about response relevant features of the target. Finally, placing the target object at the observer's point of fixation in the scene guarantees a high rate of search success following a single look, but it does not produce fast responses to the target on the first look. Rapid resumption in gaze contingent experiments occurs only on the second look at the target, following a first look that was unsuccessful (van Zoest, Lleras, Kingstone, & Enns 2007).

Although our initial discovery of rapid resumption was serendipitous (Lleras et al., 2005) we have since found that the early-phase responses are quite a ubiquitous feature of visual search tasks: (1) that have some probability of not being completed in a single glance at a display, and (2) for which the observer has a reasonable expectation that the display will reappear following an interruption. So far this has included searches for Ts among Ls (as in the present study), search for faces of strangers, friends, and oneself (Riebe & Enns, in preparation), searches that involve targets on every trial that must be discriminated from one another (as in the present study) and searches that involve both target present and absent trials (Riebe & Enns, in preparation). It also seems we have had an easier time finding variations on the basic interrupted search task that preserve the rapid resumption phenomenon (e.g., randomly varying the duration of the interruption, relocating all the distractors from look to look) than it has been to find conditions that eliminate the effect. To date these have included randomly relocating only the target from look to look

(Lleras et al, 2005), changing a response relevant feature of the target from look to look (Lleras et al., 2007) and mixing a large number of single look trials among multiple look trials (Lleras, Rensink & Enns, 2004).

The present study examines the relationship between focused spatial attention and rapid resumption. This is important because it is well established that when spatial attention is prepared in advance of a visual stimulus, perception becomes both faster and more accurate (Luck & Vecera, 2002; Yeshurun & Carrasco, 1999), the effects of backward masking are sharply reduced (Enns, 2004), and success in change detection experiments is vastly improved (e.g., O'Regan et al., 2000; Rensink, 2000). It is therefore worth studying the relationship between rapid resumption and spatial attention, if only because of these established empirical relationships. They suggest that a major contributing factor to the fast responses following an interrupted look may be that attention is already focused on a particular spatial location when the target reappears. However, there is a deeper theoretical reason that makes this relationship an important one to study too. Lleras and colleagues propose that rapid resumption responses are different in kind from the responses that occur after 500 ms; they are not merely responses that have been speeded by the appropriate pre-focusing on a specific spatial location. If so, then manipulations of spatial attention should have effects on an interrupted search task that are dissociable from the influences associated specifically with rapid resumption.

We begin this study by considering the role of involuntary (also called exogenous) spatial orienting of attention prior to the onset of one of the looks in an interrupted search task (Experiment 1). It is possible that in the normal course of searching for a target, attention becomes focused on various locations in the scene prior to a look. If the target is then presented near the current focus of attention, it may be sufficient to produce the rapid resumption pattern of responding. However, it is also possible that rapid resumption is associated with voluntary (also called endogenous) orienting to a region of the scene prior to a look. If intentional orienting is required, then rapid resumption may occur when there is an intention to orient to the general region of the display containing the target (Experiment 2) or to the

specific location in which the target item is presented (Experiment 3). Thus, the main hypothesis we derive from the possibility that focused spatial attention contributes to rapid resumption is that conditions involving a valid spatial cue in advance of the search display should produce a greater number of early-phase responses than conditions involving no cue or an invalid cue. The alternative hypothesis — the one favored by our account of rapid resumption as an index of implicit perceptual prediction (Lleras & Enns, 2008) — is that spatial cues will not increase the likelihood of early-phase responses. To anticipate the results, we report that although spatial orienting speeds responding and greatly increases the probability of success in the next look, these effects are completely independent of the rapid resumption effect, consistent with reentrant processing theory (Lleras et al. 2005).

## Experiment 1: Non-predictive spatial orienting to the target region

We began by examining the effects of a non-predictive spatial cue in order to test for a relationship between involuntary (exogenous) spatial orienting and rapid resumption. In this and subsequent experiments, observers searched for a single T among 15 Ls on every trial, until they indicated the color of the T (blue, red) with a speeded key press. The search display was shown for 100 ms looks, interrupted by 900 ms waits, until a response was made. Observers were cued by four small dots, presented 400 ms in advance of a look, to attend to one of the four quadrants of the search display. No cue was presented on 25% of the trials (no cue baseline) and when the cue was presented on the remaining trials, it appeared randomly prior to the first, second, or third look at the search display. In Experiment 1, the cue was not predictive of the location of the target, allowing us to measure whether there were any differences in rapid resumption when attention was oriented correctly (valid cue) on 25% of the cued trials versus when attention was misdirected (invalid cue) on 75% of the cued trials.

**Method**

Observers. Sixteen students from the University of Illinois at Urbana-Champaign took part in this study in exchange for course credit. All were naïve as to the purpose of the experiment and had normal or corrected-to-normal visual acuity. Data from one student was disregarded because search accuracy was less than 65% correct.

Displays and Apparatus. A schematic of the display sequence is shown in Figure 1. All the experiments were generated using Matlab and the Psychophysics toolbox (Brainard, 1997; Pelli, 1997). The experiments were run on 3.4 GHz Pentium IV PCs, using a 17-in CRT monitors. The programs recorded observers' key presses and response times. The displays consisted of colored items (one T and 15 Ls), which were either red or blue (presented as color values [255 0 0] and [0 0 255], respectively), and were displayed on a white background. The items subtended 0.71° x 0.71° at a viewing distance of 57 cm, and were presented in one of four possible orientations (rotated 0, 90, 180 or 270 degrees), with an equal number of red and blue items on every display. The colored items were randomly assigned to locations within an invisible grid, which was subdivided into 4 3x3 "regions" (a total of 36 possible locations). Each cell in a grid subtended 1.07° x 1.07°. There was one grid on each quadrant of the display. Each grid occupied an area of 7.5° x 7.5°, and the distance between each grid was 5.36°. The total search array occupied 20.36° x 20.36° of visual angle. Finally, each item was randomly jittered within each cell. Finally, the four dots used to cue a quadrant of items were black and subtended about 0.15° x 0.15°. They were located in the outermost corners of the cued quadrant, without overlapping any items in the display.

Design and Procedure. There were two different conditions in the experiment: uncued (25% of trials) and cued (75% of trials). Uncued trials began with the presentation of the search display for 100 ms, which alternated with a blank display of 900 ms, until a response was recorded or 16 seconds had elapsed. We use the term 'epoch' (Rensink, 2000) to refer to one search display + blank display cycle. Here, all epochs lasted 1000 ms. Cued trials alternated between search and blank

displays in the same way, except for the inclusion of a cue dots, which could appear once, either before the first presentation of the display (25% of trials), the second presentation (25% of trials) or the third presentation (25% of trials). The cue dots were presented for 400 ms immediately preceding a search display. On trials in which the cue display appeared after the start of the first search display, the duration of the blank display was reduced by 400 ms so that the total duration of the epoch continued to be 1000 ms. Finally, the cued quadrant was chosen randomly and the cue was entirely non-predictive of the target's region, its specific location, or color. There was an inter-trial interval of 1.5 seconds between trials. Observers completed one practice set of 10 trials before being tested on 560 trials (8 sets of 64 trials with short breaks between sets). The experiment took about 45 minutes to complete.

**Results**

Figure 2 shows the frequency of correct responses for six epochs (epoch = a 100 ms look followed by a 900 ms blank). Five cuing conditions are shown (no cue, valid cue and invalid cue on looks 1 and 2). Not shown are the few responses that were made after 6 seconds (< 2.4%), and responses made when the cue appeared before look 3, because they are so similar to the data when the cue preceded look 2. Accuracy of responses exceeded 94% overall.

The response time (RT) distribution for no cue trials (Figure 2, top panel) replicated previous studies of rapid resumption. Following the first look at the search display (epoch 1) less than 2.4% of all responses occurred in the first 500 ms period (4/230). In contrast, the first 500 ms period following each subsequent look contained more than 35% of the responses (look 2 = 161/425, look 3 = 141/387, look 4 = 131/347, look 5 = 77/176, look 6 = 41/73). This establishes that the trials in this experiment on which no cue was presented led to the rapid resumption effect found in previous studies with no cue (Lleras et al., 2005; 2007).

The influence of the cue was examined in two ways: (1) its effectiveness in increasing overall search efficiency, measured by mean correct RT, and (2) the

cues' influence on the proportion of responses made early in an epoch (rapid resumption) relative to those made later within an epoch.

Overall search efficiency was estimated by computing mean correct RT in the various conditions for each observer. Analyses of variance (ANOVA) comparing the seven cue conditions (no cue, valid look 1, invalid look 1, valid look 2, invalid look 2, valid look 3, invalid look 3) indicated that the mere presence of a cue reduced RT significantly over the no cue condition (mean RT = 2588 ms vs. 3144 ms, respectively, $F(1, 14) = 9.30$, $p < .01$, MSe = 249,941) and that RT on valid cue trials was significantly less than on invalid cue trials (mean RT = 2489 ms vs. 2687 ms, respectively, $F(1, 14) = 4.58$, $p < .05$, MSe = 192,736). These analyses confirmed that the non-predictive spatial cue generally decreased search times, as in many previous studies.

The relative distribution of correct responses within an epoch is shown in Figure 3 for the various cuing conditions. To facilitate comparison among epochs differing greatly in overall frequency of response, all bin frequencies are plotted relative to the bin with the highest peak (in all three panels this is bin 7 or 600-699 ms), which has been set to 1.0. The first panel shows that the relative RT distributions in the first epoch contain very few early-phase responses (RT < 500 ms), even when the region of the display containing the target is preceded by a spatial cue. The second panel shows that there was a secondary peak at bin 3 (200-299 ms) for all conditions in epochs 2 and 3, but importantly, cueing had very little influence on the relative number of early-phase responses. Finally, the third panel shows the data from the epochs that followed the cued epoch (that is, epochs 2, 3, and 4 following cued epochs 1, 2, and 3, respectively), indicating that the relative RT distributions under these conditions were very similar to both cued and uncued epochs after the first look (epoch 1).

These observations were tested by statistically comparing the proportion of early-phase (RT < 500 ms) and later-phase responses (RT > 500 ms) for each of the observers in each of the 8 distributions shown in Figure 3. We refer to this measure as proportion RR. We readily admit that 500 ms represents somewhat of an arbitrary cutoff, but we are using it merely as a matter of convenience for

distinguishing between early- and later-phase responses. Readers should note that all the conclusions in this study remain unaltered if we adopt either a stricter (e.g., 400 ms cutoff) or a more lax criterion. Proportion of RR was remarkably stable at between .30 and .45 in all conditions shown in Figure 3, with the exception of the three cuing conditions in epoch 1, where it was less than .04. ANOVA revealed a significant interaction of epoch (1, average of 2-3, epoch following cue) x Cue (no cue, valid cue, invalid cue) overall, $F(1, 112) = 8.49$, $p < .01$, $MSE = .03$, but when epoch 1 was excluded, there were no longer any significant differences between conditions, $F < 1.0$.

**Discussion**

The results of Experiment 1 showed that a non-predictive spatial cue, intended to draw attention involuntarily to one quadrant in advance of the search display, had a significant effect on the time required to identify the target. The cue decreased mean RT by about 200 ms when it correctly indicating the target quadrant (valid) compared to when it was indicated a non-target quadrant (invalid). The same cue, however, had no effect on the shape of the response distribution following a look at the display. The proportion of correct responses that occurred in the first 500 ms following a look (rapid resumption responses) was not increased by the cue and RT distributions that were normalized to control for different baseline frequency of responses (Figure 3) also gave no hint that a valid cue altered either the portion of the distribution that peaked at bin 3 (rapid resumption responses) or the portion of the distribution that peaked at bin 7 (normal search responses). This implies that the effect of the cue on mean RT was to increase the probability that the target was found in an earlier epoch when it was valid than when it was invalid. This result is analogous to a previous finding that the number of items in a search display had no effect on rapid resumption (Lleras et al., 2005): proportion RR was not reduced when displays contained fewer items, although smaller set sizes did decrease overall RT by increasing the probability that the target would be found in an earlier epoch.

## Experiment 2 Predictive spatial cuing of the target region

Although Experiment 1 revealed no relationship between involuntary (exogenous) spatial orienting and rapid resumption, it is possible that rapid resumption is associated with voluntary (endogenous) orienting to a region of the scene prior to a look. To test for this possibility, the design of Experiment 2 was identical to the previous experiment, with the exception that the cue, when it was presented, was 100% predictive of the quadrant of the search display containing the target. Observers were informed of the predictive nature of the cue and were told to use it to shorten their search.

### Method

The methods of Experiment 2 were identical to those of Experiment 1, except that there were no invalid cued trials, as cues always perfectly predicted the target quadrant. The four experimental conditions were equally likely: on 25% of trials there was never a cue (no cue), and on the remaining 75% of trials, a cue appeared to indicate a target quadrant immediately before the first, second or third look at the display (25% of trials on each condition). Eighteen students from the University of Illinois at Urbana-Champaign took part in this study in exchange for course credit. All were naïve as to the purpose of the experiment and had normal or corrected-to-normal visual acuity.

### Results

Figure 4 shows the frequency of correct responses for the first six epochs in the four cuing conditions (no cue, cued epochs 1 to 3). There were only a few responses not shown that were longer than 6 seconds (< 0.5%) and the accuracy of responses exceeded 96% overall. The RT distributions for no cue trials (top panel in

Figure 4) showed the typical pattern of rapid resumption. Following the first look at the search display (epoch 1) less than 2% of all responses occurred in the first 500 ms period (4/226). In contrast, the first 500 ms period in each subsequent epoch contained more than 36% of the responses within an epoch (epoch 2 = 215/633, epoch 3 = 158/493, epoch 4 = 155/420, epoch 5 = 112/263, look 6 = 51/95).

The general effectiveness of the cue was examined by computing mean correct RT in the four conditions for each observer. ANOVA indicated significant differences, with no cue (mean RT = 2695 ms) significantly greater than the cued conditions as a whole (mean RT = 1723 ms), $F(1, 17) = 301.11$, $p < .01$, MSe = 28,252, and look 1 cued (mean RT = 951 ms) significantly less than look 2 cued (mean RT = 1813 ms), $F(1, 17) = 1101.02$, $p < .01$, which in turn was less than look 3 cued (mean RT = 2316 ms), $F(1, 17) = 374.49$, $p < .01$, MSe = 17,653. These analyses confirmed that predictive cuing of the target quadrant had a large effect on search time overall.

The relative distribution of correct responses within an epoch is shown in Figure 5 for the various cuing conditions. The first panel (epoch 1) shows that although spatial cuing has the systematic effect of increasing the relative frequency of responses in bins 5-7 (400-700 ms), there are nonetheless very few early-phase responses (RT < 500 ms). The middle panel is the most striking in showing a pattern of dissociation between spatial cuing and the rapid resumption phenomenon. Here spatial cuing increases responses over no cue in the range of 500-700 ms. However, at the same time, the early-phase responses that are normally associated with a second or third look at a display, evident in the no cue condition, are virtually absent in the cued condition, and no longer represent a significant mode of responses. This implies that whereas a predictive spatial cue is able to increase the overall speed of response, as well as the likelihood of a response in the 400-1000 ms range, it does not contribute to a greater proportion of rapid resumption responses. In fact, it does the opposite, actually reducing the relative frequency of early-phase responses in favor of later-phase responses. The third panel shows the data from epochs 2, 3, and 4 following a cue (that is, following cues in epoch 1, 2, and 3, respectively). The results show that following the second look at a spatially

cued target region, a vast majority of responses are in the rapid resumption period (RT < 500 ms).

These observations were tested by statistically comparing the proportion of early-phase (RT < 500 ms) and later-phase responses (RT > 500 ms) for each of the observers in each of the 5 distributions shown in Figure 5. ANOVA indicated a significant interaction of epoch (1, average of 2-3, epoch following cue) x cue (no cue, cued), $F(2, 34) = 23.31$, $p < .01$, $MSe = .005$. Proportion of RR in epoch 1 was less than .01 for the uncued condition and .09 in the cued condition, a significant difference, $F(1, 17) = 4.94$, $p < .03$, due entirely to the small increase of responses in bin 4. In epoch 2, the direction of these differences was reversed, with the proportion of RR averaging .35 in the no cue condition and only .23 in the cued condition, $F(1, 17) = 10.85$, $p < .01$). Finally, proportion RR in the look immediately following the cued epoch was more than .65, which was significantly greater than no cue in epochs 2 and 3, $F(1, 17) = 147.15$, $p < .01$, and greater than any cued epochs, $F(1, 17) = 247.71$, $p < .01$. There were no differences among the second-look after cue epochs, $F < 1.0$, $MSe = .015$.

**Discussion**

Experiment 2 showed that a spatial cue that correctly predicted the target region in a search display led to a significant improvement in search times. This was evident in the significant decrease in mean RT on cued trials and it was evident in the normalized response distributions, which showed that the leading edge of the cued distribution began about 100 ms in advance of the distribution corresponding to a first look at a display. Yet, this shift toward earlier responses with a predictive cue still occurred primarily within the normal search period (500-999 ms).

At the same time, the predictive cue had no positive effects on the rapid resumption effect. In fact, when the target was cued in advance of epochs that otherwise show rapid resumption (second and subsequent looks at the display), the predictive cue significantly reduced the proportion of responses that fell within the rapid resumption period (0-499 ms). None of the cued distributions showed any

evidence of secondary peak at bin 3 (300-399 ms). Where the cue did have a positive impact on rapid resumption was on the *second* look that occurred following the cue. In these epochs, the proportion of RR responses rose above .65, which is significantly higher than the proportion RR observed without a cue (about .35 in this experiment).

## Experiment 3: Predictive spatial cuing of the target location

Focusing spatial attention on one quadrant of a search display prior to the appearance of the items effectively reduced the number of items that had to be inspected during a search. Yet, spatial orienting of this kind had no influence on the proportion of rapid resumption responses, either when it was involuntary (Experiment 1) or when it was voluntary (Experiment 2). As a final stringent check on the possible relationship between spatial orienting and rapid resumption, the present experiment examined voluntary spatial orienting to the specific location of the target item in advance of the search display. The methods and design of Experiment 3 were identical to Experiment 2, with the exception that the cue was now 100% predictive of the location of the target within the search display.

### Method

Unlike Experiments 1 and 2, the cuing dots were now presented within the search grids, at the outermost corners of the grid cell that would eventually contain the target in the subsequent search display, so that the dots would surround but not overlap with the target item. Four analogous conditions to Experiment 2 were examined: no cue, look 1 cued, look 2 cued and look 3 cued. All conditions were equally likely. Twenty students from the University of Illinois at Urbana-Champaign took part in this study in exchange for course credit. All were naïve as to the purpose of the experiment and had normal or corrected-to-normal visual acuity.

**Results**

Figure 6 shows the frequency of correct responses for the first six epochs. Only a few responses were not shown because they were longer than 6 seconds (< 5.0%) and the accuracy of responses exceeded 95% overall. The RT distribution for no cue trials (Figure 6, top panel) showed the typical pattern of rapid resumption. Following the first look at the search display (epoch 1) less than 1.5% of all responses occurred in the first 500 ms period (8/564). In contrast, the first 500 ms period following each subsequent look contained more than 44% of the responses within an epoch (look 2 = 412/856, look 3 = 264/608, look 4 = 169/410, look 5 = 92/235, look 6 = 63/137).

The general effectiveness of the cue was examined by computing mean correct RT in the four conditions for each observer. ANOVA indicated significant differences, with no cue (mean RT = 2561 ms) being significantly greater than the cued conditions as a whole (mean RT = 1308 ms), $F(1, 19) = 178.60$, $p < .01$, MSe = 87,915. Cued epoch 1 (mean RT = 538 ms) was significantly lower than cued epoch 2 (mean RT = 1430 ms), $F(1, 19) = 931.06$, $p < .01$, which in turn was lower than cued epoch 3 (mean RT = 1949 ms), $F(1, 19) = 242.60$, $p < .01$, MSe = 11,082. These analyses confirmed that cuing the target location provided a large benefit on search time overall.

The relative distribution of correct responses within an epoch is shown in Figure 7 for the various cuing conditions. The first panel (epoch 1), as in the previous experiment, showed that spatial cuing increased the relative frequency of responses in bins 5-6 (400-599 ms). The peak of the response distribution in epoch 1 was 100 ms earlier with a target-specific cue than with no cue. However, the middle panel showed that the distribution of responses associated with the cue in epochs 2 and 3, which peaked in bin 5 (400-499 ms), was still not as early as that associated with a second look in the absence of any cue. The first peak in the no cue distribution was centered on bin 3 (200-299 ms). Finally, the third panel (epoch following cued epoch) showed a two-peaked distribution of responses similar to those in the absence of a cue.

These observations were tested by statistically comparing the proportion of early-phase (RT < 500 ms) and later-phase responses (RT > 500 ms) for each of the observers in each of the 5 distributions shown in Figure 7. ANOVA indicated a significant interaction of epoch (1, average of 2-3, epoch following cue) x cue (no cue, cued), $F(4, 76) = 56.16$, $p < .01$, $MSe = .025$. Proportion of RR in epoch 1 was .01 for the uncued condition and .36 in the cued condition, a significant difference, $F(1, 19) = 56.81$, $p < .03$, due entirely to the increases in responses in bin 5 (400-499 ms). In epoch 2, the direction of these differences was reversed, with the proportion of RR averaging .53 in the no cue condition and only .38 in the cued condition, $F(1, 19) = 8.20$, $p < .01$). Finally, proportion RR in the look immediately following the cued epoch was more than .49, which was similar to the no cue in epochs 2 and 3, $F(1, 19) < 1.0$, and greater than the cued epochs, $F(1,19) = 6.16$, $p < .02$.

Response Speed and Accuracy. An important question that is relevant to the interpretation of all three experiments here, as well as the data from previously published experiments on rapid resumption, is how the phenomenon of rapid resumption is related to the response biases of the observer. For example, is it possible that these early-phase responses reflect a tendency for observers to be overly cautious, taking the opportunity to have one more look even though it is unnecessary, before making their response? If so, then a more liberal response criteria should reduce and maybe even eliminate the RR phenomenon.

We addressed this question in the present data in two ways. First, we examined the relationship between response accuracy (proportion errors) and the proportion of RR in the three experiments. The accuracy measures we used included the proportion of errors made on all no cue trials (uncontaminated by any effects of spatial cuing) and the percentage of errors made overall (across both cued and uncued trials). The speed of response measures included the proportion of RR responses (RT < 500 ms) in epochs 2 and beyond in the no cue condition (uncontaminated by any effects of spatial cuing) and the proportion of RR responses made overall (across all trial types).

This yielded data for a total of 53 participants (n = 15, 18, 20 in the three experiments), with average error rates ranging from .01 to .16 in the no cue condition and from .01 to .14 overall. Proportion of RR ranged from .15 to .68 in the no cue condition and from .17% to .72 overall. The correlation among the two error measures was very strong (r = .72) as was the correlation between the two measures of rapid resumption (r = .81). Yet, the correlations among the error measures and the measures of rapid resumption were all near zero (r = -.03 to +.22). The slight positive correlations suggest if anything, that higher error rates tend to be associated with a larger proportion of rapid resumption responses. This is opposite to the hypothesis that a liberal response criterion might reduce or eliminate the rapid resumption phenomenon.

Our second approach to the question of whether response biases contribute to early-phase responses involved inspection of the distribution of response errors over time. When we combined data from all three experiments in order to maximize our opportunity for detecting a pattern in these relatively rare responses (53 observers yielded a total of 1356 errors) we observed that errors were distributed in a very similar way to correct responses over time. In epoch 1 almost no responses were made in less than 500 ms (< 5%), whereas in epochs 2-6 errors were distributed between the early- and late-phases of each epoch in much the same way as correct responses (493/977 = .51 were made in < 500 ms, 484/977 = .49 were made > 500 ms). However, when we examined the proportion of errors made in the early-phase separately for no cue and cued epochs it was clear that the cue contributed to an increase in early phase errors (41.8% of errors < 500 ms in the no cue condition; 55.4% of errors < 500 ms in the cued conditions, chi-square = 15.74, p < .001). Taken together, these analyses do not support the hypothesis that a liberal response bias contributes to early-phase correct responses. However, what the analyses do show is that the spatial cue used in this experiment contributed to early-phase response errors over and above the baseline likelihood of making a response error during this period.

**Discussion**

Experiment 3 showed that a spatial cue in the precise target location increased search speed to an even greater extent than a cue that was correctly predictive of only the general target region (previous experiment). The distribution of normal search responses was shifted forward by more than 100 ms by this cue. The target location cue also guaranteed search success in the epoch following the cued epoch to a greater extent than the general region cue, as very few responses occurred more than one epoch after the cue was presented. Yet, this large increase in responses that were facilitated by the target cue occurred primarily within the normal search period (500-999 ms following a look). The proportion of early-phase responses (0-499 ms) was not increased by the presence of this otherwise highly effective search cue, with the exception of the bins 4 and 5 (300-499 ms). In fact, the proportion of RR in the target cue condition was still significantly less than the proportion of RR following the second and third look in the no cue condition (see in particular bin 3 in the second panel of Figure 7). It was also notable that there was no hint of an early-phase peak of responses in the cued condition, both when the target in the first look was cued (top panel) and when the second and third looks were cued (second panel). From this we conclude that focused spatial attention does not in itself contribute to the phenomenon of rapid resumption of an interrupted search. Moreover, cuing the location of the target in advance serves to actively reduce the likelihood of an early-phase correct response at the same time that it vastly increases the likelihood of a correct late-phase response.

## General Discussion

These three experiments were conducted to determine whether focused spatial attention plays a causal role in the rapid resumption of an interrupted search. Specifically, we asked the question: Do the fast correct response times that are observed when an interrupted visual search is resumed (Lleras et al., 2005) occur because of a coincidence between the spatial focus of the observer's attention and the location of the target in the display? This is an important question to consider because it has long been known that focused spatial attention provides a number of

benefits to perception, including faster and more accurate responding (Luck & Vecera, 2002; Yeshurun & Carrasco, 1999), immunity from backward masking (Enns, 2004), and success in detecting changes to scenes (O'Regan et al., 2000; Rensink, 2000). If spatial orienting also contributes to the rapid resumption of an interrupted search, then this phenomenon should properly be re-interpreted as an instance of "lucky" spatial orienting, rather than as evidence of an implicit perceptual hypothesis testing process that is awaiting confirmation, as proposed by Lleras et al. (2005, 2007).

Experiment 1 showed that exogenously cuing observers in advance, to the general region in which the target later appeared, produced a significant reduction in average search time. This is the traditional spatial cuing effect many others have noted previously in visual search experiments (Cheal, Lyon & Gottlob, 1994). It is also evident in Figure 2 when valid cue (second and fourth panels) and invalid cue conditions (third and fifth panels) are compared. This comparison shows an increased number of correct responses for valid cues in the latter half of each epoch (i.e., RT between 500-100 ms). Yet, despite search benefiting in this way, observers in Experiment 1 were unable to use this spatial cue to produce more early-phase responses to a target immediately following the presentation of the cue. This is shown in the near absence of any rapid resumption responses (RT shorter than 500 ms) when a cue preceded the first look at the display (e.g., valid cue epoch 1). It is also shown in Figure 3 as the relative proportion of rapid resumption responses in epochs 2 and 3 following a valid cue (middle panel). These data show rapid resumption at no greater rate following a valid cue than an invalid cue, or even no cue, in the second epoch and beyond. The epoch that following on the heels of a cued epoch (lower panel in Figure 3) also showed no influence of the cue on rapid resumption responses that normally occur in the second and subsequent looks at a search display.

When we explored the role of a perfectly predictive (endogenous) region cue in Experiment 2, the results were not much different. The first panel of Figure 5 shows that the relative frequency of early-phase responses in the first epoch did not differ much, depending on whether there was a cue that reduced the effective

number of search items to a quarter of the total. Having completely reliable evidence of the region in which the target would appear did, however, have a large benefit on search success, in that many more correct responses were made in the second half of the epoch (RT between 500 and 1000 ms). However, this foreknowledge still did not allow observers to produce early-phase responses (RT < 500 ms) at a greater rate.

When we directed observers' attention to the exact location of the target in Experiment 3, the cue was even more overwhelmingly effective at ensuring search success in the epoch immediately following the presentation of the cue. Figure 6 (second panel) shows that a vast majority of the correct responses occurred within 1000 ms following the first look. Yet, this highly effective spatial cue nonetheless still failed to produce the many early-phase responses that characterize rapid resumption. In summary, these three experiments reveal dissociable effects of focused spatial attention and the rapid resumption of search. Although spatial cuing can increase the speed and accuracy of the perceptual processes of visual search, it does not in itself contribute to the rapid resumption phenomenon. We believe that occurs, as we have described elsewhere (Enns & Lleras, 2008; Lleras et al, 2005; 2007), because observers are taking advantage of the perceptual processing that was begun following one look (activation and prediction) and using it to complete the perception cycle (confirmation) in a second look.

In two previous reports, Lleras et al (2005, 2007) examined the conditions that give rise to rapid resumption. Their experiments were guided by the theoretical idea that rapid resumption is an index of the benefit of having already created a perceptual hypothesis about the target (based on the first look), and prior to the appearance of the second look, that must only be confirmed in the second look for conscious perception of the target to occur. To illustrate this idea in greater detail, we will refer to the last look at the display, prior to making a response on any given trial, as look "L". The authors proposed that on trials on which rapid resumption was observed, observers had generated a perceptual hypothesis about the target on the previous look (i.e., on look "L - 1"). But, because sensory information regarding the target was removed from the visual system before this hypothesis could be

confirmed, observers did not become aware of the target. In other words, the perceptual hypothesis about the target remained unconfirmed. However, upon re-presentation of the display (i.e., on look "L"), the partial information about the target contained in this perceptual hypothesis was combined with current sensory information to accelerate target processing, resulting in both faster awareness of the target and faster responses.

Within this framework, the present results can be easily accounted for: cuing attention to the target location cannot produce rapid resumption results because regardless of how effective the cue is, it is no substitute for the formation of a perceptual hypothesis about the target's identity. Whereas focused attention may hasten the perceptual processing at the cued location, processing of the target features necessary to confirm its identity must start from scratch. In contrast, on rapid resumption trials, the perceptual hypothesis created on look "L – 1" allows for much more efficient processing of (and then responding to) the target simply because some of the critical perceptual processing has already taken place before that look occurred. Note too that the generation of a perceptual hypothesis can induce a motor preparation for the response that is strongly associated with the features in that perceptual hypothesis, even before observers become aware (or sometimes even in the absence of awareness) of the target (e.g., Lleras, Rensink & Enns, 2007; Lleras & Enns, 2004, 2006). It is therefore likely that this motor preparation is also partly responsible for the extremely fast responses observed in rapid resumption.

This framework can also make sense of the pattern observed in the bottom panel of Figure 5: on the epoch following the cued epoch (epoch L + 1), there is a dramatic increase in rapid resumption responses. This observation is consistent with the cue having increased the likelihood that a perceptual hypothesis about the target will be created on look L (immediately after the cue). If the hypothesis is confirmed on that epoch, a rise of normal responses is observed (middle panel). If, on the other hand, the hypothesis does not have a chance to be confirmed on look L, it will certainly be ready for confirmation on look L+1. This explains why a vast majority of responses on epoch L+1 are of the rapid resumption kind.

The difference between the bottom panels in Figures 5 and 7, then, is also quite informative: when the cue is spatially vague (Figure 5, the cue only generally indicates the quadrant containing the target), almost all responses on Epoch L+1 are rapid resumption, whereas when the cue is spatially accurate (Figure 7, the cue perfectly directs attention to the target location), this increase in rapid resumption responses is more subdued. This follows because with spatially accurate cues, the likelihood of forming and confirming a hypothesis about the target during a single epoch is substantial (as indicated by differences in overall responses frequencies between cued Epochs in Figures 4 and 6). In sum, the current results suggest that a "key" ingredient for rapid resumption responses is spatial proximity to the target, coupled with spatial uncertainty about it (as was the case in Experiment 2): under these conditions, the chances of perceptual hypotheses about the target being created on one look and confirmed on a subsequent look seem maximal.

This tentative conclusion fits well with a recent report, in which we recorded eye movements during an interrupted visual search task (van Zoest et al., 2007). The primary factor determining whether any given look would produce a rapid resumption response (within 500 ms of last display onset) or a later response (between 500 ms and 1000 ms after the last display onset) was not the distance between current eye position and the target on look L. In fact, eye-target distance on look L did not discriminate between the two types of responses. However, the eye-target distance on look L – 1 did predict the relative frequency of rapid resumption responses, with increased rapid resumption correlated with decreased eye-target distance. This is consistent with the present data in supporting the idea that what is crucial in rapid resumption is having the opportunity on a previous look to do some (albeit incomplete) processing of the target.

In van Zoest et al (2007), this proposal was partially confirmed by using fixation-contingent search displays in two experiments. In these experiments, the target was presented to the center of gaze regardless of where the observer was fixated. This meant that after one of the waits between looks, the search display reappeared and the target was exactly at the center of the observer's gaze, regardless of where they were looking. Just as in the present study with spatial

cues, giving the observer prior information about target location sharply increased the likelihood of a successful search within the next two epochs. In fact, search success in the look immediately following gaze contingent target relocation was 75% (van Zoest et al., 2007, Experiment 2) and in the look immediately following a spatial cue that was completely predictive of the target location it was over 80% (present Experiment 3). Yet, this high baseline rate of search success did not contribute to a higher proportion of rapid resumption responses in either case. Those responses still occurred primarily after the second look at a gaze-contingent target or following a predictive cue.

One of the limitations of the fixation-contingent studies (van Zoest et al, 2007) is that the (fixation-contingent) rearrangement of the target from look to look also involved altering the stability of the search display. Because the target no longer remained in a fixed location it is possible that observers were somewhat slower to respond on those trials simply because the new information in each display did not match their expectations (either consciously or unconsciously) about what would be at a given location. Moreover, the rearrangement of the target also changed the spatial configuration of items at the fixated region, and previous studies have reported that changing the configuration of the search display in this way disturbs rapid resumption (Lleras, Rensink & Enns, 2005, 2007; Jungé, Brady, & Chun, in press). In contrast to these limitations, the present spatial cuing manipulations did not alter the information in the search display; they simply allowed observers to form a spatial expectancy about where to look prior to the search display, and during one of the waits between looks. As such, the present finding that spatial orienting is independent of the rapid resumption phenomenon is converging evidence that rapid resumption responses is not the consequence of either “lucky” eye fixations (van Zoest et al., 2007) or “lucky” spatial expectancies. Instead, it suggests that rapid resumption is critically dependent on observers having the opportunity to partially process the target (Lleras, Rensink & Enns, 2007) and the spatial layout of items immediately around it (Jungé, Brady, & Chun, in press) during a prior look.

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## Figure Captions

Figure 1. Schematic illustration of the sequence of events in Experiments 1 and 2. Brief glimpses (100 millisecond looks) of a search display were interrupted by longer blank screens (900 millisecond waits) until the target (a blue T-shape in this example) was identified. Randomly selected looks were preceded by a cue (the four dots shown for 400 milliseconds in advance of the search display) to focus attention on one of the four quadrants in which search items appeared. In the example shown, the cue indicates the upper left quadrant but the target is in the lower left quadrant, illustrating an invalidly cued search trial.

Figure 2. Frequency distributions of correct response times (RT) in Experiment 1 as a function of various cue conditions. Histograms shaded in gray are responses made within 500 milliseconds of a look, the operational definition of rapid resumption in this study.

Figure 3. The normalized proportion of correct responses across all 10 bins (bin 1 = 0-99 ms, bin 2 = 100-199 ms, etc) in an epoch in Experiment 1. For each cue condition, the bin with the highest frequency of responses was set to 1.0, in order to compare the relative distribution of responses in the other 9 bins. The middle panel shows average data from epochs 2 and 3 of the no cue condition and compares it to the average data of epochs that occurred immediately following a cue: cued epoch 2 and cued epoch 3. The bottom panel presents average data from the epochs following a cued epoch (epoch 2 in the cued epoch 1 condition, epoch 3 in the cued epoch 2 condition, and epoch 4 in the cued epoch 3 condition).

Figure 4. Frequency distributions of correct response times (RT) in Experiment 2 as a function of cue condition. Histograms shaded in gray are responses that

occur within 500 milliseconds of a look, the operational definition of rapid resumption.

Figure 5. The normalized proportion of correct responses across all 10 bins (bin 1 = 0-99 ms, bin 2 = 100-199 ms, etc) in an epoch in Experiment 2. For each cue condition, the bin with the highest frequency of responses was set to 1.0, in order to compare the relative distribution of responses in the other 9 bins. The middle panel shows average data from epochs 2 and 3 of the no cue condition and compares it to the average data of epochs that occurred immediately following a cue: cued epoch 2 and cued epoch 3. The bottom panel presents average data from the epochs following a cued epoch (epoch 2 in the cued epoch 1 condition, epoch 3 in the cued epoch 2 condition, and epoch 4 in the cued epoch 3 condition).

Figure 6. Frequency distributions of correct response times (RT) in Experiment 3 as a function of cue condition. Histograms shaded in gray are responses made within 500 milliseconds of a look, the operational definition of rapid resumption.

Figure 7. The normalized proportion of correct responses across all 10 bins (bin 1 = 0-99 ms, bin 2 = 100-199 ms, etc) in an epoch in Experiment 3. For each cue condition, the bin with the highest frequency of responses was set to 1.0, in order to compare the relative distribution of responses in the other 9 bins. The middle panel shows average data from epochs 2 and 3 of the no cue condition and compares it to the average data of epochs that occurred immediately following a cue: cued epoch 2 and cued epoch 3. The bottom panel presents average data from the epochs following a cued epoch (epoch 2 in the cued epoch 1 condition, epoch 3 in the cued epoch 2 condition, and epoch 4 in the cued epoch 3 condition).

Figure 1

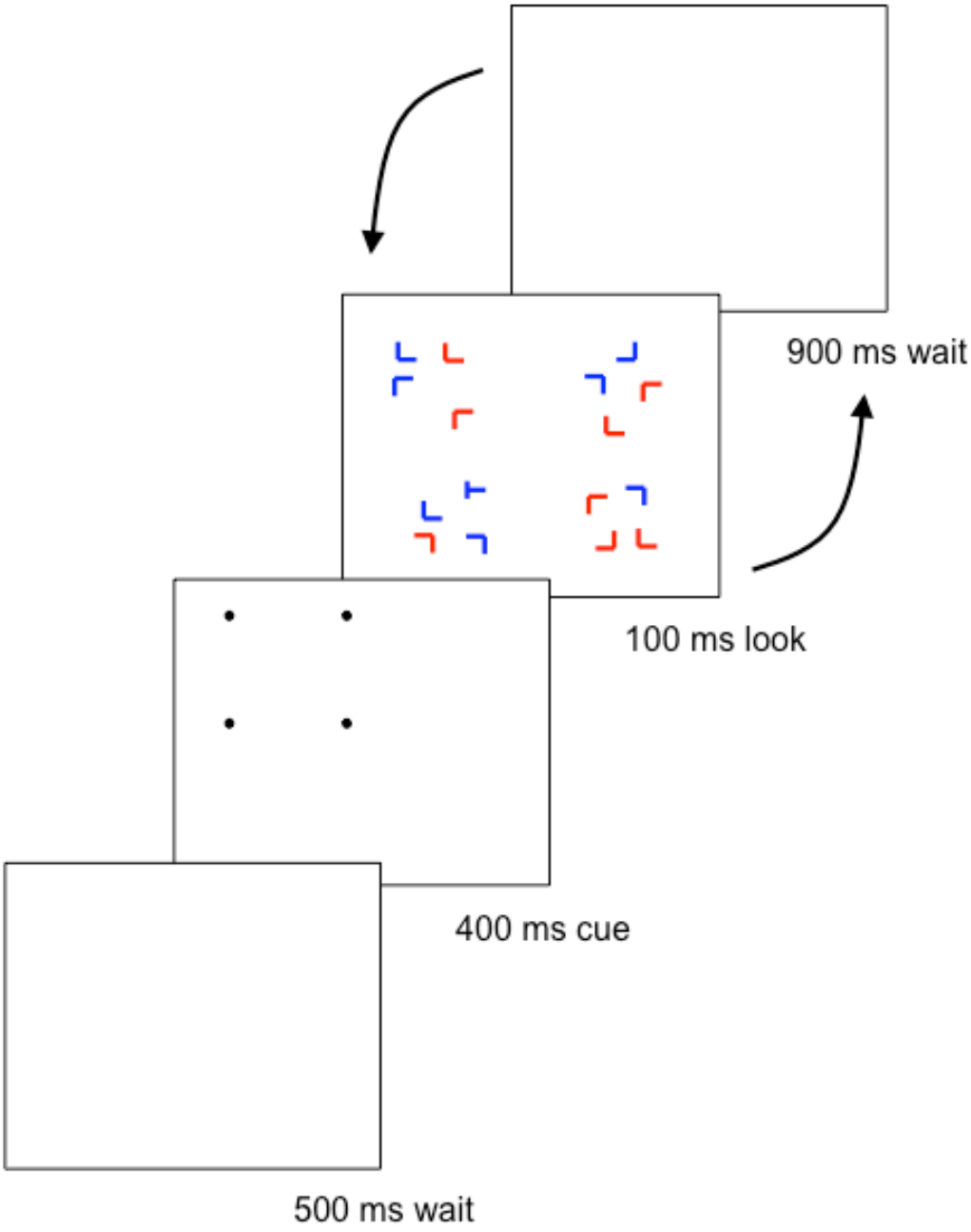
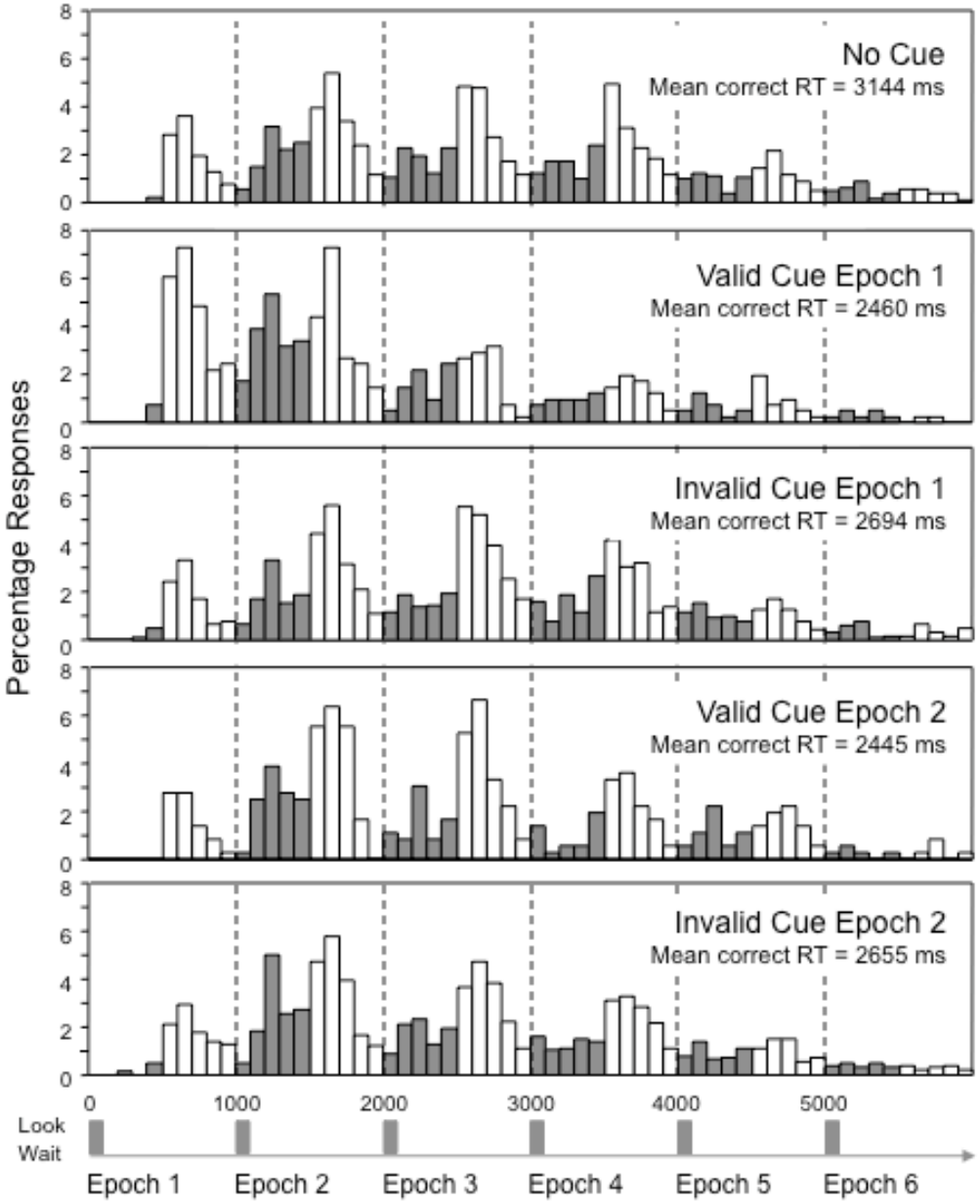


Figure 2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Mean correct RT = 3144 ms
Valid Cue Epoch 1
Mean correct RT = 2460 ms
Invalid Cue Epoch 1
Mean correct RT = 2694 ms
Valid Cue Epoch 2
Mean correct RT = 2445 ms
Invalid Cue Epoch 2
Mean correct RT = 2655 ms
Percentage Responses
0
2
4
6
8
0
1000
2000
3000
4000
5000
Look
Wait
Epoch 1
Epoch 2
Epoch 3
Epoch 4
Epoch 5
Epoch 6

Figure 3

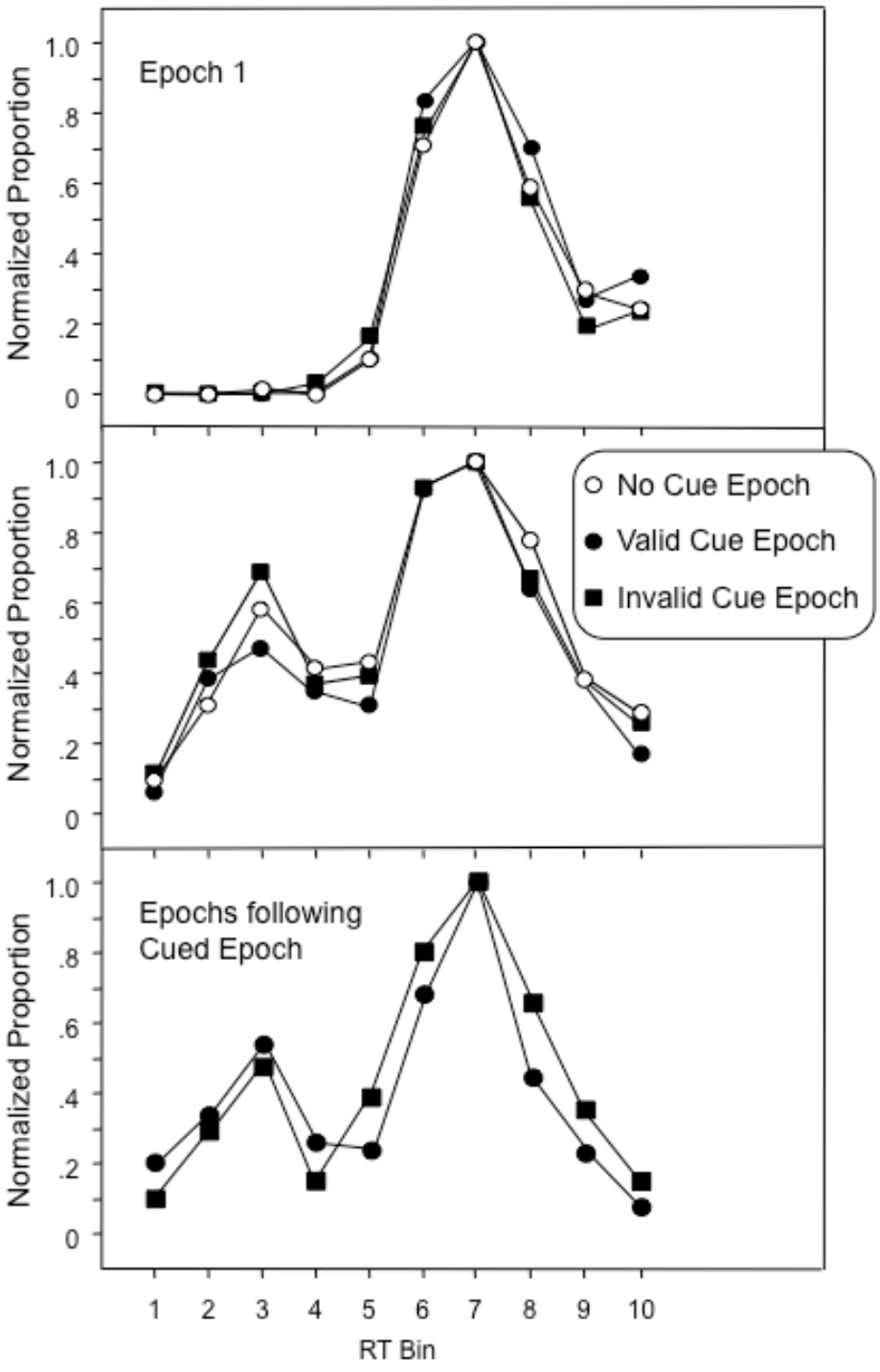

Epoch 1
Epochs following Cued Epoch
Normalized Proportion
1.0
.8
.6
.4
.2
0
No Cue Epoch
Valid Cue Epoch
Invalid Cue Epoch
1
2
3
4
5
6
7
8
9
10
RT Bin

Figure 4

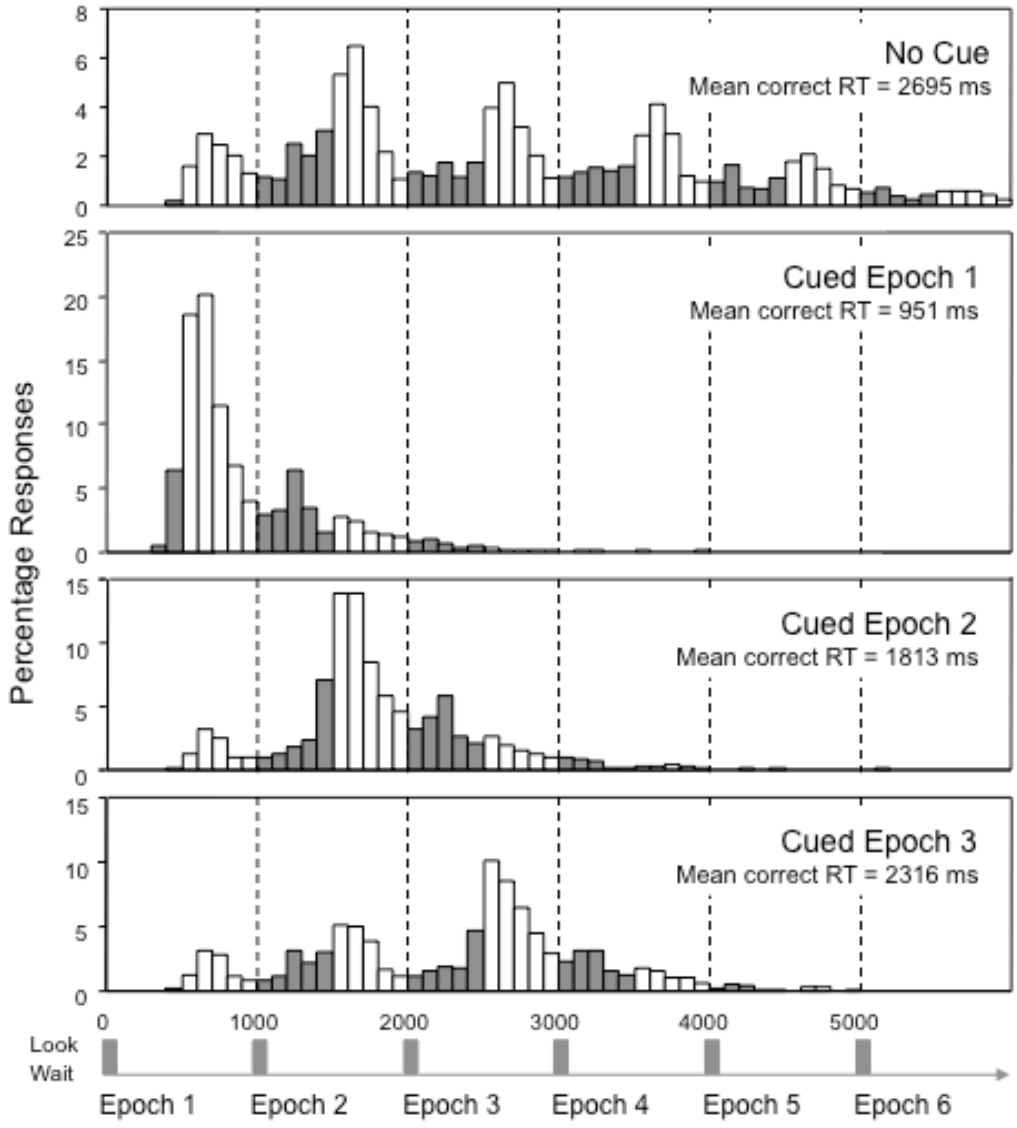

No Cue
Mean correct RT = 2695 ms
Cued Epoch 1
Mean correct RT = 951 ms
Cued Epoch 2
Mean correct RT = 1813 ms
Cued Epoch 3
Mean correct RT = 2316 ms
Percentage Responses
0
1000
2000
3000
4000
5000
Look
Wait
Epoch 1
Epoch 2
Epoch 3
Epoch 4
Epoch 5
Epoch 6

Figure 5

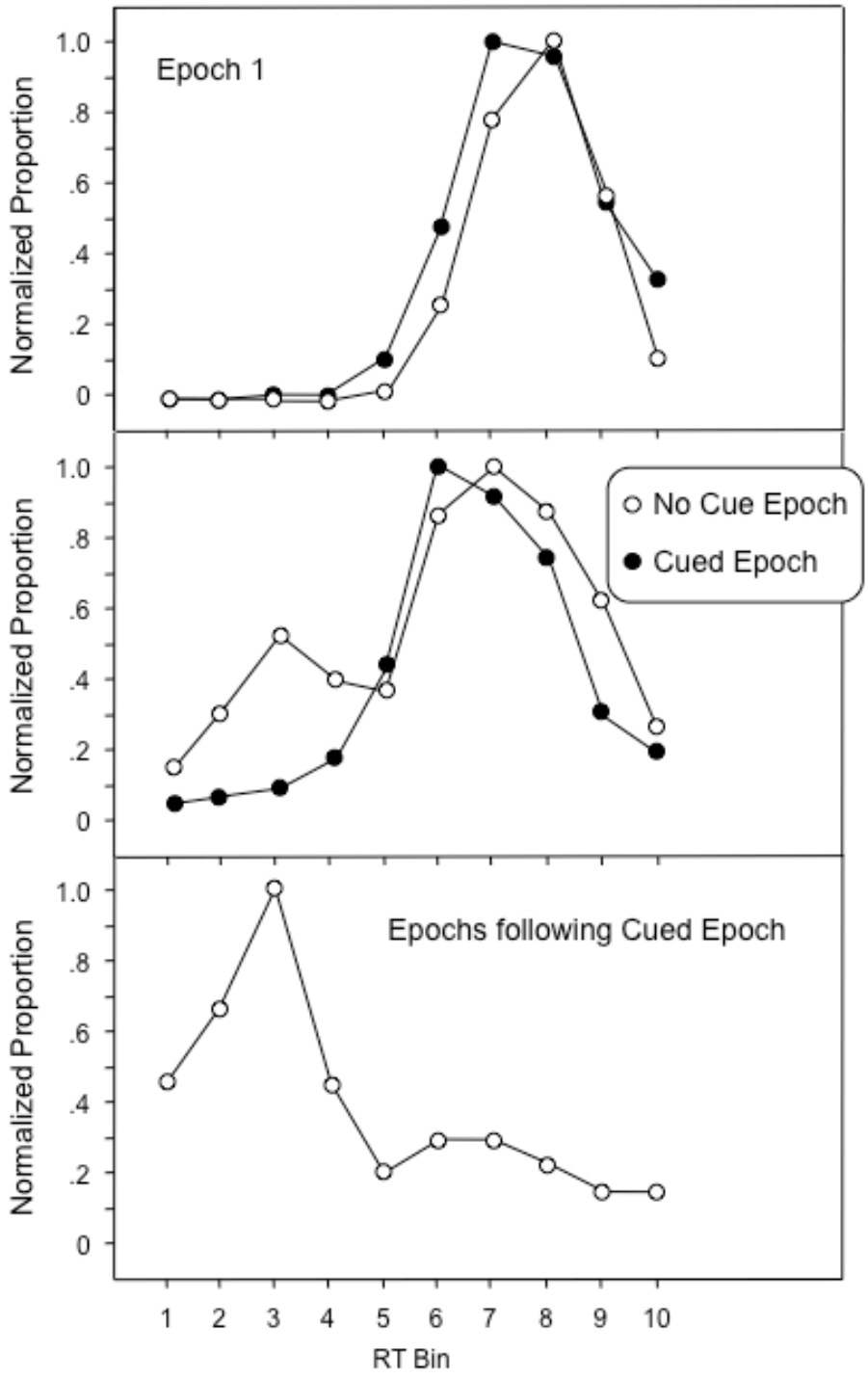

Epoch 1
Normalized Proportion
1.0
.8
.6
.4
.2
0
No Cue Epoch
Cued Epoch
Epochs following Cued Epoch
1 2 3 4 5 6 7 8 9 10
RT Bin

Figure 6

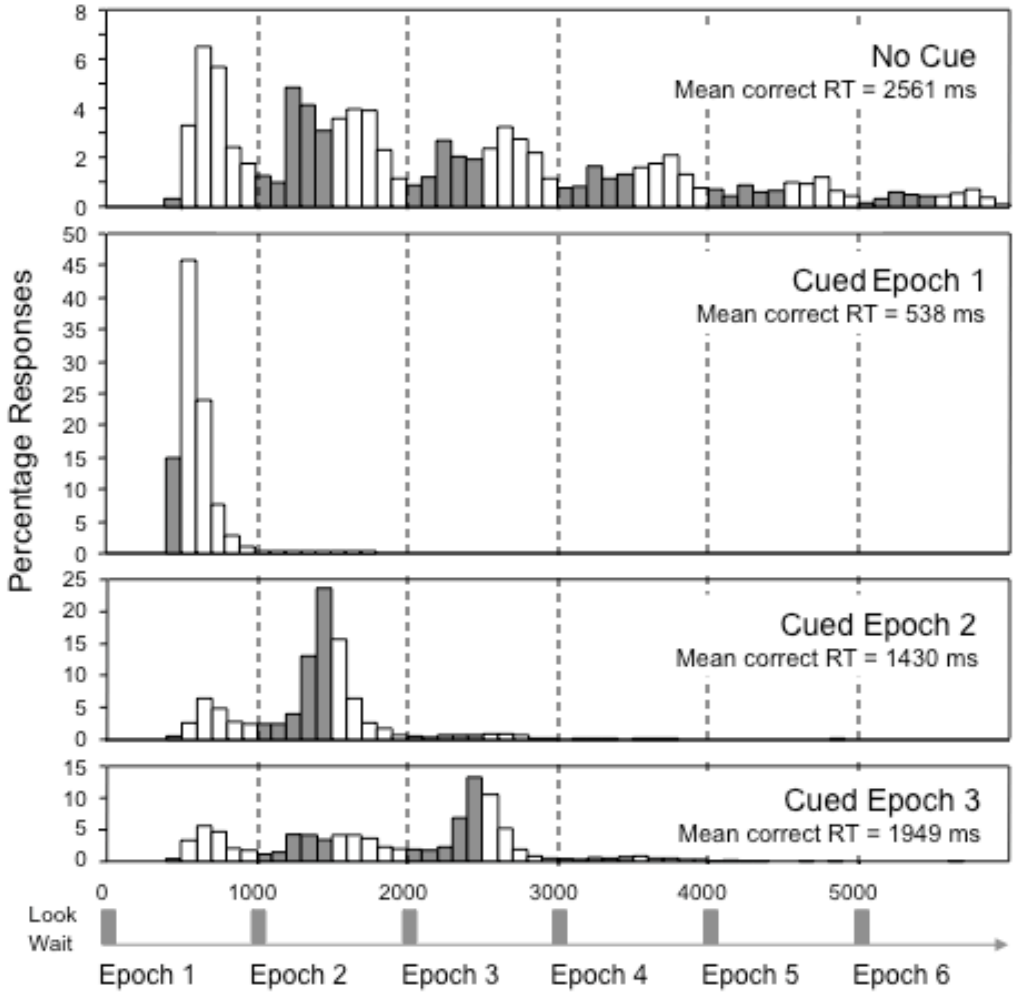
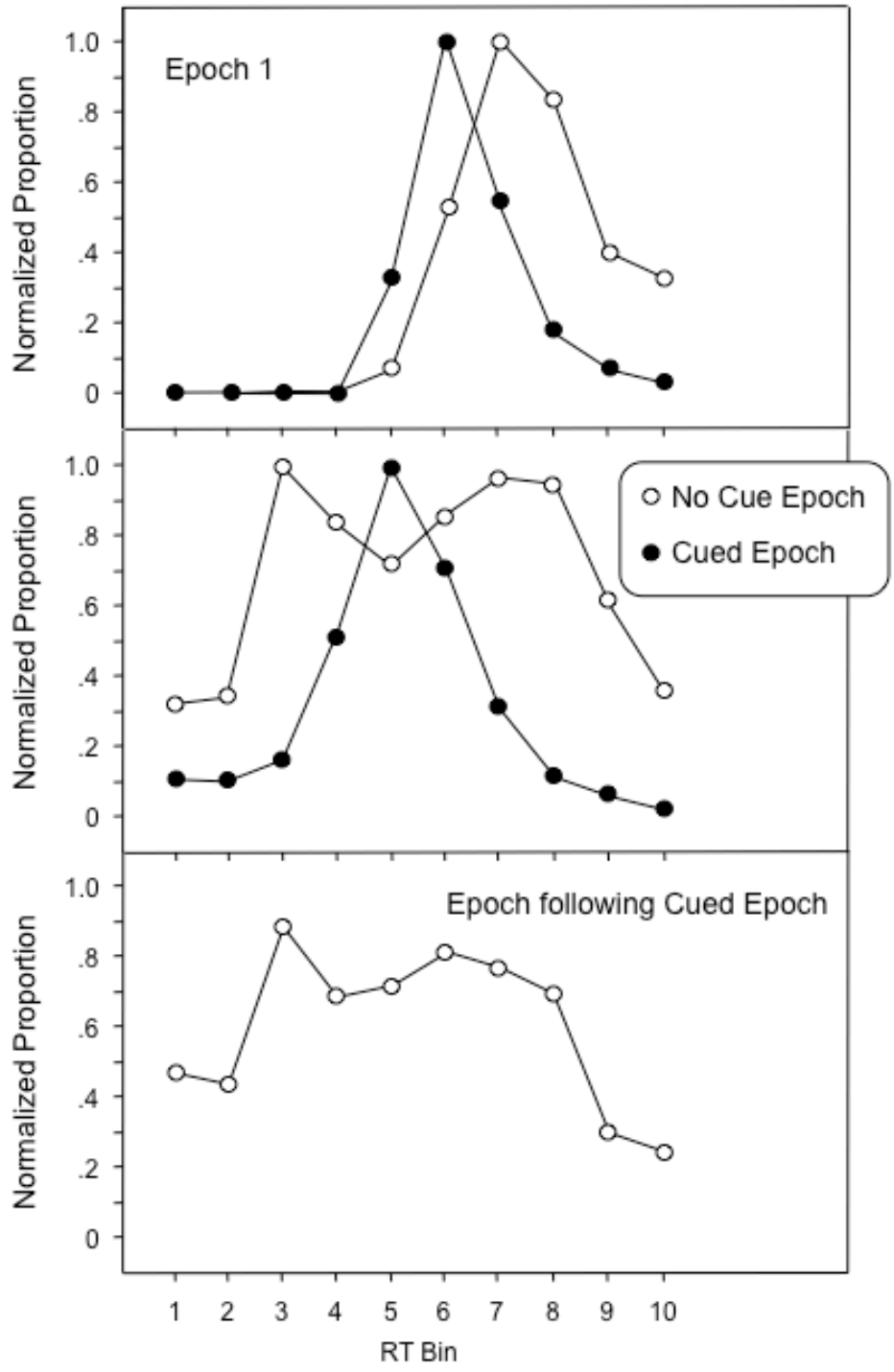

No Cue
Mean correct RT = 2561 ms
Cued Epoch 1
Mean correct RT = 538 ms
Cued Epoch 2
Mean correct RT = 1430 ms
Cued Epoch 3
Mean correct RT = 1949 ms
Percentage Responses
0
1000
2000
3000
4000
5000
Look
Wait
Epoch 1
Epoch 2
Epoch 3
Epoch 4
Epoch 5
Epoch 6

Figure 7


Epoch 1
Normalized Proportion
1.0
.8
.6
.4
.2
0
No Cue Epoch
Cued Epoch
Epoch following Cued Epoch
1 2 3 4 5 6 7 8 9 10
RT Bin