Singleton Search is Guided by Knowledge of the Target, but Maybe it Shouldn't Be

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Abstract

Among studies of visual search for a singleton, some studies show evidence of top-down attentional guidance driven by goals, while others do not, leading to uncertainty as to how goal-driven guidance should be included in attentional theories. Six experiments tested this guidance when a target shape is found by locating a singleton feature (color or shape) and an orientation within the target is then reported. Experiments 1 and 2 use the dimensional priming paradigm underlying the most effective arguments against goal-driven guidance, and show evidence for guidance in many circumstances. Experiment 3 extends the results to feature priming, and demonstrates a complex interaction between attentional goals and memory for previous targets. In Experiment 4, symbolic (word) cues were just as effective as image cues, further strengthening the case for goal-driven guidance. In Experiments 5 and 6, as in the previous experiments, valid cues again produced faster responses than invalid cues, showing the advantage of goal-driven guidance. Surprisingly, however, responses were even faster when the cues were uninformative. Furthermore, participants who began the experiment with neutral cues seemed to ignore informative cues later in the experiment. The results show that attention can be guided by goals even in easy searches, but that searchers have much flexibility in the use of this guidance, and may choose not to use it. Furthermore, their decisions about using this guidance are not always well informed, because they are not aware of the relative costs and benefits.

Keywords: singleton search, current goals, top-down, inter-trial priming, symbolic cues

1. Introduction

Many visual searches are difficult without foreknowledge of the appearance of the possible targets, and the properties that differentiate them from the distractors. Some targets, however, differ so markedly from their surroundings that their salience makes them easy to find. In the endeavor to understand how different attentional mechanisms contribute to visual search, some very helpful insights have emerged from studies that have asked whether the foreknowledge that helps in difficult searches also contributes to these easy “pop-out” searches.

In one of the early studies in this area, Bravo and Nakayama (1992) showed that even though a color singleton target was found quickly, it was found even more quickly when the colors of the target and distractors were constant across trials. The initial interpretation was that certainty about the target feature led to more effective attentional guidance. In a later study, Wolfe, Butcher, Lee, and Hyle (2003) combined manipulation of target feature certainty with manipulation of target dimension uncertainty (following up on studies such as Müller, Heller, & Ziegler, 1995). They found that both types of certainty could speed search. In these experiments and others of this type, keeping target and distractors constant across trials allows participants to know which features to search for from the beginning of the trial, but as Maljkovic and Nakayama (1994) pointed out, it can also produce a form of inter-trial priming in which the target feature seen on one trial is more easily detected on the next trial.

As more and more singleton search experiments have been done, it has become clear that multiple factors are interacting to determine search performance. Awh, Belopolsky, and Theeuwes (2012) have argued that these different factors should be thought of as comprising three different categories. In singleton search, the most obvious is **physical salience**: the difference in color, orientation, size, or some other feature that sets the target apart from all the distractors. This aspect is often described as bottom-up or stimulus driven, because it is determined solely by physical properties of the stimulus. Awh *et al.* also included the searcher's **current goals** in their framework. When participants know that the target on the upcoming trial will be red, their goal is to attend to red items and to ignore items of other colors. Guidance directed by these goals is often described as top-down. The third category is **selection history**, which includes the inter-trial priming that was first demonstrated by Maljkovic and Nakayama (1994), and has been shown to consist of multiple different factors that affect different processing stages (Huang, Holcombe, & Pashler, 2004, Töllner, Gramann, Müllller, Kiss, & Eimer, 2008; Yashar & Lamy, 2011). Within Awh *et al.*'s framework, the objective is to determine how each of these factors contributes to visual selection, and how they interact with one another. Each of these three factors will play an important role in the experiments described below.

Although all three factors have been the subject of multiple visual search experiments, there is not universal agreement that all three play a role in visual search, especially in search for singletons. Some of the evidence favoring a role for current goals in singleton search comes from Müller, Reimann, and Krumenacher's (2003) search experiments in which participants detected singleton targets more quickly when they knew the dimension of the target. Surprisingly, however, Theeuwes, Reimann, and Mortier (2006) argue that current goals play no role in these singleton searches, and that these effects were instead entirely caused by inter-trial priming, *i.e.* selection history. Their strongest evidence for this claim comes from their Experiment 2, in which participants search for a singleton after seeing a cue indicating the probable dimension of the target (color or shape). In order to prevent response priming, Theeuwes *et al.* used a compound search task: after finding the singleton target, participants report the orientation of a line segment within it. The orientation that is reported is independent of the singleton that defines the target, and thus the information from the cue cannot facilitate the choosing of the response. This experiment showed no effect of the cue on search performance, leading Theeuwes *et al.* to conclude that the goal set by the cue was unable to guide attention to the target.

While Theeuwes *et al.* (2006) found no cue effects in their Experiment 2, other studies *have* demonstrated such effects in similar circumstances, including one by Müller & Krummenacher (2006), who added a rating task to prompt participants to use the cue information to establish search goals. (See also Leonard & Egeth, 2008, and Zehetleitner, Krummenacher, Geyer, Hegenloh, & Müller (2011); and see Lamy & Kristjanson, 2013, and Theeuwes, 2010, 2013, for reviews). Thus, one of the key questions in building theories of attention is whether current goals can be used to guide attention in singleton search, and if so, what factors determine when this guidance is effective and when it is not. The experiments reported here will investigate how search is affected by preknowledge of the target that allows for search goals to be established, with the ultimate objective of understanding interactions among current goals, physical salience, and search history.

The 6 experiments reported in this study investigated the effect of pre-knowledge on visual search for a feature singleton. Specifically, we focused on the following issues: how knowledge of the target dimension could guide search, whether search history could influence the cue validity effect, how an intra-dimensional cue and the type of cue (i.e., word vs. image) contribute to the validity effect, and whether the cost in processing an informative cue would outweigh the benefit provided by the cue. In all the experiments, participants made a speeded response to the orientation of a tilted bar inside a color or shape singleton preceded by either an informative cue (the cue trials) or a non-informative cue (the neutral trials). The cue indicated the likelihood of the singleton having a specific feature (*i.e.* red) or coming from a specific feature dimension (*i.e.* color). In Experiment 1, half of the participants received neutral dimensional cues before informative dimensional cues, and this order was reversed for the other half. At first glance, no validity effect was apparent in RTs, but a closer look revealed strong validity effects in both RTs and error rates. In Experiment 2, the two types of trials were intermixed within each block, and a significant validity effect was found. Experiment 3 investigated the effects of intra-dimensional cues and the degree to which the observed validity effect was augmented by priming from the target in a previous trial. Experiment 4 compared the effectiveness of a word cue with that of an image. No difference was found. Experiment 5 found that participants who were provided with an informative cue were outperformed by those who were provided with no cue, suggesting that the cost in processing the cue outweighed the benefit provided by the cue in visual search for a feature singleton. Experiment 6 further showed that participants could ignore informative cues if they began the experiment with neutral cues.

2. Experiment 1

Experiment 1 was modelled after Experiment 2 of Theeuwes et al. (2006), which showed no effects of validity. The task was to judge the orientation of a tilted bar inside a color or shape singleton, with the target display preceded by a cue word that indicated the likely feature-dimension of the singleton. As in Theeuwes et al., a block design was used. In one block, the cue was informative (“Colour” or “Shape”). In the other block, it was non-informative (“Equal”). The experiment had two goals: (1) to determine whether the results of Theeuwes et al. could be replicated with our stimuli; and (2) to investigate whether interblock search history would influence response strategy, which in turn might alter the cue validity effect.

2.1. Method

2.1.1. Ethics statement. This study received prior ethical approval from the University of Canterbury Human Ethics Committee. The study was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Written consent was obtained from the participants.

2.1.2. Participants. Thirty-four students from the University of Canterbury volunteered for the experiment in exchange for course credit or the payment of NZ$10.

2.1.3. Apparatus and stimuli. Stimuli were presented against a white background on a PC with a 16-in. monitor, and E-Prime was used to generate the stimuli and collect responses. Participants were tested individually in a dimly lit room. The viewing distance was about 60 cm.

Each trial consisted of a cue followed by a target display. The cue was a black word written in bold, 18-point Courier New font at the center of the screen. In the neutral condition, the word was “Equal”. In the cue condition, it was “Colour” or “Shape” with equal probability. The target display (see Figure 1) consisted of a central fixation and 6 outline objects each containing a tilted bar. The fixation was a small black cross that subtended .2^{o} in length and width. The 6 objects were located at equal distances along the perimeter of an imaginary circle with a radius of 3.3^{o} and its center at fixation. Five of them were identical black circles, each with a diameter of 1.1^{o}, and the 6th had either a unique color (color singleton) or a unique shape (shape singleton). The color singleton was equally likely to be a red or green circle of the same size as that of the other circles. The shape singleton was equally likely to be a black square that was 1.1^{o} in length and width or a black diamond that was 1.1^{o} along both its horizontal and vertical axes. Each of the 6 objects contained a bar subtending 0.8^{o} in length. Each bar was randomly and independently tilted 20^{o} left or right from either the vertical or horizontal axis.

Insert Figure 1 about here

2.1.4. Design and procedure. The experiment used a 2 x 2 x 3 mixed design, with BlockOrder (neutral-first vs. cue-first) as a between-subjects variable, and SingletonType (color vs. shape singleton) and Validity (valid, neutral, and invalid) as within-subjects variables. The target display was equally likely to contain a color or a shape singleton, and the two types of trials were intermixed randomly within a block. In the cue block, which comprised two-thirds of the total trials, the target display was preceded by either the word “Colour” or “Shape” with 75% validity. In other words, following the cue word “Colour”, a color singleton (equally likely to be red or green) would appear in the target display on three-fourths of the trials (valid trials) and a shape singleton (equally likely to be a square or diamond) would appear on one-fourth of the trials (invalid trials). These probabilities would reverse when the cue word was “Shape”. Thus, the cue was informative with regard to the singleton’s dimension, but not its specific feature within the dimension. In the neutral condition, which comprised one-third of the total trials, the word “Equal” preceded each target display, indicating that the odd object in the target display was equally likely to be a color or shape singleton. The participants were randomly assigned to one of two groups. Half of them completed the neutral block before the cue block (the neutral-first group), and the order was reversed for the other half (the cue-first group).

Each trial started with the presentation of the cue word for 1000 msec. Following an interval of 1000 msec after its offset, the target display was shown for 200 msec. It was then followed by a blank screen until the participant responded. The inter-trial interval was 500 msec.

The participants were told that the target was the tilted bar inside the singleton, and that their task was to respond to the orientation of the bar. They were fully informed about the cue validity. They used the index and middle fingers of their right hand to press one of the two labeled keys on a computer keyboard (the “4” key if the bar was more horizontal than vertical, and the “5” key if it was more vertical than horizontal). Both speed and accuracy were emphasized. The entire experiment consisted of 32 practice trials followed by 480 experimental trials. The participants were encouraged to take short breaks after every 80 trials, and the entire experiment took about 40 minutes to complete.

2.2. Results

We first determined whether our results replicated those reported by Theeuwes *et al*. (2006, Experiment 2), who did not include BlockOrder as an independent variable in their analyses. The results are shown in Figures 2A and B.

In all the figures in this paper, the error bars show the within-subjects standard error of the mean (Cousineau, 2005). The data from four participants were not included in the figures or in the subsequent analyses due to high error rates and/or extreme reaction times.[1]

As in Theeuwes *et al*. (2006), we performed a 2 x 3 repeated-measures analysis of variance (ANOVA) on RTs[2], ignoring BlockOrder as a factor. A significant effect of SingletonType was found, $F(1, 28) = 89.51$, $MS_e = 4785$, $p < .001$, $\eta_p^2 = .76$, indicating faster RT when the target was a color singleton (779 msec) than a shape singleton (878 msec). Neither Validity nor its interaction with SingletonType was significant, $F(2, 56) = 1.48$, $MS_e = 4778$, $p = .24$, $\eta_p^2 = .05$, and $F(2, 56) < 1$, *ns*, respectively.

Insert Figures 2A and 2B about here

A similar analysis was conducted on the error rates. Consistent with the RT results, responses were more accurate when the target was in a color singleton (8.6% error rate) than when it was in a shape singleton (17.7% error rate), $F(1, 28) = 31.36$, $MS_e = 117$, $p < .001$, $\eta_p^2 = .53$. Both Validity and its interaction with SingletonType were significant, $F(2, 56) = 5.18$, $MS_e = 50$, $p < .01$, $\eta_p^2 = .16$, for Validity, and $F(2, 56) = 3.40$, $MS_e = 20$, $p < .05$, $\eta_p^2 = .11$, for Validity x SingletonType interaction. Tukey's Honestly Significant Differences (HSD) test indicated no significant differences among the three types of trials when the target was a color singleton. However, when the target was a shape singleton, there was a higher error rate in the invalid trials (21.1% error rate) than in both the valid (16.3% error rate) and neutral trials (15.8% error rate), with no difference between the latter two. Thus, when the data from the two groups of participants were collapsed, there was a significant validity effect (i.e., the difference between the valid and invalid trials) in accuracy on shape singleton trials, but not in RTs.

Next, we performed analyses with BlockOrder included as an independent variable. The neutral cues were in a different block from the valid and invalid cues, and neutral RTs tended to be slower than nonneutral RTs when the neutral block came first, and faster when it came last. These practice effects would lead to interactions between Validity and BlockOrder that would make it more difficult to identify any true validity effects. Therefore, for these analyses, the neutral trials were excluded, and the Validity factor included only valid and invalid trials.

Figure 3A shows the RTs for the neutral-first group, Figure 3B shows the RTs for the cue-first group, with neutral trials included in both figures. Table 1 shows the error rates for the two groups. (Note that within-subjects standard errors of the mean (Cousineau, 2005) are used in Table 1 and in all the other tables except for Table 4, which used between-subjects standard errors). Two 2 x 2 x 2 repeated-measures ANOVAs with BlockOrder as a between-subjects factor and SingletonType and Validity as within-subjects factors were performed; one on the RT and the other on the accuracy data. For the sake of brevity, we report only the significant interactions that involve BlockOrder. In RT, BlockOrder interacted with SingletonType, $F(1, 27) = 7.78$, $MS_e = 3299$, $p < .01$, $\eta_p^2 = .22$. There was also a three-way interaction including, BlockOrder, SingletonType, and Validity, $F(1,27) = 5.54$, $MS_e = 779$, $p < .05$, $\eta_p^2 = .17$. The accuracy ANOVA showed no interactions involving BlockOrder. To clarify the RT interactions, we conducted separate ANOVAs of both RT and accuracy for the two groups.

Insert Figures 3A, 3B, and Table 1 about here

All of these ANOVAs show consistent main effects of SingletonType, because the color singletons always produce faster RTs and lower errors than the shape singletons. We will set that effect aside and focus on the main effects and interactions involving validity.

For the neutral-first RTs, there was a significant effect of validity, $F(1, 14) = 6.19$, $MS_e = 1212$, $p < .05$, $\eta_p^2 = .31$. SingletonType and Validity did not interact, $F(1, 14) < 1$, *ns*. In a similar analysis on the accuracy data for the neutral-first group, validity approached significance, $F(1, 14) = 4.14$, $MS_e = 69$, $p = .061$, $\eta_p^2 = .23$. The interaction between SingletonType and Validity was not significant, $F(1, 14) = 1.17$, $MS_e = 21$, $p = .3$, $\eta_p^2 = .08$. This pattern of data shows an effect of cue validity in RT, and a suggestion of an effect in accuracy.

Similar analyses were conducted for the cue-first group. In RT, the main effect of Validity approached significance, $F(1, 13) = 4.41$, $MS_e = 1332$, $p = .056$, $\eta_p^2 = .25$. There was a significant Validity by SingletonType interaction, $F(1, 13) = 7.32$, $MS_e = 808$, $p < .05$, $\eta_p^2 = .36$, suggesting that the effect of the cue differed as a function of the type of singleton in the target display. Importantly, when the target was in a color singleton, RT was significantly slower on the invalid (827 msec) than the valid (786 msec) trials ($p < .01$). In contrast, when the target was in a shape singleton, response latencies were comparable between the two conditions (875 msec in both cases).

Analysis on the accuracy data showed no evidence of a speed-accuracy tradeoff. Neither the validity effect, $F(1, 13) = 3.32$, $MS_e = 54$, $p = .09$, $\eta_p^2 = .20$, nor the interaction between SingletonType and Validity, $F < 1$, was significant.

2.3. Discussion

When BlockOrder was ignored as a factor, the results of Experiment 1 largely resembled those of Theeuwes *et al*. (2006). In both experiments, performance was better with color singletons than with shape singletons. Furthermore, neither study showed a significant validity effect in RT. However, the two studies differed in the accuracy data. Whereas our participants showed a significant validity effect, those in Theeuwes *et al*. did not. It is worth noting that Müller and Krummenacher (2006), who modelled their experiment after Theeuwes *et al*. but required their participants to rate how well the cue was used, reported a small, but significant validity effect in RT. Taken together, these results suggest a weak validity effect when BlockOrder was not included as an independent variable in the data analyses.

The cue validity effect became clearer when BlockOrder was taken into consideration and the effects of learning across blocks were not allowed to interfere with the measurement of the validity effect. When participants started the experiment with informative cues, they used the color cue very effectively, but not the shape cue. A similar difference between color and shape trials was reported by Theeuwes *et al*. (2006, Experiment 1) in a singleton detection task. The other group of participants completed a block of trials before they received informative cues. For these participants, the color cue was still helpful, but not as much as for the cue-first group. These participants also made use of the shape cue; perhaps their extra experience with the stimuli allowed them to prepare more effectively to detect the shape differences.

Other studies have shown that selection history can influence visual search at an inter-trial level (see Awh *et al*., 2012, and Krisjánsson & Campana, 2010, for reviews), an inter-block level (Yeh, Lee, Chen, & Chen, 2014), and at an inter-experiment level with the effect of search history lasting hours or even days (Leber & Egeth, 2006; Leber, Kawahara, & Gabari, 2009; Zehetleitner, Goschy, & Müller, 2012). In the case of the present experiment, the cuing effect was present regardless of history, but the history was able to cause a shift towards effective use of the shape cue.

There are two other differences between this experiment and Theeuwes *et al.'s* Experiment 2 that may contribute to the different conclusions. In this experiment, the singleton target could be either red, green, square, or diamond. Without the cue, participants would have to search for two features within each dimension, which makes for a difficult search (Stroud, Menneer, Cave, & Donnelly, 2012). In Theeuwes' experiment, the target was always either red or diamond, which may allow for an easier search if the cue information is ignored. In fact, as Nordfang and Bundesen (2010) have argued, it may be relatively easy for search to be guided simultaneously by one feature from each of two different dimensions. Also, in the current experiment, each target and distractor's bar was tilted 20

˚ one way or the other. There was no way to distinguish the target from the distractors solely by orientation; participants were forced to use the color/shape singleton to find the target. In Theeuwes *et al.'s* Experiment 2, the distractor bars were oriented 22.5˚, but the target was horizontal or vertical, allowing the target orientation to be found without searching for color/shape. Even though it should still be easier to search for the color/shape singleton than the orientation singleton in these displays, this aspect of the procedure, like the use of a single feature from each dimension, makes the cue information less important for finding the target, and lowers the participants' motivation to use the cue information to direct attention.

Experiment 1 shows that participants can use dimensional cues effectively to enhance the detection of a feature singleton, but the effect is not always strong, and it can be shaped by practice. Thus, it is easy to see how a cuing effect might not be detected in Theeuwes *et al.* (2006) Experiment 2. One important factor here may be the separation of informative and noninformative cues into separate blocks. This factor will be tested in Experiment 2.

3. Experiment 2

In Experiment 1, the cue and neutral trials were in separate blocks. In Experiment 2, we used a within-block design instead of a between-block one. If the block design used in Experiment 1 indeed played a role in the manifestation of the cue validity effect, the participants in Experiment 2 should show a reliable validity effect now that all types of trials were intermixed within a block.

3.1. Method

The method of Experiment 2 was the same as that of Experiment 1 except that the neutral and cue trials were randomly mixed within a block, and the cue word for the neutral trials was “Either” instead of “Equal”. The participants performed two blocks of 16 practice trials before the experimental trials began. Twenty-eight new undergraduate students from the same population as in Experiment 1 took part in the study.

3.2. Results

Figure 4A shows the RTs and Figure 4B shows the error rates. Three participants’ data were excluded due to long RTs. The mean RT for each of them was over 3 standard deviations above the average RT of the rest of the participants. Two 2 x 3 repeated-measures ANOVAs, one on the RT and the other on the accuracy data, were conducted. The neutral trials were included in these ANOVAs, because they were mixed into the same blocks as the other trials, so that practice effect did not complicate the comparisons. Responses were again faster and more accurate when the target was in a color singleton than when it was in a shape singleton, $F(1, 24) = 29.84$, $MS_e = 13076$, $p < .001$, $\eta_p^2 = .55$ for RT, and $F(1, 24) = 65.23$, $MS_e = 91$, $p < .001$, $\eta_p^2 = .73$ for accuracy. Validity was also significant, both for RT, $F(2, 48) = 14.32$, $MS_e = 3873$, $p < .001$, $\eta_p^2 = .37$, and for accuracy, $F(2, 48) = 8.27$, $MS_e = 99$, $p < .001$, $\eta_p^2 = .26$. Subsequent analyses indicated better performance in both RT and error rates in the valid (791 msec with 13.2% error rate) and neutral (801 msec with 14.4% error rate) trials than in the invalid trials (853 msec with 20.7% error rates), $p < .01$ in all cases. There was no significant difference between the valid and neutral conditions in either RT or accuracy. SingletonType and Validity did not interact in RT or accuracy, $F(2, 48) = 1.58$, $MS_e = 2179$, $p = .22$, $\eta_p^2 = .06$ for RT, and $F(2, 48) < 1$, *ns* for accuracy.

Insert Figures 4A and 4B about here

3.3. Discussion

The most important findings of Experiment 2 were the significant validity effects in both RT and accuracy, indicating that the cue affected the guidance of attention in singleton search. These results provided converging evidence to the results of Experiment 1, suggesting that the lack of a validity effect found in previous research could be caused, at least partly, by separating the neutral trials from the cue trials.

Due to insufficient numbers of trials per experimental condition, we did not analyze separately the data in which two consecutive trials contained the same singleton vs. different singletons. In other words, we do not know to what degree the validity effect was influenced by inter-trial priming. However, even if a significant validity effect was found only in the same-singleton trials, this result would still indicate the influence of the cue in guiding attention. Figure 5 shows two trial sequences, one valid and the other invalid. In both cases, a red color singleton appeared in the current and preceding trials. Because the informative cue was a symbolic one (i.e., a word), there was no systematic difference in stimulus-driven processes between the valid and invalid trials. If the symbolic cue had played no role in guiding attention, there would have been no validity effect. The fact that a cue validity effect was found supports the notion that the knowledge provided by the cue was utilized in visual search for singletons.

Insert Figure 5 about here

4. Experiment 3

In Experiment 2, the cue provided information about the likely feature dimension of the singleton, and a cue validity effect was found. In Experiment 3, we investigated the effect of the cue when it indicated the likely color of the singleton. The goal was to see whether knowledge about the specific feature value of a singleton (i.e., red vs. green) within a feature dimension (i.e., color) would result in a similar pattern of data as that observed in Experiment 2.

Using only color singleton trials also allowed us to have more trials per experimental condition so that we could determine the degree to which the validity effect was caused by inter-trial priming. Inter-trial priming occurs in some circumstances but not in others; for instance, Rangelov, Müller, and Zehetleitner (2013) found priming in displays of 3 items but not in displays of 36. Becker and Ansorge (2013) demonstrated priming in displays of 6 or 12 items, suggesting that priming might appear with our displays. Yashar and Lamy (2010) found priming only in a compound task in which one feature causes the target to be selected and another visual property is then reported. Given that these experiments use a similar compound search task, we might expect priming to appear here.

4.1. Method

Experiment 3 was similar to Experiment 2 except for the following differences. First, only color singleton trials were used. Second, the cue word was equally likely to be “Red” or “Green” for the cue trials, and was “Either” for the neutral trials. Finally, the number of practice trials was reduced from 32 to 24. As before, there were 480 experimental trials. Two-thirds of them were cue trials, and the cue validity was again 75%. Twenty-seven new participants took part in the experiment.

4.2. Results

Table 2 shows the results. A repeated-measures ANOVA on RTs indicated a significant validity effect, $F(2, 52) = 8.26$, $MS_e = 1198$, $p < .001$, $\eta_p^2 = .24$, with slower responses in the invalid (742 msec) than in both the valid (705 msec) and neutral

(716 msec) trials ($p < .05$ in both cases). No difference was found between the latter two. There was no evidence of a speed-accuracy tradeoff. The validity effect was not significant in the error rates, $F(2, 52) = 2.37$, $MS_e = 26$, $p = .1$, $\eta_p^2 = .08$, although the invalid condition had a numerically higher error rate (9.3%) than both the valid (6.5%) and neutral (6.8%) conditions.

Insert Table 2 about here

To determine the degree to which the validity effect in RT was influenced by inter-trial priming, we separated the trials in which the color of the singleton was repeated from the previous trial (the repeat trials) from those in which the color was switched from the previous trial (the switch trials). Figure 6 shows the RTs for the repeat and switch trials. A 2 x 3 repeated-measures ANOVA with TrialType (Repeat vs. Switch) and Validity as the two factors found that in addition to the validity effect, $F(2, 52) = 7.79$, $MS_e = 2360$, $p < .01$, $\eta_p^2 = .23$, there was a main effect of TrialType, $F(1, 26) = 4.76$, $MS_e = 645$, $p < .05$, $\eta_p^2 = .15$, with faster RT when the color of a singleton was repeated (715 msec) compared with when it was switched (724 msec). TrialType also interacted with Validity, $F(2, 52) = 3.52$, $MS_e = 825$, $p < .05$, $\eta_p^2 = .12$. The validity effect (invalid – valid) was larger in the repeat trials (48 msec) than in the switch trials (24 msec), although both effects were statistically significant ($p < .001$ and $p < .01$ for the repeat and switch trials, respectively).

Insert Figure 6 about here

4.3. Discussion

The results from the featural cues in Experiment 3 were similar to the results from the dimensional cues in the color singleton trials in Experiment 2. As in Experiment 2, a cue validity effect was found, suggesting that the cue contributed to search performance. Because the cue was symbolic, there were no systematic differences in the stimulus-driven processes between the valid and invalid conditions. Thus, the finding of the validity effect indicated the influence of search goals.

Although significant validity effects were found in both the repeat and switch trials, the magnitude of the effect was larger in the repeat trials, indicating that the memory of a previous trial also affected responses. Given that both the cue and the inter-trial memory processes contributed to performance, the question is: how did they jointly influence visual processing in the present paradigm?

Many previous studies have explored inter-trial effects, and have attributed them to both early and late stages of procession (Krummenacher, Grubert, & Müller, 2010; Rangelov *et al*., 2013). A number of these studies have shown evidence that intra- and inter-trial memory traces can guide visual search (Chen & Yeh, 2013; Chun & Jiang, 1998; Kahneman, Treisman, & Gibbs, 1992; Müller *et al*., 1995; Hillstrom, 2000; Huang *et al*., 2004; Maljkovic & Nakayama, 1994; Neill, Valdes, Terry, & Gorfein, 1992; Wolfe *et al*., 2003), and that the memory trace, which decays over time (Leonard & Egeth, 2008; Maljkovic & Nakayama, 1994), includes, among other things, a representation of the features in the display and the priorities assigned to them (Hillstrom, 2000; Neill *et al*., 1992). Building on these and other prior studies, we assume that in cued visual search for a feature singleton, there is always a memory representation based on the previous trial, and a target template based on the cue. Furthermore, when the cue matches the target in the memory trace, the memory trace is retrieved and the target is positively activated. When they mismatch, the target in the memory trace is inhibited.

With regard to Experiment 3, it is conceivable that the interaction between cue and the memory representation occurs either early in the trial, as a target representation is constructed to guide search, or it might occur later, during a check of a selected item. However, the task in these experiments makes it less likely that cue information would be used in a post-selectional check, because the presence of invalid cues adds a large amount of uncertainty to the check. Also, a post-selectional account requires that the memory of the previous trial be maintained throughout the search process. Thus, the cue-memory interaction is more likely to be part of the early preparation for search. In the repeat trials of Experiment 3 (see Figure 7A), the singletons in the n-1 and n trials are identical. The memory representation from trial n-1 provides extra activation of the target singleton in trial n. This extra boost is added to the validity effect in the repeat-valid trials, and it also speeds responses in the repeat-neutral trials. However, any boost from the memory of the trial n-1 target is lost when the cue is invalid. In fact, the invalid-repeat RT is actually somewhat longer than the invalid-switch RT, suggesting that when the cue does not match the memory of the previous target, extra inhibition might be applied to counteract the memory effects.

In the switch trials (see Figure 7B), the singletons in the n-1 and n trials are different. Because the memory representation of the target singleton in trial n-1 can no longer aid the activation of the target in trial n, the validity effect in the switch trials is smaller than that in the same trials.

Insert Figures 7A and 7B about here

This experiment was not designed to test Becker's (2008) relational mechanism of inter-trial priming, but the results are relevant to this theory. Becker's proposal is tied to D'Zmura's (1991) claim that visual search will be easy and efficient if target and distractor features are linearly separable in feature space. Specifically, Becker proposed that inter-trial effects should only appear when singleton target features are not linearly separable from the nontarget features. If we focus only on the hue of the stimulus elements in Experiment 3, we might conclude that it would be difficult to draw a line in hue space that has both the red and green targets on the same side. However, if we consider luminance, both the red and green targets should have higher luminance than the black nontargets, and so the targets should be linearly separable from the nontargets. Becker's relational mechanism would predict no effects of the previous target on the current target, but those effects do appear. Thus, these results suggest a rethinking of this proposal, at least in the luminance dimension.

Our account of the interaction between cue and memory is consistent with the pattern of data we observed in Experiment 3. Nothing in the results so far suggests that this account should include a qualitative difference in the magnitude of the cue validity effect when the cue is a symbolic word cue or a direct image cue, especially if the two types of trials are intermixed within a block. This possibility was tested in Experiment 4.

5. Experiment 4

In Experiments 1 through 3, we used a symbolic (word) cue and found evidence for the cue validity effect. In Experiment 4, we added a new condition by using a direct image cue consisting of the stimulus item that serves as the singleton in the search displays. Previous research has shown inconsistent results regarding the type of cue that could elicit the validity effect. Whereas Theeuwes *et al*. (2006) found a significant validity effect with image cues but not with verbal cues, Müller and Krummenacher (2006) reported no difference between the two types of trials. In both studies, the trials with the image and the symbolic cues were presented in different blocks and were completed by different participants. As the effect of response strategies could not be controlled when the two types of trials were in separate blocks, the relationship between the cue type and cue validity is unclear. To minimize the effect of response strategies, we mixed the two types of cues within the same block. The goal was to compare the magnitude of the cue validity effect as a function of cue type while holding constant the response strategies that might be associated with the different cue types. Based on our account described above, we predicted a comparable validity effect regardless of the cue.

5.1. Method

Experiment 4 was similar to Experiment 3 with the following differences. The cue was either a word or an image. When it was a word, it was either the word “Red” or “Diamond” with equal frequency. When it was an image, it was equally likely to be a red circle or a black diamond, identical to the two target singletons used in the target displays. As before, the cue validity was 75%. In all trials, the cue could be used to infer both the feature dimension and the feature value of the singleton, and all types of trials were presented randomly within a block.

The experiment used a 2 x 2 x 2 within-subjects design, with CueType (word vs. image), SingletonType (red circle vs. black diamond) and Validity (valid vs.

invalid) as the three independent variables. Altogether, there were 480 trials divided into 5 blocks of 96 trials each. The participants completed 48 practice trials before they started the experiment. Again, the cue validity information was explicitly provided to the participants, and both speed and accuracy were stressed. Sixteen new participants took part in the experiment.

5.2. Results and Discussion

Figure 8 shows the RTs and Table 3 shows the error rates. Two participants' data were excluded due to long RTs. The proportion of their data that exceeded the 2000 msec cutoff was over 3.5 standard deviations above the mean of the rest of the participants. Two 2 x 2 x 2 repeated-measures ANOVAs were conducted; one on the RT and the other on the error rates. Once again, the participants were faster and more accurate when the target was in a color singleton than in a shape singleton, $F(1,13) = 24.11$, $MS_e = 11475$, $p < .001$, $\eta_p^2 = .65$ for RT, and $F(1, 13) = 14.30$, $MS_e = 109$, $p < .01$, $\eta_p^2 = .52$, for accuracy. They were also faster and more accurate when the cue was valid than invalid, $F(1,13) = 19.06$, $MS_e = 10293$, $p < .001$, $\eta_p^2 = .59$ for RT, and $F(1, 13) = 5.30$, $MS_e = 382$, $p < .05$, $\eta_p^2 = .29$, for accuracy. The main effect of CueType was not significant in either RT or accuracy. Importantly, neither CueType x Validity nor CueType x SingletonType x Validity was significant in either RT or accuracy, $F < 1$ in all cases. No other effects reached significance either. These results show no evidence that the magnitude of the cue validity effect was influenced by the type of cue when all types of trials were intermixed within a block. Because this experiment once again produces a validity effect, the results are also consistent with the notion that the use of a block design in Theeuwes *et al*.'s (2006) study might have contributed to the lack of a significant validity effect when the cue was a symbolic one.

Insert Figure 8 and Table 3 about here

6. Experiment 5

In Experiment 5, we explored further the role of a precue in singleton search. Specifically, we investigated whether the benefit of knowing the specific feature value of an upcoming target would outweigh the cost in processing the cue in singleton search. It has been well established that a salient feature singleton supports pre-attentive texture segmentation and attracts attention (see Wolfe, 1998, for a review). Given that feature singletons are effective in attracting attention, if we assume that resources are required to process a cue when the cue is unpredictable on a given trial, then all else being equal, we might expect participants to perform worse when they are provided with an informative cue that requires processing than if they are provided with a neutral cue that does not require processing. In other words, it could be more efficient to find the target if participants simply let stimulus-driven processes guide their attention to the target. Experiment 5 tested this hypothesis.

6.1. Method

Experiment 5 was similar to Experiment 3, with the major difference being that the new experiment used a between-subjects design. Thirty-two new participants were recruited, and they were randomly assigned to one of two groups. In the cue group, an informative cue was shown before each target display. It was equally likely to be the word "Red" or "Green", and the cue validity was 75%. In the no-cue group, the word "Ready" was shown before the target display, and a red or green singleton was equally likely to be the target. All the other aspects of the experiment were identical to those of Experiment 3.

6.2. Results and Discussion

Table 4 shows the RTs and error rates. The data from one participant in the no-cue group were not included due to high error rate, which was over 4 standard deviations above the average error rate of the rest of the participants. We first examined the effectiveness of the cue for the cue group. A t-test for dependent means revealed a significant effect in RT, $t(15) = 2.3$, $p < .05$, $d = .58$, indicating faster responses in the valid than the invalid condition. No significant effect was found in accuracy. These results replicated the findings of Experiment 3, suggesting that the cue guided the deployment of attention in singleton search.

Insert Table 4 about here

Next, we compared the response latencies between the cue trials with the no-cue trials. Two separate t-tests for independent means showed that the RT in the no-cue condition was faster than the RT in both the valid condition, $t(29) = 2.10$, $p < .05$, $d = 2.09$, and the invalid condition, $t(29) = 2.36$, $p < .05$, $d = 2.36$. Similar analyses conducted on the accuracy data showed no significant results.

These results indicated that processing the cue incurred a cost, and that the cost outweighed the benefit provided by an informative cue. One might wonder whether these results are consistent with those from Experiment 1, in which the RT in the neutral condition from the neutral-first group was not faster than the RT in the valid condition from the cue-first condition. The difference in results was likely caused by methodological differences between the two experiments. Whereas the cue indicated a feature dimension (i.e., color or shape) in Experiment 1, it indicated a feature value in Experiment 5. Prior research in visual search has shown that the cue validity effect was much larger in inter-dimensional than in intra-dimensional cuing tasks (Müller *et al*., 1995; Treisman, 1988). It is likely that the pattern of data we observed in Experiment 5 is limited to intra-dimensional cuing tasks only.

In Experiments 2 and 3, the neutral cue trials were intermixed within a block, making the cue type unpredictable on a given trial. Consequently, the participants would have to process and interpret the cue across all trials, thereby equating the processing load between the neutral condition and the cue conditions. As a result, there was no advantage in having a neutral cue compared with a valid cue.

7. Experiment 6

Experiment 5 showed faster RTs in the no-cue condition than in both the valid and invalid cue conditions, and we attributed these effects to increased processing demand of the cue in the cuing conditions. Experiment 6 was designed to replicate the results of Experiment 5 and to investigate the effect of search history on the efficiency of target identification in singleton search.

7.1. Method

Experiment 6 was identical to Experiment 5 except for the following differences. First, each participant completed both the no-cue block and the cue block. Half of them started with the no-cue block before proceeding to the cue block (the no-cue 1st group), and this order was reversed for the other half (the cue 1st group). Thus, the experiment used a mixed design, with BlockOrder (no-cue block 1st vs. cue block 1st) as a between-subjects variable, and TrialType (valid, invalid and neutral trials) as a within-subjects variable. Second, each block consisted of 192 trials, and the participants were encouraged to take a short break after 96 trials. Depending on the specific block, the target display was preceded by either an informative cue (the word “Red” or “Green” with 75% cue validity) or an uninformative word “Ready”. Third, the participants were explicitly informed of the type of trials in each block and the order of the blocks. However, there was only one practice session; it was at the very beginning of the experiment, before the first block, and included only the type of trials included in the 1st block. In other words, those in the no-cue 1st group practiced on the no-cue trials but not the cue trials. Likewise, those in the cue 1st group practiced on the cue trials but not the no-cue trials. We limited the practice to only one type of trials to prevent participants from trying out different response strategies in response to different types of trials. This would allow us to compare the results of Experiment 5 to those of Experiment 6, especially the between-group results from the 1st block, in which one group performed the no-cue trials while the other group the cue trials. Thirty-two new participants took part in the experiment. They were randomly assigned to either the no-cue 1st or the cue 1st group. All the other aspects of the experiment were identical to those of Experiment 5.

7.2. Results and Discussion

The mean RTs and error rates are in Table 5. The data from one participant in the cue 1st group were not included due to high error rate (close to 50% in all the conditions). We first determined whether the results of Experiment 5 were replicated by examining the data from the 1st block of each group. To assess the effectiveness of the cue in the cue 1st group, we performed 2 t-tests for dependent means, one on the RTs and the other on the accuracy data. The results on RTs showed a near significant effect, $t(14) = 1.75$, $p = .05$, $d = .45$, indicating faster responses in the valid than the invalid condition. No significant effect was found in the accuracy data, $t(14) = 1.14$, *ns*. We then compared the response latencies between the cue trials in the cue 1st group with the no-cue trials in the no-cue 1st group. Two t-tests for independent means were performed. The results showed faster responses in the no-cue condition than in both the valid condition, $t(29) = 2.13$, $p < .05$, $d = .77$, and the invalid condition, $t(29) = 2.54$, $p < .05$, $d = .91$. Similar analyses on the accuracy data showed no significant results, $t(29) < 1$ in both cases. These results confirmed the finding of Experiment 5 that in easy singleton searches it is more efficient to let the singleton guide search rather than to process an informative cue.

Insert Table 5 about here

Next, we examined the effect of search history. Two mixed ANOVAs with BlockOrder as a between-subjects factor and TrialType as a within-subjects factor were conducted, one on the accuracy data and the other on the RT data. For the accuracy data, no significant effects were found. For the RT data, a significant main effect of BlockOrder was found, $F(1, 29) = 4.98$, $MS_e = 28553$, $p < .05$, $\eta_p^2 = .15$, indicating faster responses for the no-cue 1st group (653 msec) than the cue 1st group (731 msec). The main effect of TrialType and its interaction with BlockOrder were also significant, $F(2, 58) = 6.91$, $MS_e = 1113$, $p < .01$, $\eta_p^2 = .19$ for TrialType, and $F(2, 58) = 13.49$, $MS_e = 1113$, $p < .001$, $\eta_p^2 = .32$ for TrialType by BlockOrder interaction.

To clarify the interaction, we conducted two repeated-measures ANOVAs on RTs, one for each group. For the no-cue 1st group, there was no significant effect on RTs, $F(2, 30) = 2.51$, $MS_e = 584$, $p = .1$, $\eta_p^2 = .14$. This result suggests that when participants performed the no-cue trials in the 1st block, they tended to ignore the cue in the 2nd block, possibly because they learned from experience that relying on the singleton to guide search was an efficient way to accomplish the task. In contrast to the no-cue 1st group, the participants in the cue 1st group showed a significant effect in TrialType, $F(2, 28) = 12.28$, $MS_e = 1679$, $p < .001$, $\eta_p^2 = .47$. Paired t tests indicated faster responses in the neutral condition (690 msec) than in both the valid condition (742 msec), $t(14) = 3.31$, $p < .01$, $d = .85$, and the invalid condition (762 msec), $t(14) = 4.22$, $p < .001$, $d = 1.09$. This pattern of data suggests that the participants processed the cue in the 1st block. When no cue was available in the 2nd block, they relied on the singleton to guide search, which turned out to be a more efficient way to locate the target.

8. General Discussion

These results have implications for all three of the factors that have been proposed to affect attentional guidance in search, and we will consider each of them separately.

8.1. **Current Goals.** Theeuwes *et al.* (2006) claimed that current goals based on knowledge of the target play no role in guiding search for a singleton target. However, guidance based on current goals is reflected in the fast responses after valid cues in the experiments described above. Experiment 2 uses a procedure and stimuli similar to Theeuwes *et al.*'s Experiment 2 to demonstrate that guidance based on a target dimension cue becomes apparent when trials with valid, neutral, and invalid cues are intermixed. Additionally, Experiment 1 shows that cuing effects can arise even when neutral cues are in a separate block from the informative cues, as long as the cue is very helpful in finding the target. Just as Experiments 1 and 2 show effects of dimensional cues, Experiment 3 shows effects of feature cues using a similar procedure. All of these experiments, along with Experiment 4, demonstrate that symbolic (word) cues can effectively be converted to target templates that guide search toward the singleton target.

These experiments, along with earlier studies, make it clear that target knowledge can be used to guide attention to a feature target. However, the fact that this guidance is hard to detect in some circumstances emphasizes that it is not very important in these tasks, and participants may choose not to use it. There appears to be some flexibility in how attentional resources are used in these easy searches.

8.2. **Search History.** Experiment 3 also illustrates the effect of priming from trial to trial, and shows a rather complex interaction between search history and the current search goal. If the current target matches the previous target, it is generally found more quickly, but if that target is not the expected target, the facilitation from priming disappears, and may even be converted to inhibition. More studies are necessary to get a clearer picture of this interaction.

Experiment 1 illustrates another effect of search history, which unfolds over a longer time frame. If participants start this task with informative cues, they make heavy use of the color cue, but don't seem to be able to prepare effectively when given the shape cue. However, if they first have experience in the task with neutral cues, they use both types of cue with approximately equal effectiveness. Experiment 6 shows a different effect of search history over a longer time frame: participants who begin the experiment with neutral cues seem to ignore informative cues later in the experiment. The concept of search history includes multiple different effects, which should probably be considered separately.

8.3. **Physical Salience.** Perhaps the most novel and unexpected result from these experiments is that participants find the target and respond more quickly if they rely only on physical salience to find the target, rather than also building a target template based on the feature cue. The extra mental effort required to interpret the cue apparently interferes with the very easy task of moving attention to the singleton location. Participants apparently do not appreciate how effectively they can use physical salience to guide search, and they engage in extra preparation and guidance that is actually detrimental to their performance.

The results from the no-cue 1st group in Experiment 6 suggest that the extra effort expended on the color cue is not automatic and can be avoided. However, these results do not show us what sort of cognitive operations are being conducted with the cue. It seems likely that the cue is used to establish a target representation that is then used to guide seach for that specific color. However, it is possible that in these experiments, the singleton search is done without guidance from a target color representation, and that the cue information is used to check the selected item after the search is completed. It is certainly possible that adding a cue to the procedure could affect later stages of processing; Töllner, Rangelov, and Müller (2012) have used the lateralized readiness potential to show late-stage effects linked to different search tasks. Mortier, Theeuwes, and Starreveld (2005) have also reported cuing effects on response times that are linked to late-stage processes in non-search tasks. However, as discussed before, for this particular task, it seems less likely that the cue would be used for a post-selection check, because the cue is invalid on 25% of the trials. Thus, even if the cue does not match the selected item, it is not a very clear indication of a search error.

In summary, when guiding visual search, we have multiple tools at our disposal, but we are not necessarily experts in how to use those tools most effectively.

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Notes:

1. One participant had a mean error rate over 50%. Two had mean RTs more than 3 standard deviations above the mean of the rest of the participants. The fourth participant was excluded due to a large number of extremely short RTs (15% of the RTs were under 100 msec). One additional participant did not complete the experiment due to a computer failure.
2. In all experiments, response latencies greater than 2000 msec were excluded. These constituted less than 2% of the total data in each experiment. Only trials with correct responses were included in the analyses of the RT results.

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Table 1

Error rates (percent incorrect) from Experiment 1 as a function of block order, singleton type, and cue validity. Within-subjects standard errors are in parentheses.

	Color Singleton			Shape Singleton		
	Valid	Neutral	Invalid	Valid	Neutral	Invalid
Neutral-first	5.0 (1.8)	9.7 (1.0)	8.1 (2.0)	14.3 (1.8)	16.4 (1.6)	20.0 (2.4)
Cue-first	8.8 (1.0)	8.1 (1.4)	12.0 (1.8)	18.4 (1.2)	15.2 (1.3)	22.4 (2.3)

Table 2

Mean reaction times (in milliseconds) and error rates (percent incorrect) from Experiment 3 as a function of cue validity. Within-subjects standard errors are in parentheses.

Reaction Times (msec)			Error Rates (% incorrect)		
Valid	Neutral	Invalid	Valid	Neutral	Invalid
705 (5.9)	716 (3.4)	742 (8.6)	6.5 (0.6)	6.8 (0.7)	9.3 (1.3)

Table 3

Error rates (percent incorrect) from Experiment 4 as a function of cue type and cue validity. Within-subjects standard errors are in parentheses.

Cue Type	Color Singleton		Shape Singleton	
	Valid	Invalid	Valid	Invalid
Word	6.2 (2.2)	14.4 (2.4)	11.9 (1.8)	21.0 (3.3)
Image	5.7 (2.1)	13.7 (3.1)	14.2 (2.0)	22.8 (2.2)

Table 4

Mean reaction times (in milliseconds) and error rates (percent incorrect) for Experiment 5. Between-subjects standard errors are in parentheses.

	Cue Group		No-Cue Group
	Valid	Invalid	Neutral
RT	762 (31)	776 (33)	680 (24)
Error rates	6.4 (1.0)	7.7 (1.5)	7.3 (1.7)

Table 5

Mean reaction times (in milliseconds) and error rates (percent incorrect) for Experiment 6 as a function of block order and trial type. Within-subjects standard errors are in parentheses.

	No-cue Block First			Cue Block First		
	Valid	Invalid	Neutral	Valid	Invalid	Neutral
RT	643 (3.9)	654 (4.7)	663 (6.0)	742 (5.4)	762 (6.4)	690 (10.5)
Error rates	6.7 (0.6)	7.9 (0.9)	8.1 (0.4)	6.7 (0.4)	7.9 (0.8)	4.7 (0.7)

Figure Captions

Fig. 1. Examples of valid, invalid, and neutral trials from Experiment 1. In informative cue trials, a verbal cue ("Colour" or "Shape") indicated with 75% validity the feature dimension of the upcoming color or shape singleton. In the non-informative neutral trials, the singleton was equally likely to be defined by color or shape. The task was to judge the orientation of the line segment inside the singleton.

Fig. 2. Results from Experiment 1 with the block order collapsed. A. Mean reaction times. B. Error rates. Error bars show the within-subjects standard error of the mean.

Fig. 3. Results from Experiment 1 separated by block order. A. Mean reaction times from the participants who completed the neutral block before the cue block. B. Mean reaction times from the participants who completed the cue block before the neutral block. Error bars show the within-subjects standard error of the mean. Note that practice effects raise the neutral cue RTs relative to other conditions in the neutral-first condition, and lower neutral cue RTs relative to the others in the cue-first condition.

Fig. 4. Results from Experiment 2. A. Mean reaction times. B. Error rates. Error bars show the within-subjects standard error of the mean.

Fig. 5. An example of two trials in which the singleton targets on two consecutive trials are the same. Because the cue is symbolic, there should be no systematic differences in the stimulus-driven processes between the valid and invalid trials. Thus, the finding of a validity effect indicated the influence of top-down knowledge.

Fig. 6. Mean reaction times for the repeat and switch trials from Experiment 3. Error bars show the within-subjects standard error of the mean.

Fig. 7. Examples of repeat and switch trials when the cue was valid, invalid, or neutral.

Fig. 8. Mean reaction times from Experiment 4. Error bars show the within-subjects standard error of the mean.

Figure 1

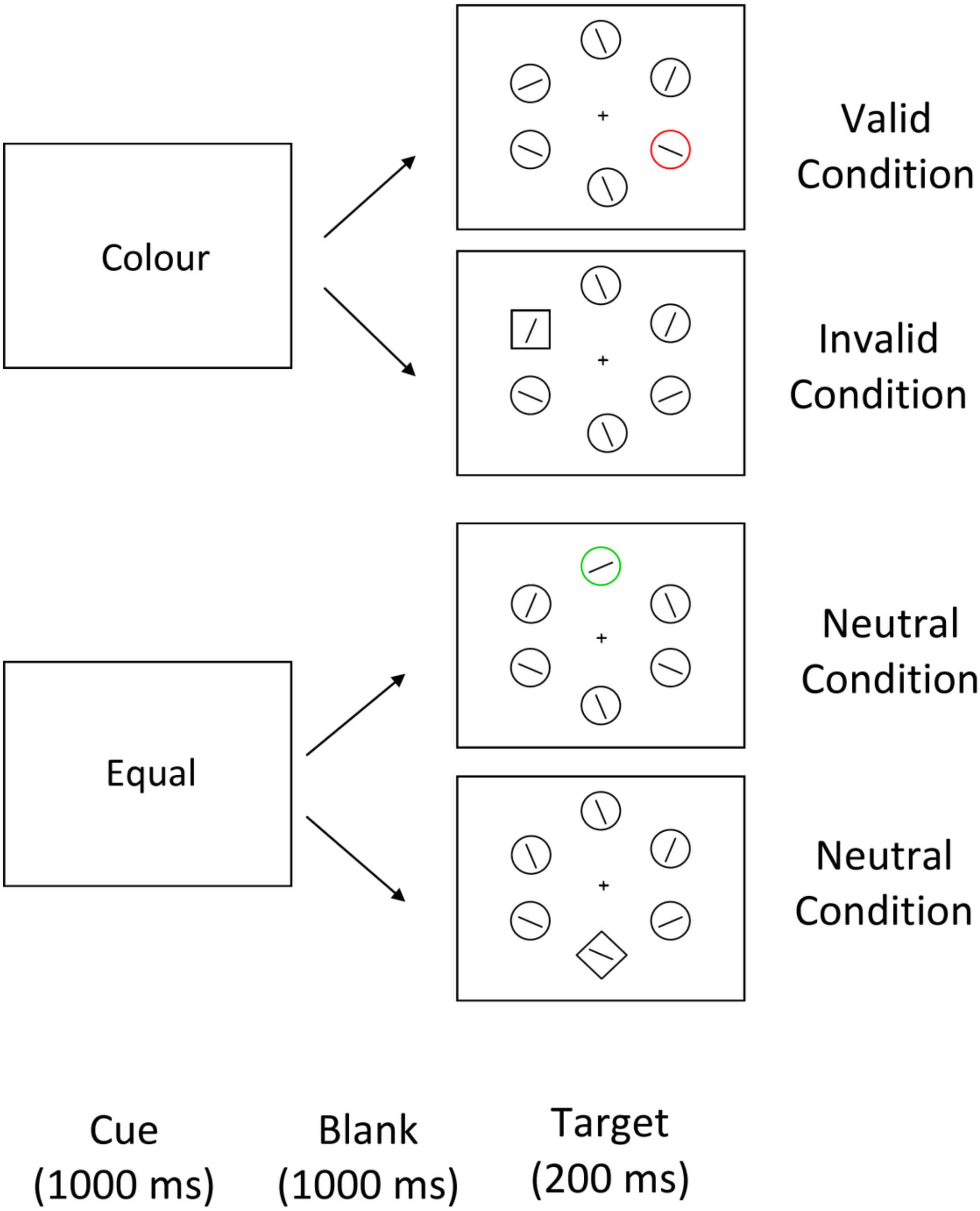

Colour
Valid Condition
Invalid Condition
Equal
Neutral Condition
Neutral Condition
Cue (1000 ms)
Blank (1000 ms)
Target (200 ms)

Figure 2A

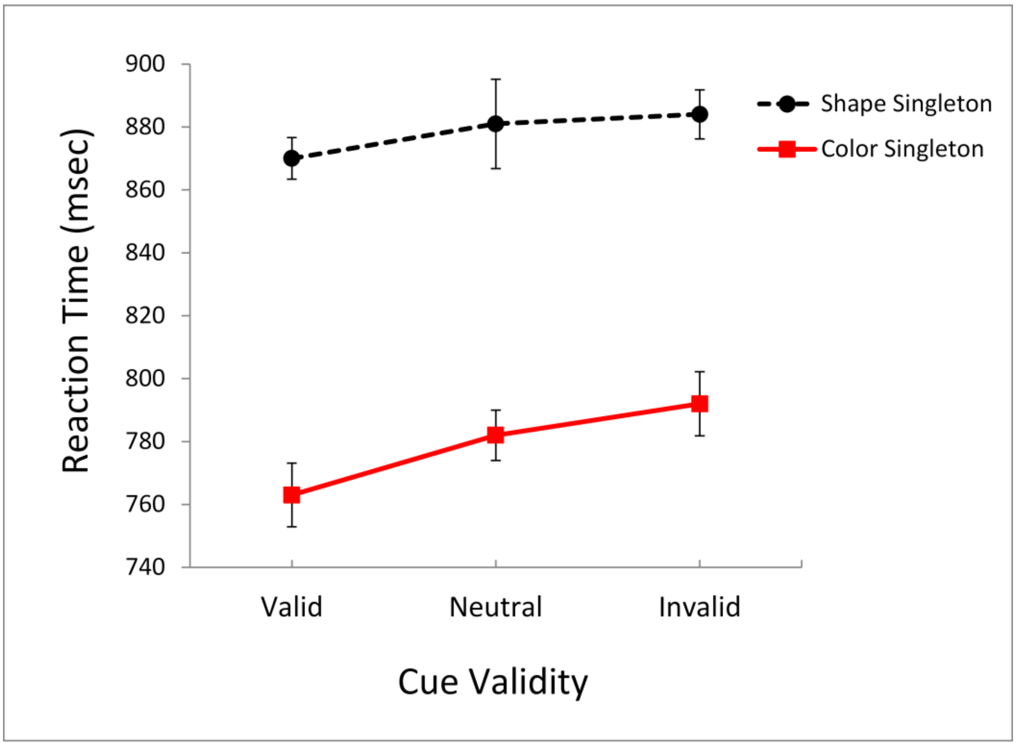


Figure 2B

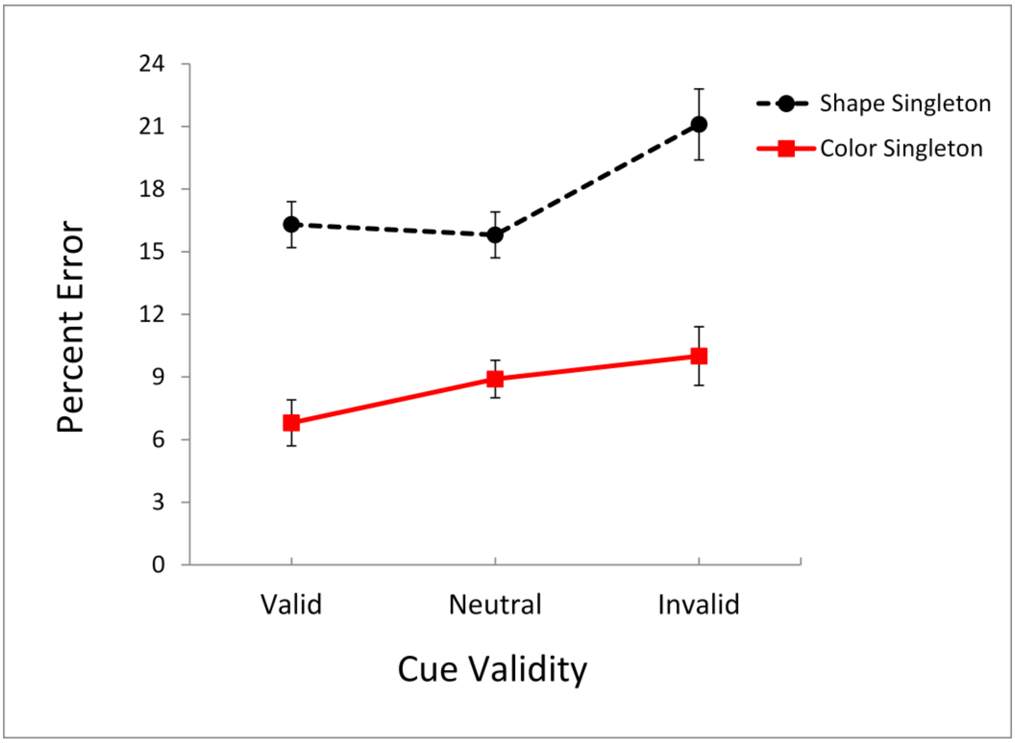


Figure 3A

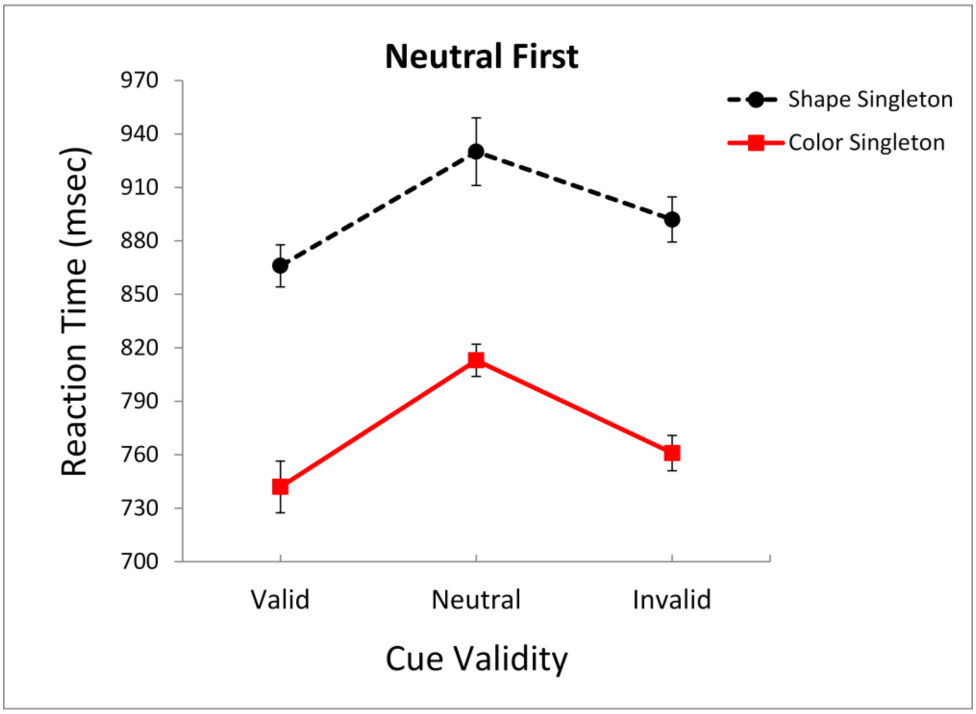


Figure 3B

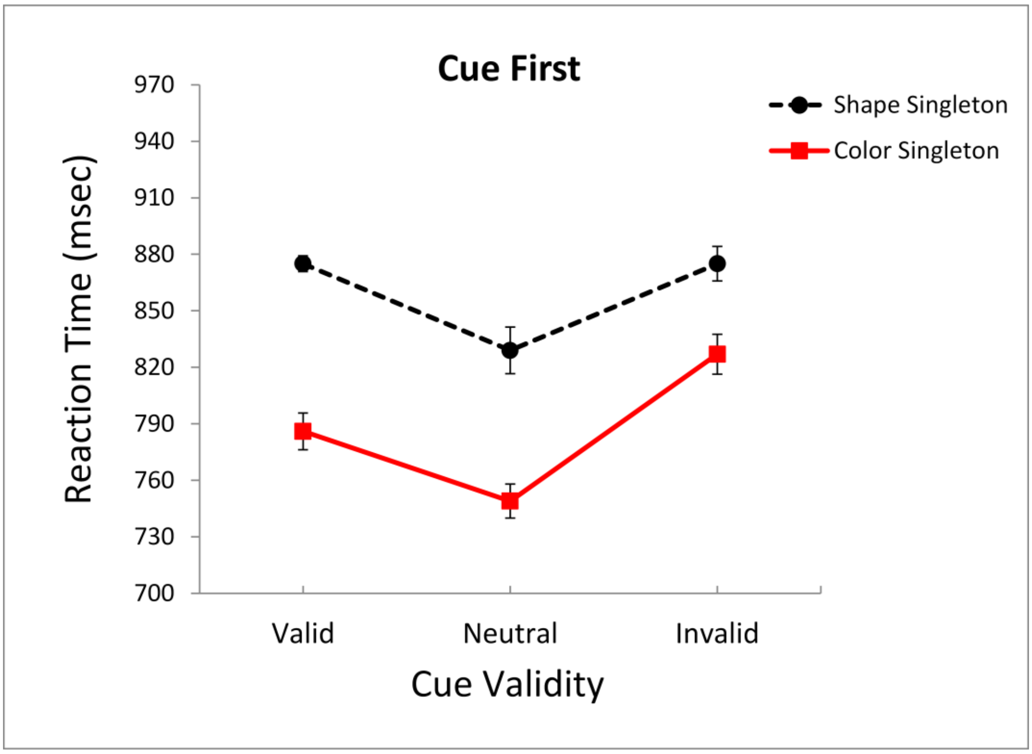


Figure 4A

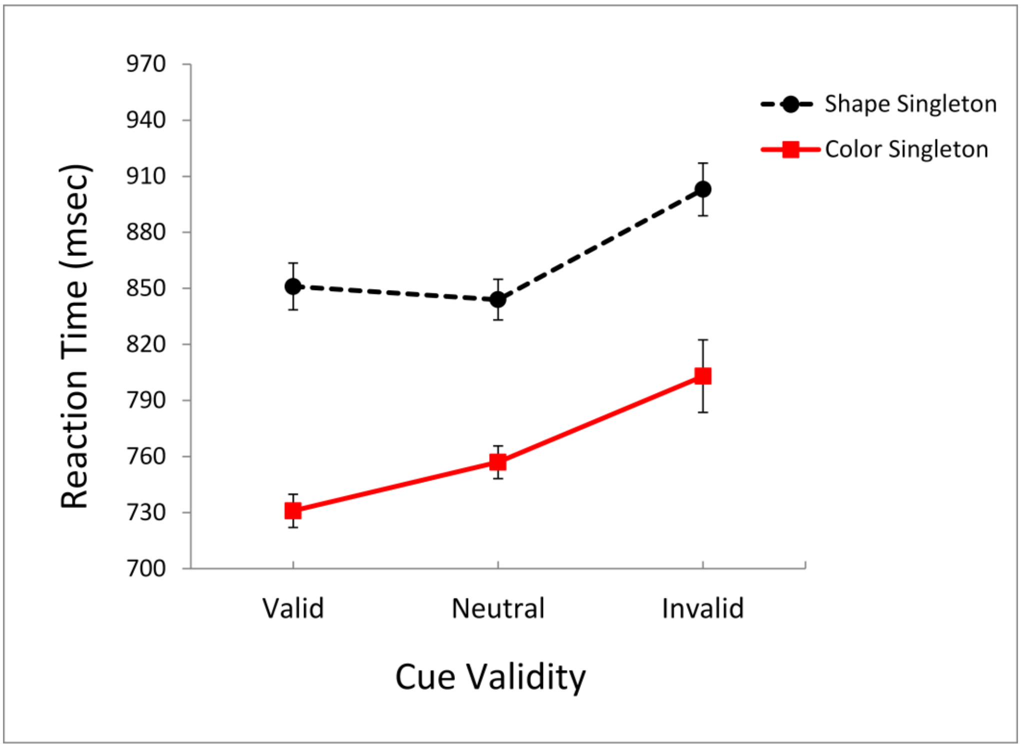


Figure 4B

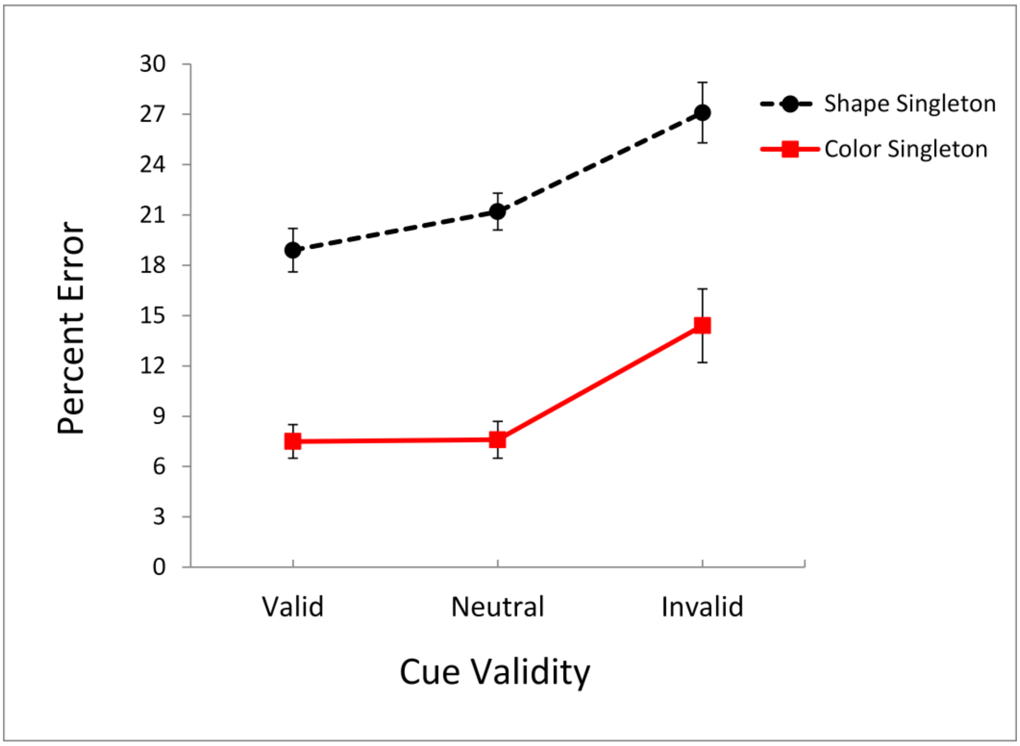


Figure 5

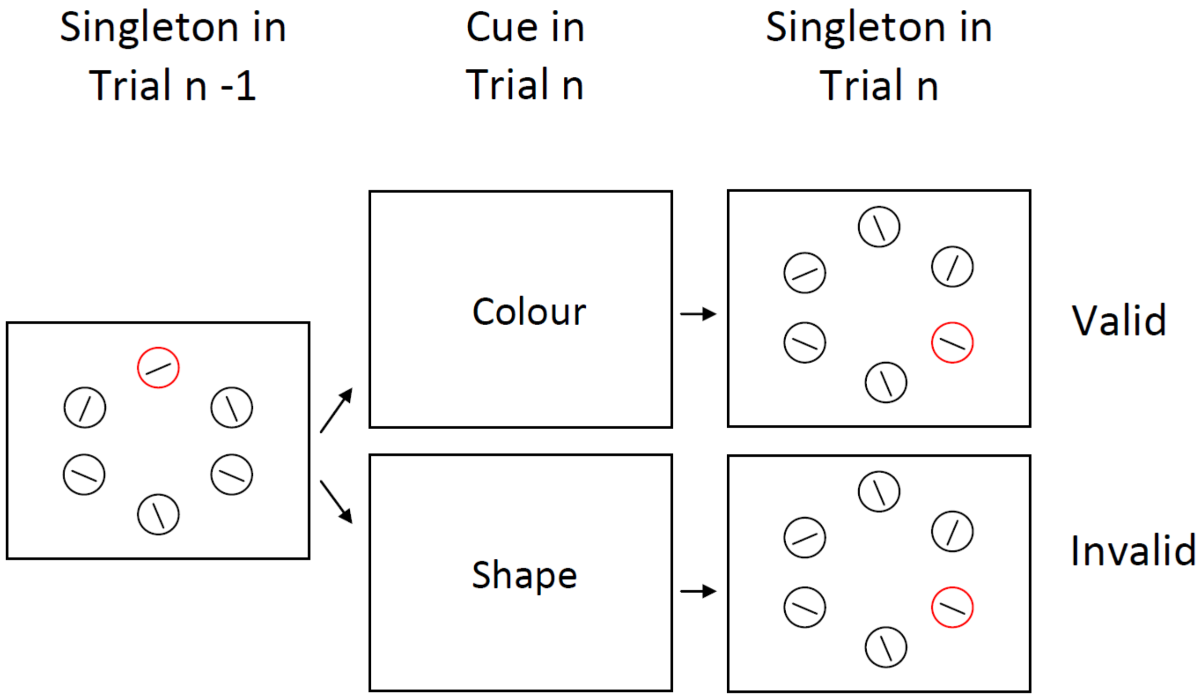

Singleton in
Trial n -1
Cue in
Trial n
Singleton in
Trial n
Colour
Shape
Valid
Invalid

Figure 6

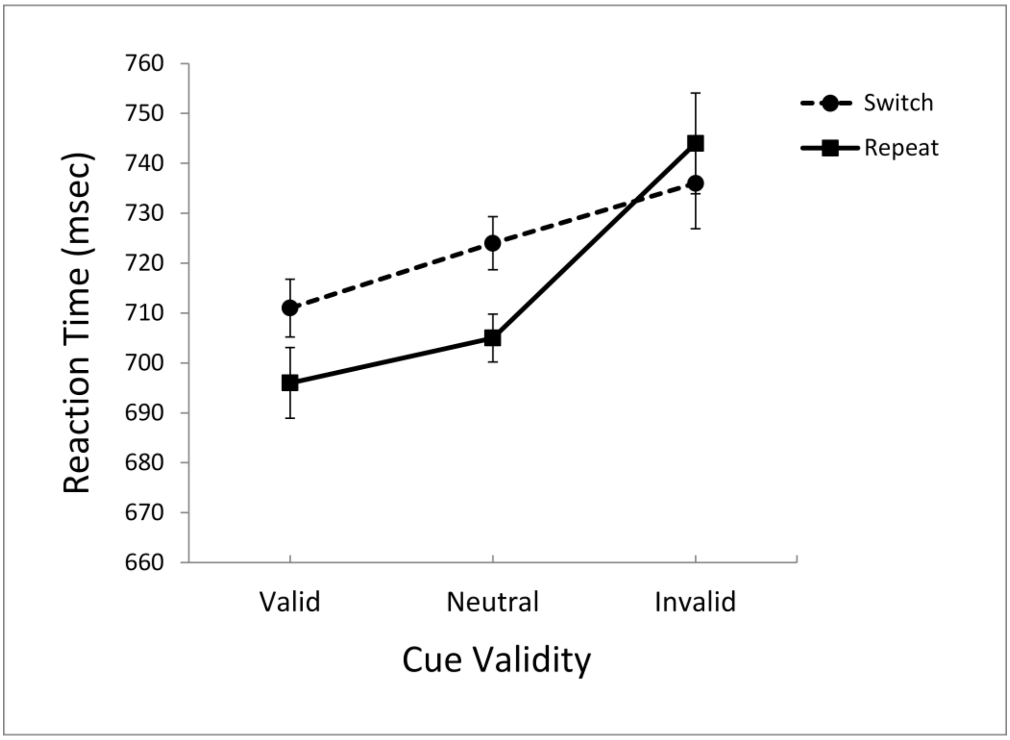
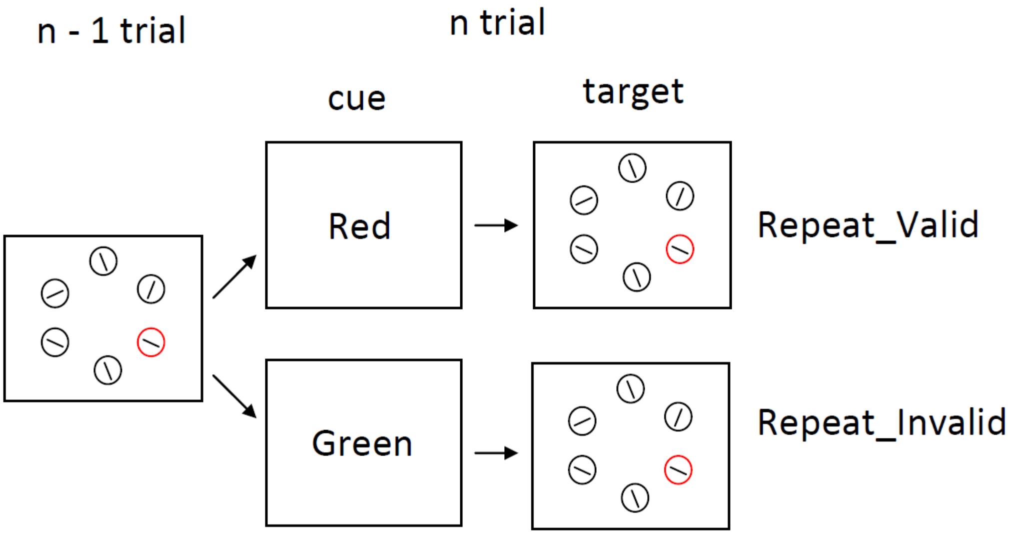

760
750
740
730
720
710
700
690
680
670
660
Reaction Time (msec)
Switch
Repeat
Valid
Neutral
Invalid
Cue Validity

Figure 7

A. Examples of a valid and an invalid trial when the singleton in the n -1 trial was repeated in the n trial.



B. Examples of a valid and an invalid trial when the singleton in the n -1 trial was different from the singleton in the n trial.

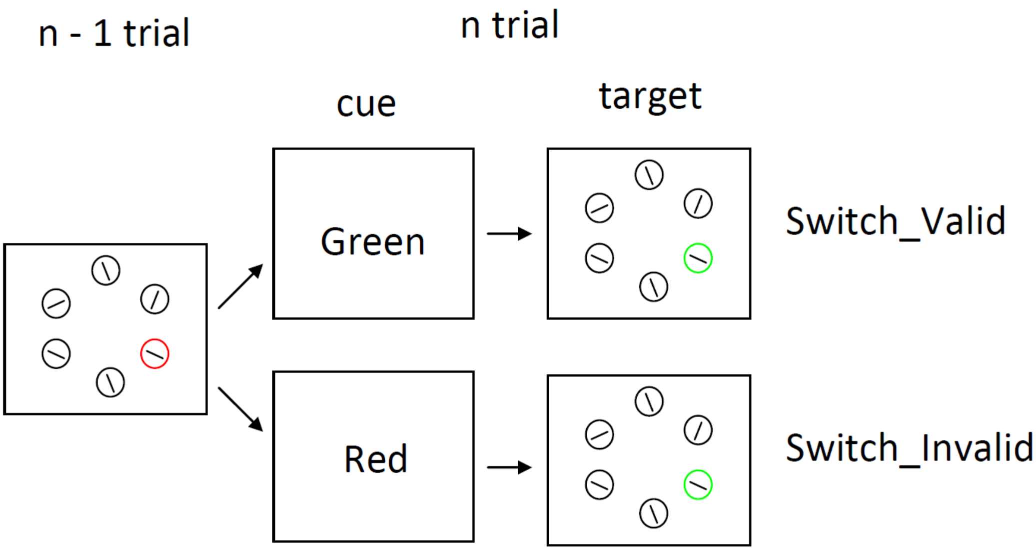
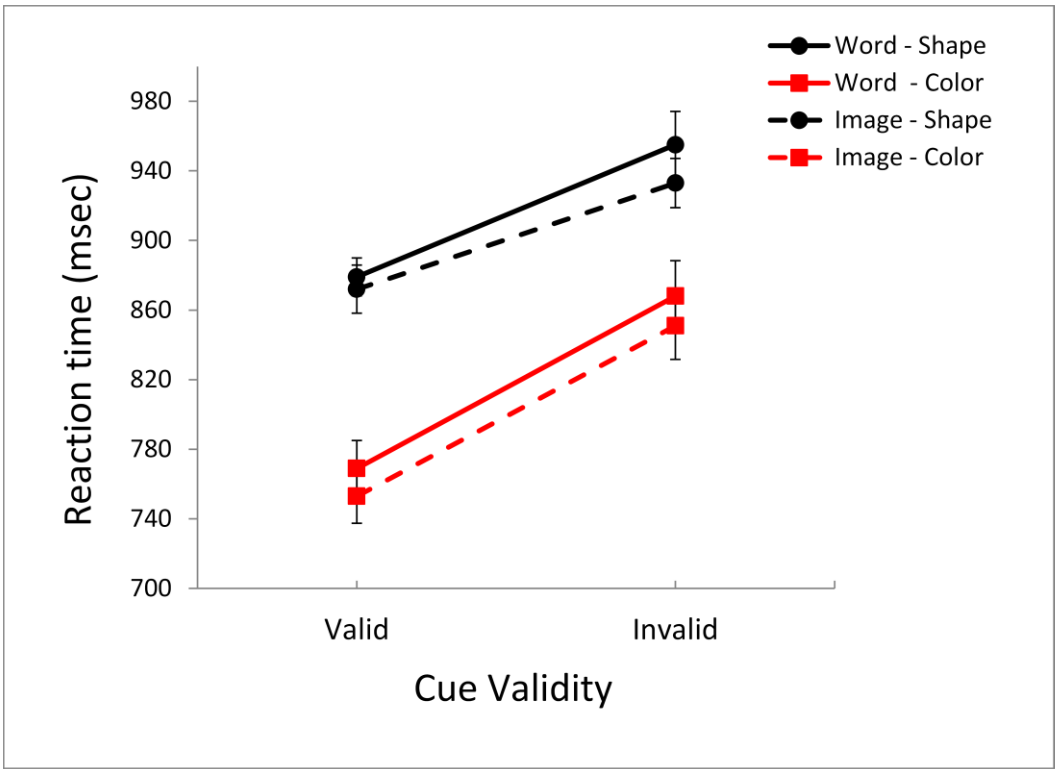


Figure 8


Word - Shape
Word - Color
Image - Shape
Image - Color
Reaction time (msec)
980
940
900
860
820
780
740
700
Valid
Invalid
Cue Validity