Cueing effects for simple detection can be accounted for by a decision model of selective attention

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Abstract

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Visual cues help observers detect a target when it appears at the cued location. One hypothesis for this cueing effect, called *spatial selective perception*, is that spatial attention directed to the cued location enhances the perceptual encoding of the stimulus. Another hypothesis, called *selective decision*, is that the perceptual encoding is unchanged by attention and instead the cue provides information for decision making. We aimed to distinguish these hypotheses using simultaneous and sequential displays with two spatial locations or two temporal intervals. The simultaneous condition used a partially-valid spatial cue, and the sequential condition used a partially-valid temporal cue. The spatial selective perception hypothesis predicts no cueing effect for sequential displays, while the selective decision hypothesis predicts cueing effects for sequential displays that are well separated in time. Results show cueing effects for the sequential condition, supporting a decision account of selective attention for simple stimuli. We discuss other possible temporal attention hypotheses.

Whether we are reading a book, driving a car, or having a conversation in a crowded room, selective attention allows us to select relevant information while limiting distractions. One way to measure selective attention is to use the partially-valid cueing paradigm (Posner, 1980). In partially-valid cueing, a cue indicates where in space a target stimulus is most likely to appear. For some proportion of trials the cue is valid, meaning that the target appears at the cued location, and for a smaller proportion of trials the cue is invalid. It has been found that people are better at detecting a target when it appears at the cued location versus when it appears at an uncued location, a finding referred to as the spatial cueing effect (Posner, 1980).

There is an ongoing debate over the cause of this cueing effect. One hypothesis, which we refer to as *spatial selective perception,* poses that attention is directed to the location where a target is most likely to appear, which enhances perceptual encoding of information at the cued location. Under this hypothesis, attention is often described using a spotlight metaphor which implies limited capacity in perception across spatial locations (Posner, Snyder, & Davidson, 1980). It is additionally assumed that we can shift our attentional spotlight to different spatial locations across time.

A second hypothesis, which we call *selective decision*, poses that encoding for simple detection has unlimited capacity across space, and instead the cue provides information that is used during decision-making. During the stimulus interval, we collect information from both the cued and uncued locations and then incorporate the information from the cue to make a decision. This hypothesis is similar to Bayesian decision-making in that the cue is a prior that influences how we make decision about information at different locations.

The current study addresses whether spatial cueing effects are due to changes in perceptual encoding (spatial selective perception), or decision-making (selective decision). The question of which hypothesis better accounts for partially-valid cueing effects has been addressed in the literature, with some studies finding results in support of spatial selective perception (Dosher & Lu, 2000a, 2000b; Posner et al., 1980), and others supporting selective decision (Kinchla, Chen, & Evert, 1995; Shimozaki, Eckstein, & Abbey, 2003). However, previous research has not been able to rule out either hypothesis.

The goal of the current study is to distinguish spatial selective perception from selective decision by comparing performance using simultaneous and sequential displays (Eriksen & Spencer, 1969; Shiffrin & Gardner, 1972). This paradigm manipulates the amount of perceptual information that must be encoded within an interval, while keeping the decision component of the task constant. One of the earliest studies to use the simultaneous-sequential paradigm was conducted by Shiffrin and Gardner (1972). Their goal was to test whether the detection of individual letters is limited or unlimited in capacity. Participants were instructed to detect a target letter in an array, and the letters were shown either simultaneously within a single time interval, or sequentially across multiple intervals. In the sequential condition, only one letter was presented in each interval. A limited capacity model predicts better performance in the sequential condition than in the simultaneous condition. This is because the sequential condition allows observers to encode each letter separately, lessening the demand on capacity. An unlimited capacity parallel model predicts equal performance for the simultaneous and sequential conditions because for both the simultaneous and sequential condition, observers can encode all elements of the display in parallel. Shiffrin and Gardner (1972) found equal performance in the simultaneous and sequential conditions, which is consistent with letters being processed in parallel, with unlimited capacity.

Since the initial finding by Shiffrin and Gardner (1972), the simultaneous-sequential paradigm has often been used to test unlimited- and limited-capacity models of divided attention. The results of these studies have found that for tasks involving simple stimuli, such as contrast discrimination tasks or detection tasks involving alphanumeric digits, processing was unlimited in capacity, and for tasks requiring participants to process more complex stimuli, such as words, processing was limited in capacity (Duncan, 1980; Pashler & Badgio, 1987; Scharff, Palmer, & Moore, 2011).

The simultaneous-sequential paradigm distinguishes limited- and unlimited-capacity models of attention by assuming that, if given enough time, participants can shift attention and encode information across separate timepoints. For the sequential condition to improve performance, the delay between stimulus intervals must be long enough to allow attention to re-orient. Duncan, Ward, and Shapiro (1994) conducted a series of experiments where they measured attentional dwell time, or the length of time needed to shift attention from one object to another. In one experiment, participants were instructed to identify two aphanumeric characters presented sequentially at different locations, and the length of the delay between the first and second stimulus ranged from 0-900 ms. They found that identification of the second stimulus was worse for delays less than 450 ms, indicating that attending to the first stimulus interfered with identificiation of the second stimulus when delays were less than half a second long. Thus, to make distinctive predictions for limited- and unlimited-capacity models of attention, delays longer than 450 ms are preferred.

Although previous work using the simultaneous-sequential paradigm has primarily focused on divided attention, it can also be used to test limited- and unlimited-capacity models of selective attention. More specifically, this paradigm can be used to manipulate the number of spatial locations an observer must attend to at a time, while keeping the decision component of the task the same. Kinchla, Chen, and Evert (1995) used a partially-valid cueing design where participants were instructed to detect a target among four sequentially presented letters. A target was present in two-thirds of trials, and absent in one-third. A pre-cue indicated which interval was most likely to contain a target if a target was present. The pre-cue was either neutral in that there was an equal probability that the target could appear in each of the four intervals, or it was informative, indicating the more likely interval. In the informative cue condition, participants were told that the probability of the target appearing in the fourth interval was seven times as high as the probability of it appearing in any one of the first three intervals. The informative cue was valid on 70% of trials and invalid on 30% of trials. Spatial selective perception predicts that participants should detect the target equally well in all cue conditions because the letters are presented sequentially, allowing each element to be encoded, thus no cueing effect should be observed. Selective decision predicts that in the informative cue condition, participants should do better when the cue is valid than when it is invalid. Additionally, in the neutral cue condition, participants should do equally well regardless of which interval the target appears in. The results showed that when the cue was neutral, participants were able to detect the target in each of the four intervals. When the cue was informative, participants were better at detecting the target when it appeared in the cued interval than when it appeared in the uncued interval. These results are consistent with an unlimited capacity account of selective attention, such as the selective decision model.

Kinchla et al. (1995) proposed that the results could be accounted for by a weighted integration decision model where observers weight information from each interval according to the probability that the target appeared in the interval. For example, in the neutral cue condition, observers can weight information from each interval equally because the probability of the target appearing in each of the four intervals was uniform. However, in the informative cue condition, observers can weight information from the cued interval more heavily because this interval was seven times more likely to contain the target. Subsequent research has developed other types of selective decision models, such as a Bayesian ideal observer model (Shimozaki, Eckstein, & Abbey, 2003).

Simultaneous-Sequential Predictions

In the current study, we use the simultaneous-sequential paradigm to distinguish the predictions of the spatial selective perception and selective decision hypotheses. In our paradigm, we used two temporal intervals, each with two spatial locations. In the simultaneous condition, a partially-valid cue indicates the most likely spatial location of a stimulus ($p = .8$) and a 100% valid cue indicates the temporal interval. In the sequential condition, a partially valid cue indicates the most likely temporal interval ($p = .8$) and a 100% valid cue indicates the spatial location.

The spatial selective perception hypothesis poses that perceptual encoding has limited capacity in space, and wherever we attend, encoding is enhanced. Under the spatial selective perception hypothesis, observers must choose to select information from either the cued or uncued spatial location. For the simultaneous condition, because the cued location is more likely to contain the target, it benefits observers to attend to that location most of the time. This strategy leads to better performance when the cue is valid than when the cue is invalid. In contrast, in the sequential condition the spatial position of the target is known, and the cue indicates the temporal interval that has a higher probability of containing the target. Observers no longer have to choose between attending to one of two relevant locations, but rather they can attend to a single location and encode the target when it appears. Thus, the spatial selective perception hypothesis predicts no cueing effect for the sequential condition.

The selective decision hypothesis poses that perceptual encoding is unlimited in capacity, and the quality of perceptual encoding is not enhanced by attention. Rather, attention effects arise because of a decision rule that is implemented when observers make a judgement about a stimulus. In the simultaneous condition, observers weight information at the cued location more heavily than information at the uncued location, leading to a decision that is biased in favor of validly-cued trials. For sequential trials, the same decision rule is implemented in time, with information from the cued interval being used more than that from the uncued information. Therefore, the selective decision hypothesis predicts a cueing effect for both simultaneous and sequential displays.

Experiment

Method

Observers. Thirteen paid observers participated in this experiment. All participants had normal or corrected-to-normal acuity. One of the authors (MJ) participated in the experiment.

Stimuli. Observers judged the orientation of Gabors that were 3 degrees in diameter. The Gabors were in one of two orientations: 130 degrees (left-tilting) or 40 degrees (right-tilting). The contrast of the Gabor was adjusted for each participant such that their average performance level was between 70-80% correct ($M_{contrast}$ = 8.4%). The Gabor appeared 10 degrees to the left or right of fixation.

Procedure. Prior to completing the main experiment, each participant completed training sessions to become familiar with the partially-valid cueing paradigm. This experiment had two cueing conditions that we call simultaneous and sequential. The trial sequence for both the simultaneous and sequential conditions are shown schematically in Figure 1.

The simultaneous condition used a typical partially-valid spatial cueing procedure, in which the cue indicates where the target was most likely to appear. The temporal interval was known to the subjects and were separated into early-interval and late-interval blocks. During early-interval blocks, the trials began with fixation for 0.5 seconds, followed by the cue for 1 second. The cue consisted of one red and one blue square, each 0.75 degrees in width and height. Both squares were positioned one degree above fixation, and one degree to the left and right of fixation. Participants were assigned a cue color of either red or blue, and were taught that the cue indicates whether the target is most likely to appear on the left or right of fixation. The probability of the target appearing at the cued location was .8, and for the uncued location it was .2.

At the beginning of each trial, a cue was shown for 1000ms. Following the cue was a delay for 500 ms. To reduce spatial uncertainty, fiducial markers appeared to the left and right of fixation, indicating the two locations where the target could appear. To reduce temporal uncertainty, two 500 Hz tones were played for 250 ms each during the half-second delay period. After the delay, the stimulus interval occurred for 50 ms, during which the target appeared at the cued ($p = .8$) or uncued ($p = .2$) locations and a single 750 Hz tone was played for 250 ms. Following the stimulus interval was a second delay of half a second, during which two more 500 Hz tones were played for 250 ms each. The fiducial markers were taken off the screen during the second delay period to indicate to participants that the stimulus interval had ended and no other target would appear. Following the delay was a blank interval 50 ms, during which the fixation mark was the only thing on the screen, a single 750 Hz tone was played for 250 ms. Participants were then prompted to respond, and given as much time needed to do so.

The trial sequence for late-interval simultaneous blocks was similar to that of that of the early-interval blocks. The key difference was that the first 50 ms display was the blank interval, with no stimulus or fiducial markers, and the second 50 ms display contained the stimulus interval with fiducial markers to the left and right of fixation. The cue indicating the late interval was positioned one degree below fixation.

In the sequential condition, the target could either appear only on the left, or only on the right. Therefore, participants knew where the target would appear. The pre-cue then served as a temporal cue indicating when the target was most likely to appear; either in the first stimulus interval, or the second stimulus interval. The trial began with a fixation cross for half a second, followed by a visual cue for one second that consisted of a red and a blue square positioned either one degree to the left or one degree to the right of fixation, depending on where the target would appear within that block. The squares were positioned vertically such that one square appeared to one degree above fixation, and the other square appeared one degree below fixation. The vertical location of the assigned cue color indicated which stimulus interval the target was most likely to appear. Specifically, a cue above fixation indicated that the target had an 80% chance to appear in the first stimulus interval, and a cue below fixation indicated that the target had an 80% chance to appear in the second stimulus interval.

Following the cue was 500 ms delay, during which a fiducial marker appeared on the screen to indicate where the target would appear. There a single fiducial marker either on the left or the right side of the screen, depending on the block. The addition of fiducial markers helped to reduce spatial uncertainty, and the markers stayed on the screen throughout the duration of the trial. To reduce temporal uncertainty, two 500 Hz tones were played for 250 ms each. These tones signaled to participants that the first stimulus interval was about to occur. The first stimulus interval was then shown for 50 ms, and a single 750 Hz tone was played for 250 ms. The first stimulus interval was followed by another half a second delay containing two 500 Hz tones for 250 ms each, and then the second stimulus interval was shown for 50 ms, accompanied by a 250 Hz tone for 250 ms. Participants were then prompted to respond, and given as much time as needed to do so.

Results

Figure 2a shows the percentage correct for both the valid and invalid cueing conditions, and for both simultaneous and sequential conditions. For the simultaneous condition, average performance was 76.7 ± 1% for the valid condition, and 68.5 ± 2% for the invalid condition. The mean within-subject difference between the valid and invalid cue conditions was 8± 2% (Figure 2b). The cueing effect was reliable, $t(12) = 4.27$, $p = .001$.

For the sequential condition, average performance was 76.6 ± 1% for the valid condition, and 69.4 ± 1% for the invalid condition. The mean within-subject difference was 7 ± 2% (Figure 2b). The cueing effect was reliable, $t(12) = 4.13$, $p = .001$.

Discussion

The current study sought to distinguish two competing hypotheses that can account for partially-valid cueing effects: spatial selective perception and selective decision. We distinguished these two hypotheses using the simultaneous-sequential paradigm, where the high- and low-probability locations are either presented simultaneously within one stimulus interval, or sequentially between two stimulus intervals. We found that performance was better when the cue was valid than when it was invalid for both our simultaneous and sequential conditions, a result that is consistent with the selective decision hypothesis. This result is inconsistent with the spatial selective perception hypothesis, which poses that cueing effects occur due to limited capacity in encoding information across spatial locations.

The results observed in this study are similar to those found in previous research. A study conducted by Kinchla, Chen, and Evert (1995), described in detail above, used a sequential partially-valid cueing design and found that performance was better when the cue was valid than when it was invalid. A separate study by Coull and Nobre (1998) employed both spatial and temporal cueing in a sequential detection task using partially-valid cueing. As in the current study, there were two stimulus intervals when a target could appear, but unlike the current study, there were also two locations where the target could appear in either interval. Participants saw either a spatial cue, a temporal cue, or a spatial-temporal cue. The spatial cue indicated where the target was most likely to appear, but not when, whereas the temporal cue indicated when the target would most likely appear. The spatial-temporal cue indicated both when and where the target was most likely to appear. Each of these cue types were 80% valid. There was also a neutral cue condition that gave no information about where on when a target was most likely to appear. The results of this study showed faster reaction times when the cue was valid versus when it was invalid, for each of the three informative cue condition. What sets our study apart from previous work by Kinchla et al. (1995) and Coull et al. (1998) is that we included a simultaneous condition to allow a direct comparison of cueing effects for simultaneous and sequential.

Although our results allow us to rule out the spatial selective perception hypothesis, we cannot rule out a model that assumes both limited capacity in space and time. Such a model has been suggested in recent studies of temporal selective attention. These studies use a design similar to the original cueing paradigm developed by Posner (1980), but rather than cueing locations in space, these experiments cue the interval in time when a target is most likely to appear. Our sequential condition is an example of temporal cueing because the cue indicates when a target is most likely to appear within a trial.

Previous work in temporal selective attention has found a cueing effect similar to what we found in our sequential condition, but instead of attributing the cueing effect to decision, it is attributed to limited encoding capacity in time. A study by Griffin, Miniussi, and Nobre (2001) used a temporal cueing paradigm and discrimination task where participants were instructed to report whether a target circle had a small gap in it or not. The circle could appear in one of two temporal intervals, and a visual cue indicated with 80% validity which interval the target was most likely to appear in. In 10% of trials the target appeared in the uncued interval, and in the remaining 10% of trials no target appeared. Response times were the dependent variable. The results showed that for both temporal intervals, participants were faster at responding when the target was validly cued versus when it was invalidly cued.

Denison, Heeger, and Carrasco (2017) used a temporal cueing paradigm to investigate whether attending to a point in time leads to enhanced encoding of stimuli that appear at that time. They used a Gabor orientation discrimination task where two Gabors appeared at two separate time points. A precue was shown at the beginning of the trial that was either informative or neutral. In the informative cue condition, the cue indicated with 75% validity which interval participants would be prompted to report on at the end of the trial. In the neutral cue condition, both intervals were cued and there was 50% probability that participants would be prompted to report on either interval. Following the two stimulus intervals was a post-cue that prompted participants to report the orientation of one of the two Gabors. The results for this experiment showed a cueing effect, where participants were more accurate when prompted to report the orientation of the cued Gabor versus when they reported the uncued Gabor. Participants were also more accurate when the cue was neutral than when it was invalid. The authors concluded that the cue resulted in benefits for the cued stimulus and costs for the uncued stimulus.

Although temporal cueing effects can be explained by a model that assumes limited capacity in attention over time, these results are also consistent with decision models of selective spatial attention. Lasley and Cohn (1981) provide an interpretation of temporal cueing effects and how the cue influences decision-making. They investigated how temporal uncertainty in decision-making changes the detectability (d') of a target. In their certain stimulus condition, there was only one time point when the signal could occur. In their uncertain stimulus condition, there were either four our eight time points when the signal could occur with equal probability. The signal was a luminance increment, and participants responded with yes or no to indicate whether the signal was present. The results of this experiment indicated that as temporal uncertainty increased, detectability of the signal decreased. The authors concluded that having less knowledge about when the signal can occur resulted in more uncertainty in decision-making, make it harder for participants to decide whether the signal had occurred.

Although the results of the current experiment do not rule out all limited capacity models of selective attention, it is inconsistent with models that allow attentional switching, such as our spatial selective perception hypothesis. For observers to switch attention and encode information from different spatial locations over time, the spotlight must not have a temporal capacity limit. Previous work using the simultaneous-sequential paradigm with word and letter identification tasks, discussed in detail above, are consistent with models that assume unlimited capacity in time because participants in these experiments were able to encode words and letters presented sequentially over multiple temporal intervals better than they could judge the same stimulus presented simultaneously (Pashler & Badgio, 1987; Scharff, Palmer, & Moore, 2011; Shiffrin & Gardner, 1972). Thus, there is a conflict between theories that allow attentional switching and those requiring limited capacity in time.

The results of the current study also do not address whether selective attention to more complex stimuli, such as words, is consistent with the selective decision hypothesis. Might a partially-valid cueing experiment using simultaneous- and sequentially-presented words yield results in support of selective perception? Previous work in divided attention using the simultaneous-sequential paradigm with word stimuli (Pashler & Badgio, 1987; Scharff, Palmer, & Moore, 2011; Shiffrin & Gardner, 1972) did find improved performance when the words were presented sequentially versus when they were presented simultaneously. It is reasonable to suspect that for a partially-valid cueing experiment, there might also be a benefit of presenting the high- and low-probability stimulus locations sequentially. Such a result would be consistent with selective decision for simple detection judgments, and selective perception for word judgements.

Conclusion

The current study used the simultaneous-sequential paradigm to distinguish two competing hypotheses of selective attention: spatial selective perception, and selective decision. Using a simple-detection task, we found results consistent with selective decision, which assumes unlimited capacity in space. Our results are not consistent with spatial selective perception, which assumes limited capacity in space. Although our findings allow us to rule out spatial selective perception, we cannot rule out a perception model that assumes limited capacity in time. Such models are commonly referenced in the temporal selective attention literature.

References

Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience*, *18*(18), 7426–7435. https://doi.org/0270-6474/98/187426-10$05.00/0

Denison, R. N., Heeger, D. J., & Carrasco, M. (2017). Attention flexibly trades off across points in time. *Psychonomic Bulletin and Review*, *24*(4), 1142–1151. https://doi.org/10.3758/s13423-016-1216-1

Dosher, B. A., & Lu, Z.-L. (2000a). Noise exlusion in spatial attention. *Psychological Science*, *11*(2), 139–146. https://doi.org/10.7897/2277-4343.04136

Dosher, B. A., & Lu, Z. L. (2000b). Mechanisms of perceptual attention in precuing of location. *Vision Research*, *40*(10–12), 1269–1292. https://doi.org/10.1016/S0042-6989(00)00019-5

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, *87*(3), 272–300.

Duncan, J., Ward, R., & Shapiro, K. (1994). Direct measurement of attentional dwell time in human vision. *Nature*, *369*(6478), 313–315. https://doi.org/10.1038/369313a0

Eriksen, C. W., & Spencer, T. (1969). Rate of information processing in visual perception: Some results and methodological consiterations. *Journal of Experimental Psychology*, *79*(2), 1–16.

Griffin, I. C., Miniussi, C., & Nobre, A. C. (2001). Orienting attention in time. *Frontiers in BioScience*, *6*(12), 660–671. Retrieved from http://brain.oxfordjournals.org/content/122/8/1507.short

Kinchla, R. a, Chen, Z., & Evert, D. (1995). Precue effects in visual search: data or resource limited? *Perception & Psychophysics*, *57*(4), 441–450. https://doi.org/10.3758/BF03213070

Lasley, D. J., & Cohn, T. (1981). Detection of a luminance increment: effect of temporal uncertainty. *Journal of the Optical Society of America*, *71*(7), 845. https://doi.org/10.1364/JOSA.71.000845

Pashler, H., & Badgio, P. C. (1987). Attentional issues in the identification of alphanumeric characters. *Attention and Performance 12: The Psychology of Reading*, 63–81. https://doi.org/10.1016/B978-0-12-381460-9.00018-3

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *109*(2), 160–174. https://doi.org/10.1037/0096-3445.109.2.160

Scharff, A., Palmer, J., & Moore, C. M. (2011). Extending the simultaneous-sequential paradigm to measure perceptual capacity for features and words. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(3), 813–833. https://doi.org/10.1037/a0021440

Shiffrin, R. M., & Gardner, G. T. (1972). Visual processing capacity and attentional control. *Journal of Experimental Psychology*, *93*(1), 72–82. https://doi.org/10.1037/h0032453

Shimozaki, S. S., Eckstein, M. P., & Abbey, C. K. (2003). Comparison of two weighted integration models for the cueing task: linear and likelihood. *Journal of Vision*, *3*(3), 209–229. https://doi.org/10.1167/3.3.3

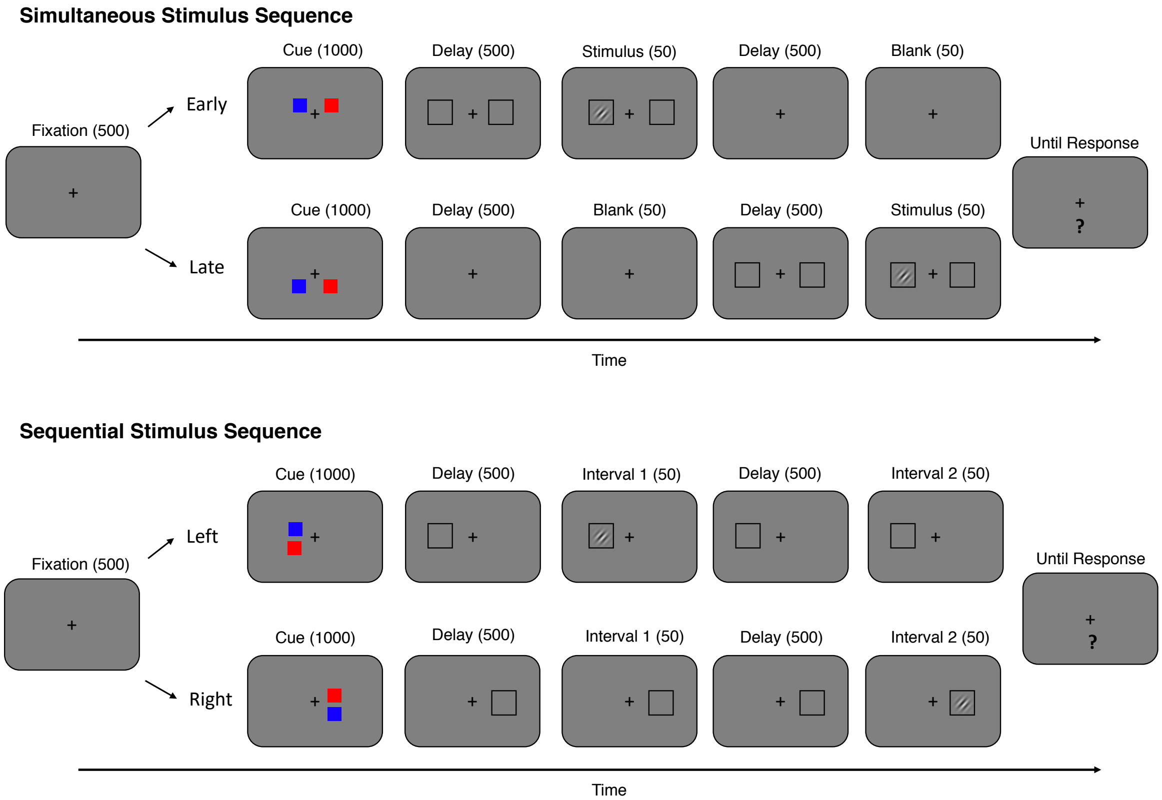

Figure 1. Schematic of the trial sequence for the simultaneous and sequential conditions. In the simultaneous condition, the cue was spatial, indicating which side of fixation the target was most likely to appear. In the sequential condition, the cue was temporal, indicating which stimulus interval was most likely to contain the target.

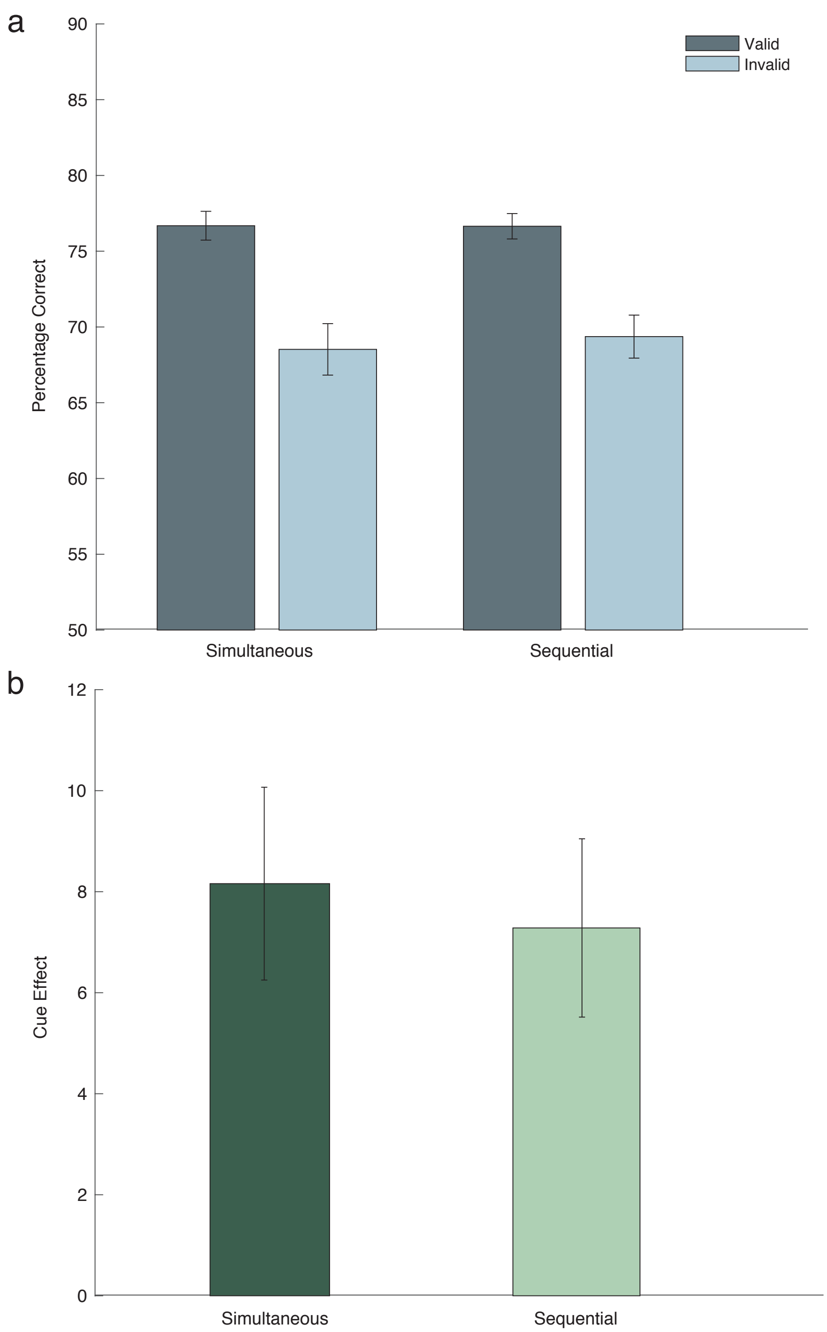

Figure 2. a) Percentage correct for valid and invalid cues, for both the simultaneous and sequential condition. Error bars represent standard errors. The dark blue bars represent performance when the cue was valid, and the light blue bar represents performance when the cue was invalid. **b)** The cueing effect for the simultaneous and sequential conditions, which is

calculated as the difference in performance when the cue was valid versus when it was invalid. The dark green bar represents the cueing effect in the simultaneous condition, and the light green bar represents the cueing effect in the sequential condition.