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Investigating the flexibility of attentional orienting in multiple modalities: Are spatial and temporal cues used in the context of spatiotemporal probabilities?

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**ABSTRACT**

Attention can be oriented in both space and time in response to trial-variant cues when, say, their colour predicts the spatial location and their shape predicts cue-to-target stimulus onset asynchrony (SOA), producing spatial and temporal cueing effects [faster response times (RTs) on validly- than invalidly-cued trials]. We investigated whether spatial and temporal cueing effects are found when spatiotemporal probability is also known (e.g., targets typically occur on the left at short SOAs and on the right at long SOAs; a trial-invariant cue). Temporal cueing effects were found in hit rates at long SOAs. Spatiotemporal probability validity effects were observed in RTs at both SOAs. Spatial cueing effects were observed in RTs except on short SOA trials when spatiotemporal probability was invalid. Our results show that participants can use the benefits of both trial-invariant (spatiotemporal probability) and trial-variant spatial and temporal cues, implicating a flexible, plastic, attentional orienting system.

The orienting of visual attention is critical for the successful performance of myriad tasks including navigation, discrimination, and detection in multimodal environments. Yet, voluntary orienting of visual attention is often assessed in highly controlled experiments where a single valid cue provides meaningful information about only one modality of a target, say its spatial location or the stimulus onset asynchrony (SOA) between the cue and the target. Cues are “valid” when the information they provide is correct more often than not across trials; for instance, a cue that indicates the location of a target on 75% of trials is valid. Valid cues are misleading on a smaller percentage of “invalid” trials (e.g., 75%-valid cues are misleading on 25% of trials), and this introduces some uncertainty regarding target location. Attentional orienting in response to the cue is probed by comparing a performance measure [such as reaction time (RT) or accuracy] on valid and invalid trials. Successful allocation of attention on the basis of a cue is implied when performance is enhanced on valid compared to invalid trials, commonly referred to as a cueing effect.

Often the cue is the only source of information about the target, providing information about only one modality (space or time). This raises the question of whether what has been learned about attentional allocation in such designs generalizes to situations with multiple cues in different modalities (e.g., space and time) and with different levels of stability across trials (e.g., cues that vary from trial-to-trial versus more stable cues that are maintained across trials such as spatial probability; Geng & Behrmann, 2005). Here, we ask whether trial-variant spatial and temporal cues guide voluntary attentional orienting in the presence of a more stable, trial-invariant, spatiotemporal probability knowledge or whether participants satsisfice (e.g., Egeth et al., 2010; Simon, 1955) by using the more stable information only (e.g., attending to a location associated with a short SOA first, then to a location associated with a long SOA). Are different cues, providing information in different modalities (spatial, temporal, and spatiotemporal), flexibly integrated? And if so, what can we learn about how they are prioritized? We live in a complex world with many concurrent sources of information about the world and we must use this information to guide our attention.

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information relevant to the tasks we perform. Hence, it is important to understand how cues that differ in modality (spatial and temporal) and characteristics (trial-variant and trial-invariant) are incorporated and prioritized.

Voluntary visual attention can be oriented in response to cues that vary from trial-to-trial (e.g., spatial cues: Posner, 1980; Posner et al., 1978; and temporal cues: Correa et al., 2004, 2006). Experiments have investigated whether cues can simultaneously guide temporal and spatial attention (Coull & Nobre, 1998; Doherty et al., 2005; MacKay & Juola, 2007; Rohenkohl et al., 2014; Weinbach et al., 2015). For instance, Weinbach et al. (2015) combined trial-variant spatial and temporal cues (each 75%-valid) into a single-coloured shape shown before each trial in a target detection task. Colour could indicate in which of two locations a target was likely to occur and shape could indicate whether the SOA between the cue and the target was likely to be short (400 ms) or long (1400 ms); the assignment of properties to target attributes was balanced. Weinbach et al. gave participants substantial practice responding to the cues for location and SOA separately before combining them. Using the combined cues, Weinbach et al. found spatial cueing effects at both short and long SOAs, and temporal cueing effects at short SOAs only. The latter was not unexpected: Temporal cueing effects are generally larger at short SOAs; indeed, they are not always observed at long SOAs where they are less informative (targets are more likely to appear at long SOAs once the short SOA time window has passed; see Correa, 2010). Thus, Weinbach et al.’s participants decoded both trial-variant spatial and temporal cues from the combined cue and used their predictions regarding time and space to orient attention.

Cues are not the only source of information that can be used to guide voluntary visual attention. Stable trial-invariant information, such as prior experience and context (e.g., Chun & Jiang, 1998; Geng & Behrmann, 2005; Miller, 1988) can also be used. Geng and Behrmann (2005) found that visual attention could be guided based on spatial probability: the target appeared in one of four possible locations on 70% of trials and in each of the other three locations on 10% of trials. They did not inform their participants about the spatial probability, and the probable location varied and was active on only three of six blocks. Nevertheless, participants were faster to detect a target appearing in a probable location. Geng and Behrmann also investigated how spatial probability was used in the presence of a spatial cue – an arrow indicating the probable location of a target on a given trial (70%-valid). Participants were told that the arrow was informative on most, but not all trials. Geng and Behrmann found a cueing effect of the trial-variant arrow cue and a validity effect of spatial probability (invariant over a block): That is, in service of their task, their participants used both spatial probability that remained stable across trials within a block and the arrow cue that varied from trial to trial. Moreover, effects of trial-variant spatial cues were evident at the most probable target location as well as at the less probable target locations indicating that spatial cueing effects were not dependent upon the spatial probability.

Previous experiments have not investigated how trial-variant and trial-invariant cues interact to guide attention in different modalities (i.e., space and time), however. In the current study, we add to the previous literature by introducing spatiotemporal probability knowledge into a combined spatial and temporal cueing paradigm modelled on that used by Weinbach et al. (2015). This allows us to investigate how cues that provide predictions differing in both modality (space and time) and type (trial-variant and trial-invariant) operate simultaneously. Spatiotemporal probability entails that targets are more likely to appear in one location at one point in time and at another location at a different point in time. Recall that Geng and Behrmann’s (2005) participants showed cueing effects of both a trial-variant cue and trial-invariant probability when both conveyed spatial information. Here we investigate whether similar results are obtained in a multimodal design with spatial and temporal information. In our experiment, participants were informed of the validity (75%) of both the trial-invariant spatiotemporal probability and the trial-variant temporal and spatial cues prior to the experiment. Note that a simple strategy of orienting to one location at the short SOA and the other at the long SOA, independent of the trial-variant cues, would result in short RTs on 75% of the trials. Using a well-powered design (within-subjects; 72 participants were entered into the final analyses), we investigate whether participants will use trial-variant cues that provide information about
both where and when targets are likely to occur as well as trial-invariant spatiotemporal probability. Doing so would result in improved detection performance and would demonstrate an impressive flexibility to orient attention across the two modalities of space and time using two types of cues (trial-variant and trial-invariant).

**Methods**

**Participants**

The participants were 80 University of Arizona students who volunteered for the experiment for course credit. Eight participants were excluded from analyses for either failing to meet a priori criteria of responding on at least 85% of target-present trials \(N = 5\) or having mean RTs more than two standard deviations from the mean calculated across conditions \(N = 3\); data from the remaining 72 participants were entered into the final analyses.

**Apparatus**

The experiment was run on an Intel®Core™ i5-3470 CPU with quad cores running at 3.20 GHz on Windows 7 64-bit using MATLAB (2016a; The MathWorks Inc., Natick, MA) and the Psychophysics Toolbox extension (Brainard, 1997; Kleiner et al., 2007). The experiment was presented using a 20-inch CRT monitor running at 85 Hz and a resolution of 1280 x 1024. Participants viewed the screen from a distance of approximately 60 cm; at this distance, the screen subtended 37.42°W x 28.50°H. Responses were collected via a keyboard.

**Stimuli**

Three square outline boxes (4.67°W x 4.67°H; border width: 0.14°) were displayed throughout the trial. One was presented in the centre of the screen; the other two were presented to the left and right such that the centre of the peripheral boxes was 5.95° from the centre of the central box. The boxes were white (RGB = [255 255 255]) on a black (RGB = [0 0 0]) background. The centre box contained the trial-variant cue. The trial-variant cue was either a circle (diameter: 2.23°) or a triangle (2.23°W x 2.23°H); it was either blue (RGB = [63 72 204]), or red (RGB = [237 28 36]). The mappings of the cue features to the predictions about the target appearance remained constant within each participant but were balanced between participants. Across participants, the shape of the cue was equally likely to predict the SOA (the circle and square were both equally likely to predict a short or long SOA) or target location (the circle and square were both equally likely to predict a left or right location). Similarly, the colour of the cue was equally likely to predict the SOA ("red" and "blue" were both equally likely to predict a short or long SOA) or location ("red" and "blue" were both equally likely to predict a left or right location). The combinations of exact predictions were balanced across participants. A square shape and white fill were "neutral cues," used only when participants learned and practiced responding to the spatial, temporal, and spatiotemporal cues as follows: Participants viewed coloured squares when they learned the mapping for the colour feature cue (squares are neutral shapes; Figure 1(b)). They viewed white triangles and circles when they learned the mapping for the shape feature cue (white is a neutral colour; see Figure 1(c)). They viewed white squares when they completed practice trials to learn the trial-invariant spatiotemporal probability (both the shape and the colour were neutral; see Figure 1(d)). Experimental cues always consisted of red or blue coloured triangles or squares (see Figure 1(a)). The two boxes on the left and right were target locations. The target, a white "x" (0.95°W x 0.95° H), could appear in either box, or not at all on target-absent trials (see “Trial structure” for further detail).

**Procedure**

Participants performed the task individually. After arriving at the laboratory, they completed a consent form;
both the consent form and experiment were approved by the Human Subjects Protection Program at the University of Arizona. Instructions were presented on the screen. Participants navigated through them by pressing the spacebar; while doing so, they could ask the experimenter questions. Participants were instructed to press the spacebar when the target – an “x” – appeared in either the left or right target box and to withhold a response on trials on which a target did not appear. The instructions stressed that participants should respond to the target as quickly and as accurately as possible. The instructions were followed by practice trials (see “Practice trials”) and then by experimental trials (see “Experimental trials”). The experimenter remained in the room during practice trials but left the room before the experimental trials began. The experimenter returned after experimental trials were complete to debrief the participants.

![ Trial structure and timing. Each row represents the participant’s view at progressing time points during the trial, from top to bottom. After a variable duration following the preceding trial, a cue appeared in the centre box (second row in figure). The cue was always either red or blue and either a triangle or a circle on experimental trials, where colour indicated one modality, such as spatial location (left or right), while shape indicated another modality, such cue-to-target SOA. Depending on SOA (amount of time from the onset of the cue to the onset of the target, where: short = 412 ms and long = 1412 ms, comprising cue duration + interstimulus interval), the target would appear as a white “x” in the box on the left or right. If a circle cue predicted that the target would appear in the left location, the trial in this figure would be a valid spatial cue trial. If the red cue predicted that the target would appear after a short SOA, but the target appeared after the long SOA, this trial would be an invalid temporal cue trial. ](image)

**Trial structure**

Each trial (experimental and practice; see Figure 2) began with the presentation of three empty boxes for a duration between 506 and 1494 ms (randomly chosen in intervals of ∼12 ms). The cue was then presented for 106 ms in the centre box, then the three boxes remained visible for an inter-stimulus interval of either 306 or 1306 ms; hence, the short and long SOAs were 412 and 1412 ms, respectively (the SOAs used by Weinbach et al. were 400 and 1400). Next, on target-present trials, an “x” was presented in either the left or right box for 106 ms. On target-absent trials, no target appeared (11.1% of trials; see Correa et al., 2004 for a discussion of target-absent trials). Finally, the boxes remained visible for up to 1000 ms to allow participants to make a response. After a response was made, or after 1000 ms elapsed without a response, a blank screen was presented for 506 ms after which at the boxes were presented again for the next trial. A tone was played to provide feedback on incorrect trials [e.g., target-present trials when a target was not detected, or target-absent trials when a false alarm (i.e., a target was incorrectly detected) was made].

**Practice trials**

After the basic instructions, participants completed three sets of practice trials. Before the practice trials, participants were told there would be target-absent trials, and that they were to withhold a response on these trials. Each set of practice trials separately introduced participants to just one of the three cues present in the experiment: the trial-variant spatial cue, the trial-variant temporal cue, or trial-invariant spatiotemporal probability. Before each set of practice trials, participants were instructed that the cue was valid on 75% of trials on which a target appeared. Each set of practice trials comprised 18 trials, 16 trials with targets (12 valid trials, 4 invalid trials) and 2 target-absent trials, which matched the probability of target-absent trials in the experimental trials. The order of the practice trial sets was counterbalanced between participants. Participants could ask clarification questions during and after the practice trials. There were no practice trials with combinations of cues before they were all incorporated in experimental trials.
**Trial-variant spatial and temporal cues**

For the trial-variant spatial and temporal cues, participants were told which feature (colour or shape) predicted which target characteristic (location or SOA) and this mapping remained constant throughout the experiment. For instance, for half of the participants, shape predicted the target’s spatial location and participants were instructed which shape predicted which location (for half of these participants, the triangle predicted the left location and the circle predicted the right location; these pairings were reversed for the other half). For the other half of participants, shape predicted the SOA and participants were instructed which shape predicted which temporal interval (for half of these participants, the triangle predicted the short SOA and the circle predicted the long SOA; these pairings were reversed for the other half). Practice trials for the spatial or temporal trial-variant feature cues contained one feature (shape or colour; balanced across participants); the other feature was a neutral shape (square) or colour (white). Participants were told to focus on the feature cue being practiced and to ignore the other (neutral) feature.

**Trial-invariant spatiotemporal probability**

For the practice trials for the trial-invariant spatiotemporal probability, participants were instructed that on 75% of trials the target would appear in one location following a short SOA and in the other location following a long SOA. A white square was shown in the central box on each of the trial-invariant spatiotemporal probability practice trials; participants were told to ignore the features (colour and shape) of the cue. For half of the participants, the left location was associated with the short SOA and the right location was associated with the long SOA – this mapping was reversed for the other half of participants.

**Experimental trials**

After the practice trials, there were three blocks of 144 experimental trials (432 trials total). On each trial, a combined cue was shown and spatiotemporal probability was operative; hence the three cues were operative on every trial (see Figure 3 for sample trials). After every 12 trials, a screen appeared indicating that participants could take a break and could continue the experiment by pressing the spacebar when they were ready. A similar screen appeared after each block. There were 16 target-absent trials per block (48 total). Target-absent trials occurred equally often following each type of trial-variant cue (i.e., 12 trials with each combination of shape and colour viewed by an individual participant). See Table 1 for a breakdown of trials per condition.

**Data analysis**

In what follows, hit rates and detection RTs are first analysed using within-participants ANOVAs with four factors: SOA (short, long), trial-variant spatial cue validity (valid, invalid), trial-variant temporal cue validity (valid, invalid), and trial-invariant spatiotemporal probability validity (valid, invalid). An interim discussion follows this analysis. Block was not included in the ANOVAs because the experiment was not designed to investigate block effects. In a subsequent “Post-hoc analysis” section, conservative post hoc analyses probe the effects of these different cue types on detection RTs using a linear trend analysis over block. This post-hoc analysis assesses whether cue usage changes over the course of the experiment, as proposed by the Least Costs Hypothesis (Pauszek & Gibson, 2016, 2018). This allows a more fine-grained analysis of cue usage over the course of the experiment. The “Post-hoc Analysis” section is followed by a Discussion section and Conclusions.

**Results**

Mean false alarm rate on target-absent trials was 4.02% (range = 0–20.83%) and mean hit rate on target-present trials was 97.61% (range = 92.97–100%). Mean detection RTs on target-present trials where the target was detected accurately (i.e., where “hits” occurred) on short and long SOA trials with every combination of cues can be seen in Table 1.

**Hit rate**

A repeated measures ANOVA was run on hit rate on target-present trials with four factors: SOA (short, long), validity of trial-invariant spatiotemporal probability (valid, invalid), validity of the trial-variant spatial cue (valid, invalid), and validity of the trial-
Figure 3. Sample trials and cue validities illustrated for one participant. Feature cues mapping onto spatial or temporal predictions were balanced across participants, as were specific predictions of feature cue (i.e., circle predicting left or right location). For this participant, shape predicted the spatial location of the target: a circle predicted that the target would appear in the box to the left and a triangle predicted the target would appear in the box to the right. Colour predicted the temporal interval of the target: red predicted it would appear after a short cue-to-target SOA and blue predicted it would appear after a long cue-to-target SOA. For this participant, spatiotemporal probability predicted that the target would appear after a short SOA in the left location and after a long SOA in the right location. (a) On this trial, all predictions were valid: the trial-variant cue is a red circle and the target appears in the left location after a short SOA; trial-invariant spatiotemporal probability is also valid. (b) On this trial: the trial-variant spatial cue is invalid, whereas the trial-variant temporal cue and trial-invariant spatiotemporal probability are valid: The cue is a blue circle, the target appears in the right box after a long SOA. (c) On this trial, the trial-variant spatial cue is valid, the trial-variant temporal cue invalid, and trial-invariant spatiotemporal probability is invalid: The trial-variant cue is a blue triangle. (d) On this trial, all predictions are invalid: The cue is a red triangle, but the target appears in the left after a long SOA which is also inconsistent with trial-invariant spatiotemporal probability. Note that SOA is calculated from the onset of the cue which was displayed for 106 ms; hence, the corresponding SOAs for the trials shown here are 412 and 1412 ms.

Table 1. Summary of target present trials per cueing condition and mean RTs.

<table>
<thead>
<tr>
<th>Spatiotemporal Probability</th>
<th>Temporal cue</th>
<th>Spatial cue</th>
<th>No. of trials</th>
<th>Short SOA</th>
<th>Long SOA</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valid</td>
<td>Valid</td>
<td>Valid</td>
<td>162</td>
<td>288.53 (3.88)</td>
<td>316.39 (3.83)</td>
<td>302.46 (3.59)</td>
</tr>
<tr>
<td>Valid</td>
<td>Valid</td>
<td>Invalid</td>
<td>54</td>
<td>293.61 (4.05)</td>
<td>323.31 (4.18)</td>
<td>308.46 (3.76)</td>
</tr>
<tr>
<td>Valid</td>
<td>Invalid</td>
<td>Valid</td>
<td>54</td>
<td>295.09 (4.05)</td>
<td>318.83 (4.23)</td>
<td>306.96 (3.79)</td>
</tr>
<tr>
<td>Valid</td>
<td>Invalid</td>
<td>Invalid</td>
<td>18</td>
<td>301.04 (5.01)</td>
<td>322.81 (4.60)</td>
<td>311.93 (4.19)</td>
</tr>
<tr>
<td>Invalid</td>
<td>Valid</td>
<td>Valid</td>
<td>54</td>
<td>308.72 (3.98)</td>
<td>322.10 (4.60)</td>
<td>315.41 (3.60)</td>
</tr>
<tr>
<td>Invalid</td>
<td>Valid</td>
<td>Invalid</td>
<td>18</td>
<td>310.12 (5.19)</td>
<td>330.60 (4.61)</td>
<td>320.36 (4.11)</td>
</tr>
<tr>
<td>Invalid</td>
<td>Invalid</td>
<td>Valid</td>
<td>18</td>
<td>311.99 (5.77)</td>
<td>318.00 (4.03)</td>
<td>314.99 (4.41)</td>
</tr>
<tr>
<td>Invalid</td>
<td>Invalid</td>
<td>Invalid</td>
<td>6</td>
<td>311.60 (5.80)</td>
<td>337.62 (6.61)</td>
<td>324.61 (4.91)</td>
</tr>
</tbody>
</table>

Notes: The number of trials per cueing condition is shown in the fourth column. Mean RTs (standard error of the mean in parentheses) are shown by cueing condition separately for short and long SOA trials in the fifth and sixth columns and averaged in the seventh column. Note that the number of trials per cueing condition is equally divided between short and long SOAs. SOA: Stimulus onset asynchrony between the trial-variant cues and the target.
variant temporal cue (valid, invalid). Hit rate was higher for short (mean = 98.98%) rather than long SOAs (mean = 95.82%), as evidenced in a main effect of SOA, \(F(1,71) = 66.968, p < .001, d_{rm} = 1.061\). Hit rates were also higher when temporal cues were valid (mean = 97.74%) rather than invalid (mean = 97.06%), as evidenced in a main effect of temporal cue validity, \(F(1,71) = 4.500, p = .037, d_{rm} = 0.254\). An interaction between SOA and temporal cue validity was observed, \(F(1,71) = 6.883, p = .011, \eta_p^2 = .088\); see Figure 4. Probing this interaction revealed that on short SOA trials, temporal cue validity did not affect hit rate, \(F(1,71) = 0.663, p = .418\), whereas on long SOA trials, hit rate was higher following a valid temporal cue (mean = 96.61%) than an invalid temporal cue (mean = 95.04%), \(F(1,71) = 6.728, p = .012, d_{rm} = 0.341\). A significant three-way interaction was also found among spatiotemporal probability validity, temporal cue validity, and spatial cue validity \(F(1,71) = 6.278, p = .015, \eta_p^2 = .081\).\(^2\) Main effects of the trial-invariant spatiotemporal probability \(F(1,71) = 1.089, p = .300\) and spatial cue validity \(F(1,71) = 0.848, p = .360\) failed to reach significance.

**Detection reaction times**

Detection RTs were analysed with a repeated measures ANOVA with the same four factors as in the hit rate analysis. This analysis revealed significant main effects of SOA (faster responses on short (mean = 302.59 ms) rather than long (mean = 323.71 ms) SOA trials; \(F(1,71) = 70.239, p < .001, d_{rm} = -0.656\), the validity of the trial-invariant spatiotemporal probability (faster responses on valid (mean = 307.45 ms) than invalid (mean = 316.24 ms) trials; \(F(1,71) = 6.883, p < .001, d_{rm} = -0.368\), and the validity of the trial-variant spatial cue (faster responses on valid (mean = 309.96 ms) than invalid (mean = 318.84 ms) trials; \(F(1,71) = 11.428, p = .001, d_{rm} = -0.204\). The effect of temporal cue validity failed to reach significance in the overall ANOVA on RTs \(F(1,71) = 3.727, p = .058\).

A significant interaction was found between SOA and the validity of the trial-variant spatiotemporal probability \(F(1,71) = 5.109, p = .027, \eta_p^2 = 0.067\), the spatiotemporal probability validity effect was larger on short than long SOA trials. A significant interaction between SOA and trial-variant spatial cue validity was also observed \(F(1,71) = 6.502, p = .013, \eta_p^2 = .084\). Spatial cueing effects were larger on long than short SOA trials. These interactions were subsumed by a significant three-way interaction between SOA, the validity of the spatiotemporal probability, and the validity of the spatial cue \(F(1,71) = 6.746, p = .011, \eta_p^2 = .087\). As can be seen in Figure 5, when the trial-invariant spatiotemporal probability was valid, significant trial-variant spatial cueing effects were observed at both short, \(F(1,71) = 6.160, p = .015, d_{rm} = -0.162, \) and long SOAs, \(F(1,71) = 5.835, p = .018, d_{rm} = -0.160, \) and these factors did not interact, \(F(1,71) = 0.001, p = .980\). But on trials on which the spatiotemporal probability was invalid, spatial cueing effects were significant at long SOAs, \(F(1,71) = 14.740, p < .001, d_{rm} = -0.371, \) but not at short SOAs, \(F(1,71) = 0.204, p = .884, \) resulting in a significant interaction, \(F(1,71) = 8.789, p = .004, \eta_p^2 = .110\).

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**Figure 4.** Temporal cueing effects on hit rate for short and long SOA trials. * \(p < .05\).

**Figure 5.** Detection RTs by SOA, spatiotemporal probability validity, and spatial cue validity. Error bars represent standard error of the mean. * \(p < .05\), ** \(p < .01\), *** \(p < .001\).
On short SOA trials, the cost of trial-invariant spatiotemporal probability being invalid on detection RTs is large, and no effects of a valid trial-variant spatial cue were observed. These results show that both trial-invariant spatiotemporal probability and trial-variant spatial cues conveyed by combined cues are used at both short and long SOAs.

Interim discussion

The current study aimed to assess how visual attention is voluntarily allocated within space and time in response to trial-variant spatial and temporal cues while trial-invariant spatiotemporal probability was operative. A combined spatial–temporal cueing procedure adapted from Weinbach et al. (2015) was used to present the trial-variant cues, while trial-invariant spatiotemporal probability knowledge was present across trials (participants were instructed and practised with both trial-variant and trial-invariant cues before the experimental trials). The spatiotemporal probability did not predict a target location or cue-to-target SOA; rather, it predicted that the target was likely to appear in one location at one of the possible times (a short or a long SOA between a combined cue conveying the trial-variant cues and the target) and in the other location at the other possible time. Therefore, trial-invariant spatiotemporal probability neither contradicted nor supported the trial-variant spatial and temporal predictions. We were interested in whether participants satisfied by using only their knowledge of the spatiotemporal probability or whether it was prioritized over the trial-variant cues. The results indicate that participants can make use of all three of the sources of information in service of completing the task and do not satsifice by only using their knowledge of the spatiotemporal probability.

Trial-invariant spatiotemporal probability validity effects were evident in RTs in both short and long SOA conditions. Participants appeared to prioritize trial-invariant spatiotemporal probability, which had the largest effect and was consistently found across trial types. Nevertheless, our results show that participants did not simply satsifice by only using spatiotemporal probability. Effects of both the spatial and temporal trial-variant cues were evident as well. RTs showed cueing effects of the trial-variant spatial cue on long SOA trials and on short SOA trials when trial-invariant spatiotemporal probability was valid; hit rates revealed a significant cueing effect of the trial-variant temporal cue on long SOA trials.

Spatial cueing effects were found in detection RTs on long SOA trials both when spatiotemporal probability knowledge was valid and when it was invalid. Spatial cueing effects were evident on short SOA trials only when spatiotemporal probability knowledge was valid, however. Thus, we observed a synergistic benefit of the trial-variant spatial cue when it predicted the target would appear in the location associated probabilistically with the short SOA via the given spatiotemporal probability (resulting in the fastest RTs). Neither a benefit nor interference was observed when the trial-variant spatial cue predicted the target would appear in the location associated with the long SOA given spatiotemporal probability, but the target appeared after a short SOA. That the trial-variant spatial cueing effect was observed only when the spatiotemporal probability was valid suggests that it might be difficult to instantiate the differing spatial predictions from both the trial-variant spatial cue and spatiotemporal probability in such a short time window, such that the former was deprioritized. (In future research, it may be interesting to increase the short SOA duration to differentiate between a cue prioritization account of this pattern and an account involving potential temporal limitations of incorporating differing predictions from different sources of information.) Alternatively, it is possible that participants’ RTs on short SOA trials where the spatiotemporal probability was invalid were slowed to the degree that that additional invalidity of the spatial cue would not further slow RTs.3 Although the trial-variant spatial cue appears to have been deprioritized under some conditions, effects of the spatial cue were still evident under other conditions, thereby demonstrating that attention can be allocated in space flexibly and adaptively by at least some of the participants at least some of the time (see “Post-hoc analysis” below).

A temporal cueing effect was observed in hit rates only and only on long SOA trials; participants were less likely to detect the target on long SOA trials when the temporal cue predicted that the target would appear after a short rather than a long SOA. This was surprising as the target detection task is relatively easy. Hit rates were high, and differences in hit rate were not expected based on previous research by
Weinbach et al. (2015), who concluded that temporal cues are not used when the target appears after a long SOA. However, our results revealed the effects of the temporal cue on long SOA trials under conditions involving three different sources of information in different modalities (space, time) and types (trial-invariant, trial-invariant).

One open question is why temporal cueing effects were not observed in detection RTs as has been found previously (e.g., Correa et al., 2004; Coull & Nobre, 1998; Lawrence & Klein, 2013; Weinbach et al., 2015). One possibility is that the RTs on short SOA trials where temporal cueing effects are typically found were quite fast (288–312 ms, see Table 1); Weinbach et al. observed longer RTs (approximately 320–345 ms) on short SOA trials in a similar task with approximately the same number of trials. Perhaps RTs in the current study were too fast for temporal cueing effects to emerge, at least in the overall analysis (see post-hoc analysis below).

It is also important to consider the role that explicit knowledge of the trial-invariant spatiotemporal probability played in these results. During practice trials, participants were told that the trial-variant spatial and temporal cues and trial-invariant spatiotemporal probability predictor were accurate on 75% of trials containing a target. The participants in Geng and Behrmann’s (2005) study extracted spatial probability over trials; they did not receive explicit instructions. Geng and Behrmann interpreted their spatial probability effect as due to implicit learning over the course of a block of trials. It is reasonable to assume that participants in the current study voluntarily and consciously incorporated the spatiotemporal probability knowledge into their orienting strategy. It will be interesting for future research to test whether implicit and explicit knowledge of trial-invariant spatiotemporal probability have the same influence and interact in a similar fashion with trial-variant cues in two modalities.

**Post-hoc analysis**

It has been theorized that the use of trial-variant symbolic cues may depend upon the relative behavioural benefit of the predictions compared to the costs of decoding the cues (Pauszek & Gibson, 2016, 2018). In support of this Least Costs Hypothesis (LCH), Pauszek and Gibson (2016) showed that participants rely on trial-variant symbolic cues less throughout an experiment as they become more accustomed to the task. In the current task, the trial-variant cues are colour and shape, which do not have an obvious mapping to space and time and may be considered difficult to decode (i.e., compared to a symbolic spatial arrow used by Pauszek & Gibson, 2018; experiments 2–4). As the use and prioritization of the cues is of central interest to the current study, we conducted a post hoc block analysis of the detection RT results to probe whether the use of the trial-variant cues varied throughout the experiment.

**Block analyses**

We conducted a linear trend analysis to examine whether cueing effects on detection RTs from the various sources of information varied across the three blocks of the current experiment. Significant linear trends would indicate a difference in magnitude of cueing effects over the course of the three blocks of the experiment; such a finding would indicate that participants responded to the target differently in response to the different sources of information over time. Our experiment was not designed to investigate block effects; hence, we did not enter block into the original ANOVAs. Moreover, with three concurrent cues, each with 75% validity, it was difficult to obtain precise estimates of the condition means within a single block (see Table 1 where the total trials per condition are shown). For instance, there was only one trial per block per SOA condition on which all three cues were invalid, which prevented a comprehensive block analysis with all cues considered concurrently. Accordingly, in the post-hoc analysis we took a conservative approach of testing only the main effects of the validity of each cue for linear trends over blocks. We also analysed short and long SOA trials separately. The trial-variant spatial cue and trial-invariant spatiotemporal probability knowledge interacted with SOA in the detection RT results. Because the spatial cue and the spatiotemporal probability knowledge interacted, the linear trends for these two cues were tested together. In the overall analysis, the trial-variant temporal cue did not result in any cueing effects in detection RTs (faster RTs on valid and invalid trials) and did not interact with the other cues. However, given that previous research has shown that temporal cues are
more likely to result in cueing effects on short SOA trials (e.g., Weinbach et al., 2015), trial-variant temporal cues were also entered into this post hoc analysis separated into short and long SOAs. Tests for linear trends in the validity of the temporal cues were conducted separately.

Performance across blocks can be seen in Figure 6. We found no evidence that trial-variant temporal cue effects varied across experimental blocks: no significant linear trend of temporal cue validity over blocks was observed at either short, $F(1,71) = 0.525$, $p = .471$, or long SOAs, $F(1,71) = 0.046$, $p = .832$. On short SOA trials, the validity effects of the spatiotemporal probability (which does not require any decoding during the trial) increased over blocks whereas the cueing effects of the trial-variant spatial cue (which required decoding the combined cue shown before each trial) decreased. This was evident in a significant interaction between the linear trends for the spatial cue and the spatiotemporal probability knowledge across blocks, $F(1,71) = 13.085$, $p = .001$, $\eta^2_p = .156$. This interaction was characterized by a significant negative trend for spatiotemporal probability validity (indicating that the effects increased over blocks as evidenced by an increasingly negative valid RT - invalid RT difference on invalid trials), $F(1,71) = 9.600$, $p = .003$, $\eta^2_p = .119$, and a significant positive linear trend for trial-variant spatial cue validity (indicating that cueing effects decreased over blocks, as evidenced by an increasingly positive valid RT - invalid RT difference on invalid trials), $F(1,71) = 4.290$, $p = .042$, $\eta^2_p = .057$. On long SOA trials, neither the trial-variant spatial cue, $F(1,71) = 0.245$, $p = .622$, nor trial-invariant spatiotemporal probability knowledge, $F(1,71) = 2.047$, $p = .157$, showed linear trends across blocks. Thus, this post hoc analysis showed that on short SOA trials, participants increasingly prioritized trial-invariant spatiotemporal probability over the trial-variant spatial cue across the blocks of the experiment.

Cueing effects for each cue within each block at each SOA was also tested for significance. Due to concerns about the number of statistical tests, cueing effects within each block and SOA were tested non-parametrically using a Monte Carlo permutation resampling simulation to approximate exact null distributions to which the observed cueing effects could be compared. For the Monte Carlo simulation, trial condition labels were shuffled for each participant within each block and SOA. This resampling procedure was repeated 10,000 times to approximate the null distribution for each cue in each block for each SOA. Cueing effects for each cue were computed on the resampled data. Observed effects were then compared to the ordered null distribution and two-tailed
Discussion

From these post-hoc analyses, it is apparent that the use of cues varies throughout the experiment. The linear trends analysis shows that for short SOA trials, the trial-invariant spatiotemporal probability was used increasingly over successive blocks and the trial-variant spatial cue was used less over successive blocks. We interpret this finding as evidence of gradually prioritizing the trial-invariant spatiotemporal probability over the trial-variant spatial cue, at least when the SOA was short. The post hoc analysis also indicated that small temporal cueing effects were present on short SOA trials in blocks 1 and 2. This finding indicates that the cueing effects of the trial-variant temporal cue in blocks 1 and 2 on short SOA trials were too small for a significant main effect of temporal cue to emerge in the overall analysis of detection RTs. The block analyses also revealed that by block 3, cueing effects of the trial-variant spatial and temporal cues were no longer discernable on either short or long SOA trials, although the validity effect from the trial-invariant spatiotemporal probability knowledge was still evident on short SOAs.

These findings are in accordance with LCH (Pauszek & Gibson, 2016, 2018) as the cues that required decoding online (during the trial) appear to be used less over time across the experiment. On long SOA trials, it appears that participants favour an unguided search strategy by block 3 rather than using any of the cues. On short SOA trials, by block 3, participants favoured the trial-invariant spatiotemporal probability knowledge; this serves as evidence that participants are choosing to satsisfice by allocating attention purely on the trial-invariant cue on short SOA trials in block 3. These findings suggest that, at least on short SOA trials, cues that do not require decoding online are prioritized. However, participants do not fully satsisfice in block 3 by using only the trial invariant spatiotemporal cue, as they do not exhibit stronger spatiotemporal validity effects in the long SOA over the course of the experiment. Participants seem to be optimizing the costs and benefits of the different cues throughout the experiment.

Why was trial-invariant spatiotemporal probability increasingly prioritized over the trial-variant spatial cue in short SOA trials as the experiment progressed rather than from the beginning of the experiment? One possibility is that participants never experienced a combination of the different sources of information during practice where each cue was trained separately. Perhaps experience with the combination of cues over the experiment was necessary in order for participants to prioritize the trial-invariant spatiotemporal probability knowledge, at least in the short SOA trials. Alternatively, it is possible that participants were fatigued or disinterested by the end of the experiment: Post-hoc tests revealed that the trial-variant cueing effects for the temporal and spatial cue were altogether absent by block 3. The task of detecting the target was easy but keeping track of and integrating three different cues in order to orient attention in time and space may have been taxing. The only source of information being used by the end of the experiment was the location associated with the short SOA by the spatio-temporal probability.

Conclusion

If we are to understand how attention is allocated in a complex multimodal world, it is important to investigate how different sources of information are utilized and prioritized. We investigated whether cues in
different modalities (space and time) and with different characteristics (trial-variant and trial-invariant) could be incorporated in the orienting of voluntary visual attention. We found evidence that the attentional system is impressively flexible in incorporating these disparate sources of information, and indeed the different cues were not used uniformly across the experiment. The results suggest that spatiotemporal probability knowledge (which does not require trial-by-trial decoding) was increasingly prioritized and the trial-variant spatial cue was deprioritized as the experiment progressed (at least on short SOA trials). The post hoc analysis also revealed small temporal cueing effects on short SOA trials. The post hoc analysis also revealed small temporal cueing effects in RTs on short SOA trials in blocks 1 and 2. No significant cueing effects of the trial-variant cues were observed by block 3, the final block, of the experiment.

Over the years, the possibility has been raised that participants might satisfice by using a subset of cues or by employing unguided search (e.g., Egeth et al., 2010; Pauszek & Gibson, 2016). Whereas there is evidence that participants may use unguided search late in an experiment, in the present experiment undergraduate volunteer participants flexibly used these cues in different modalities (time and space) and with different characteristics (trial-variant versus trial invariant) throughout much of the experiment and never resorted completely to unguided search despite the fact that there were no performance-based rewards to increase their motivation. This indicates that attentional orienting can be strategic in flexibly using and prioritizing different sources of information.

Notes

1. Some of these participants were invited to volunteer based on their responses on an individual differences survey administered at the beginning of the semester that indicated that they may vary in how they conceptualize space and time in social or cultural settings. Examining individual differences is beyond the scope of the current paper. In the future individual differences may be analyzed as they relate to time-space distanciation (Keefer et al., 2019) and whether they predict how participants use temporal and spatial information in the orienting of attention.

2. The three-way interaction was obtained because valid -invalid differences in hit rate for trial-variant spatial cues trials were positive under some combinations of trial-variant temporal cues and the trial-invariant spatiotemporal probability knowledge and negative under others, but hit rate was high in all of these conditions (0.958–0.979) and none of these differences was significant.

3. It is important to note that spatial cueing effects were present on long SOA trials with slower RTs, but functional ceiling may vary with SOA.

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