Do you have to look where you go?
Gaze behaviour during spatial decision making

Jan M. Wiener (jwiener@bournemouth.ac.uk)
Department of Psychology, Bournemouth University
Poole, BH12 5BB, UK

Olivier De Condappa (odcondappa@bournemouth.ac.uk)
Department of Psychology, Bournemouth University
Poole, BH12 5BB, UK

Christoph Hölscher (hoelsch@cognition.uni-freiburg.de)
Center for Cognitive Science, University of Freiburg,
Friedrichstraße 50, 79098 Freiburg, Germany

Abstract

In this paper we present an eye-tracking experiment investigating the relation of gaze behavior, spatial decision making and route learning strategies. In the training phase participants were passively transported along a route consisting of 18 intersections. Each intersection featured two landmarks, some of which were unique while others were non-unique. In the test phase participants were presented with static images of the intersections and had to indicate the direction in which the original route proceeded. We report systematic gaze bias towards the eventually chosen movement direction. Furthermore, we demonstrate that by dissociating the decision relevant information from the location to which a response is directed, these gaze bias effects can be systematically modulated. The results provide novel insights into how attentional processes mediate performance in a route memory task and are related to current theories of visual decision making.

Keywords: Spatial cognition, route learning, eye-tracking, gaze bias, decision making

Introduction

The relation between decision making and gaze behavior has primarily been studied in a non-spatial context. Shimojo and colleagues (2003), for example, demonstrated that when asked to choose the most attractive face, participants display a gaze bias towards the eventually chosen face in the last second before they report their decision (Shimojo, Simion, Shimojo, & Scheier,, 2003). Glaholt & Reingold (2009) have recently demonstrated that such gaze bias effects are not specific to preference choices but constitute a more general phenomenon of visual decision making. The *gaze-cascade model* provides a theoretical framework for gaze bias effects. It states that gaze does not merely reflect preferences, but is involved in the formation of preference in that gaze orientation towards a stimulus and preference for that stimulus are linked in a positive feedback loop (Shimojo et al., 2003; Simion & Shimojo, 2006).

In recent studies, Wiener, Büchner, Hölscher, and Konieczny (2009, under review) reported similar gaze bias effects in the context of wayfinding. In these studies, participants were presented with static screenshots of decision points in complex architectural environments. In one experiment, the participants' task was to decide between path options in order to find an object hidden in the environment. In a second experiment, participants were first informed about which path option to follow as if following a guided route. They were then presented with the same images and had to indicate which path option they chose during initial exposure. Both experiments revealed a robust gaze bias towards the eventually chosen path options. Results from these studies provide first evidence for gaze bias effects in the context of navigation and wayfinding. Furthermore, the fact that the temporal dynamic of the gaze bias was influenced by the wayfinding task (Wiener et al., under review) suggests that the analysis of gaze behavior is a promising mean to investigate higher-level cognitive functions and processes involved in wayfinding behavior.

The current study aims to further investigate the relationship between decision making and gaze bias effects in a spatial context. Specifically, we are interested in developing a better understanding of how the positioning of decision-relevant information and the placement of the actual choices relate. To the best of our knowledge, in the studies investigating gaze bias effects so far, the information relevant for the decision and the choice options coincided spatially. For example, when deciding which of two faces depicted on images is more attractive, the eventually chosen picture holds information relevant for that choice (e.g. Shimojo et al., 2003). Using a route-learning paradigm we spatially dissociated the information relevant for the movement decision from the actual path option that has to be chosen. The following scenario best illustrates this: Imagine learning a route through a novel environment. At a particular intersection along the route you may retrieve the required movement response as: "Turn right at the yellow house". Depending on whether the yellow house – i.e. the landmark that allows you to recognize the particular intersection – is located at the right or left side of the intersection, the decision relevant information either coincides with the required movement response or is spatially dissociated from the required movement response. This only holds true if the intersection is approached from the same direction as during initial exposure. The question of how people integrate information about the local configuration of landmarks at an intersection with route knowledge – which would allow them to also continue a route when approaching a place from a different direction – is beyond the scope of the current study.

Systematically manipulating whether or not the decision-relevant information coincides with the required response will allow us to investigate in more detail whether gaze bias effects reflect the intake of relevant information and the decision making process itself, or whether gaze bias effects are also related to the process of reporting the outcome of a decision. In addition, this manipulation will allow us to investigate the cognitive strategies participants employ during route learning.

Predictions

If gaze bias effects reflect information intake and the decision making process as suggested by the cascade model (Shimojo et al. 2003), the gaze bias should be directed towards the decision relevant information, independent of whether or not this information spatially coincides with the option that has to be chosen.

However, if gaze bias also reflects the process of reporting a decision, a gaze bias towards the eventually chosen path option is expected, independent of whether or not this options spatially coincides with the decision–relevant information.

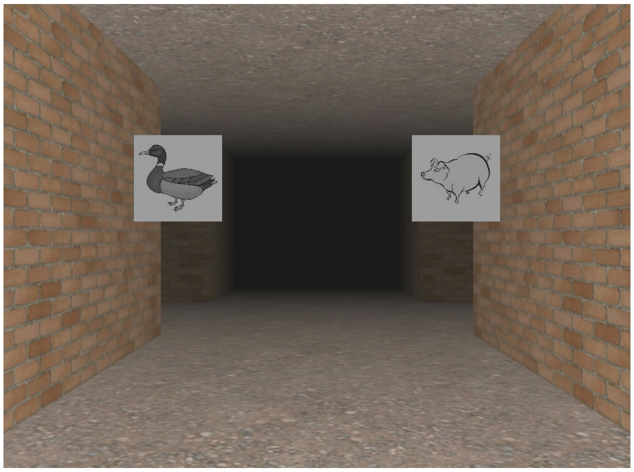

Figure 1: intersection in the virtual environment with 2 landmarks.

Methods

Virtual Environment

Using virtual environment technology (Vizard 3.0 by WorldViz) we created a route consisting of 18 intersections that were connected by corridors 30 m in length. Each intersection could be identified by landmarks – i.e. images of different animals – located at either side of the intersection (see Figure 1). During the experiment, participants were passively transported along a route at 3m/sec; at each intersection they experienced either a left turn or a right turn and a total of 9 left turns and 9 right turns.

The 18 intersections could be subdivided into two classes: six of the intersections featured two unique landmarks – i.e. landmarks only present once in the entire environment (UU intersections); 12 of the intersections contained a unique landmark and a non-unique landmark (UX intersections). The non-unique landmark was always the same image of a pig. The UX intersections were further subdivided into six UX+ and six UX- intersections. At UX+ intersections participants experienced a turn in direction of the unique animal, at UX- intersections participants experienced a turn in direction of the non-unique animal (for a summary of the types of intersections, see Table 1). For the purpose of this study it is important to note that distinguishing between different UX intersections requires attending to the unique landmark. This is true for both UX+ and UX- intersections.

Table 1: Types of intersections

Type	Landmarks	Turn-Direction
6 x UU	2 unique	Towards unique
6 x UX+	1 unique; 1 non-unique	Towards unique
6 x UX-	1 unique; 1 non-unique	Towards non-unique

Participants

17 participants (12 women) aged 18 to 28 (*M* = 19.53, *SD* = 2.35) took part in the experiment. They were mainly students from Bournemouth University and received course credit compensation for their participation.

Procedure

The experiment consisted of six *experimental blocks*; each block consisted of a training phase and a test phase.

In the *training phase*, participants were passively transported along the entire route with a movement speed of 3m/sec. They initiated the training phase by pressing the SPACE bar and were instructed to learn the route.

In the *test phase*, participants were presented with screenshots of all 18 intersections in random order. They were informed about the random presentation order and their task was to indicate the direction in which the original route proceeded as quickly and as accurately as possible by pressing either the left or the right arrow key. Performance (correct choices), response time and gaze behaviour was measured.

Experimental Setup

The stimuli were displayed at a resolution of 1024 x 768 pixels on a 20“ CRT monitor. The screen refresh rate was 100 Hz. Participants sat in front of the monitor at a distance of ~60 cm, such that the resulting visual angle of the monitor was 37 degrees (horizontally) x 28 degrees (vertically). Eye movements were recorded using a SR Research Ltd. EyeLink 1000 eye tracker sampling pupil position at 500 Hz. The participant’s head was constrained using a chin rest. The eye-tracker was calibrated using a 9-point grid. A second 9-point grid was used to calculate the accuracy of the calibration. Fixations were defined using the detection algorithm supplied by SR Research.

Analysis Gaze Behavior

For each stimulus two interest areas equally dividing the image in a left part and a right part were defined. Fixations were assigned to the different interest areas. For the time course analyses – i.e. the analyses of the likelihood that the eventually chosen part of the stimulus was inspected – we removed all fixations towards the central interest area, retaining only fixations towards the two path options.

Results

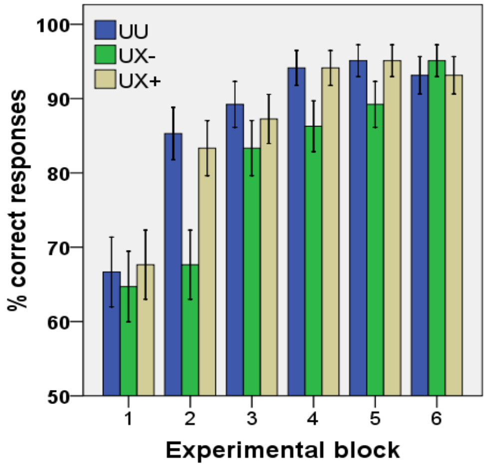

Figure 2: Performance (correct responses) increases over the experimental blocks (error bars represent SEM).

Behavior

Performance. On average participants chose the correct direction in 85% of the trials. An ANOVA (factors: experimental block [1-6] & type of intersection [UU, UX+, UX-]) revealed a significant main effect of experimental block (*F*(5,80)=22.20, *p*<.001, partial – η^2 = .58), but no main effect of the type of intersection (*F*(2,32)=1.79, *p*=.18, partial – η^2 = .10), or a significant interaction (*F*(10,160)=1.17, *p*=.31, see Figure 2).

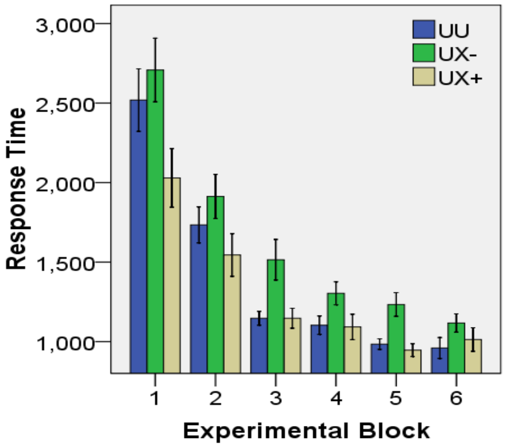

Figure 3: Response time decreases from experimental block to experimental block (error bars represent SEM).

Mean Response Time. Only trials in which participants responded correctly entered this response time analysis. An ANOVA (factors: experimental block [1-6] & type of intersection [UU, UX+, UX-]) revealed significant main effects of both experimental block (*F*(5, 85.30)=34.77, *p*<.001, partial – η^2 = .67) and type of intersection (*F*(2, 36.35)=9.00, *p*<.001, partial – η^2 = .33), but no significant interaction (*p*=.44) on mean response times. Specifically, response time decreased over experimental trials. Most importantly, Bonferroni corrected pairwise comparisons revealed that response times for UX- trials was significantly longer (1619msec) than for UU (1422msec; *p*=.001) or UX+ trials (1312msec; *p*<.001), while response times for UU and UX+ trials did not differ (*p*=.10, see Figure 3).

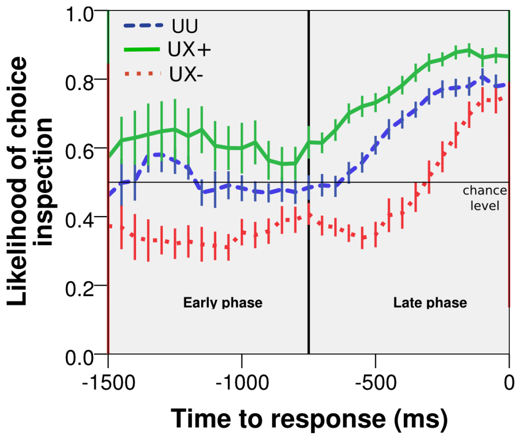

Figure 4: Likelihood that the eventually chosen part of the stimulus is inspected for all types of intersections (error bars represent SEM).

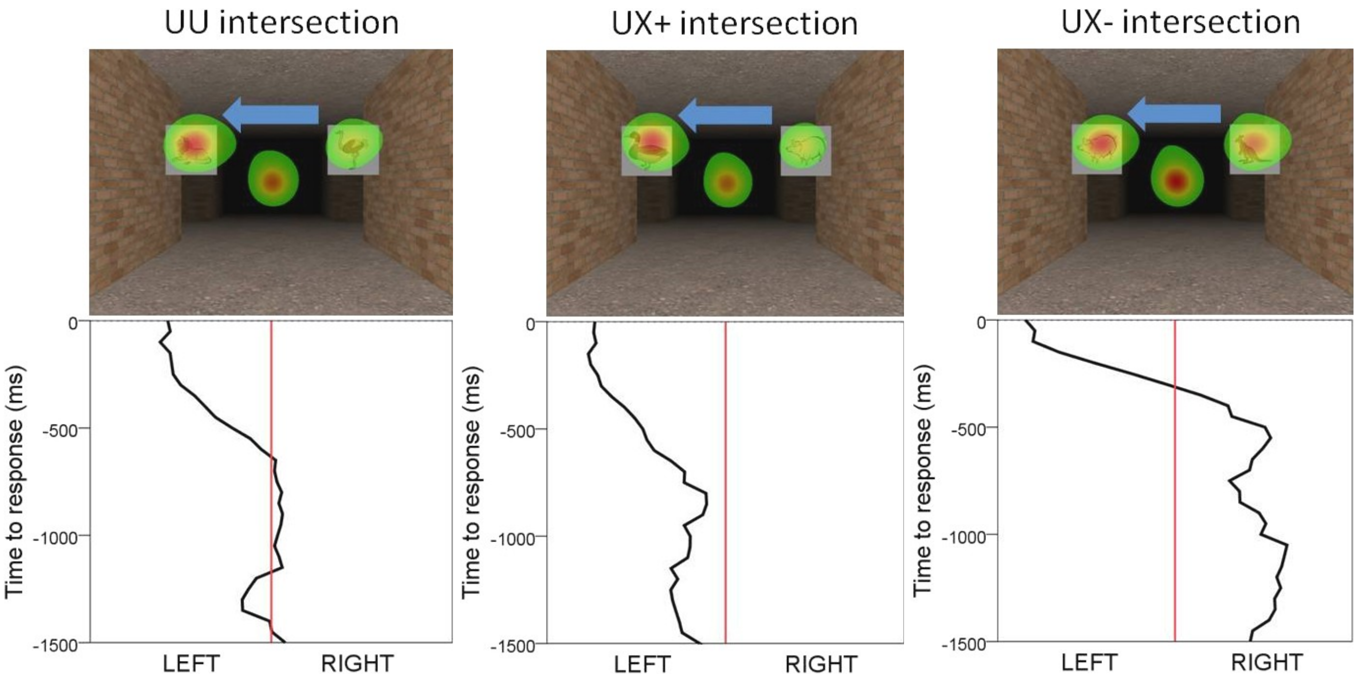

Figure 5: Upper panel: Example stimuli of the test phase with fixation patterns (heat maps); Movement direction is indicated by the arrow, superimposed on the images (not part of original stimulus); Left: UU intersection with 2 unique landmarks; Middle: UX+ intersection with the unique landmark on the left hand side (i.e. in movement direction); Right: UX- intersection with the non-unique landmark on the right hand side (i.e. opposite to movement direction; Lower panel: Gaze bias over time, from 1500msec before the decision was reported.

Eye-tracking

As seen in Figure 4, fixations during the test phase were primarily targeted at the signs displaying the animals. Most of the fixations towards the central area result from the 1500msec phase prior to the onset of the actual stimulus during which participants were required to attend to a fixation cross in the center of the screen.

Gaze Bias Analysis. In order to analyze systematic gaze bias effects, we synchronized the eye-tracking data between (correct) trials at the time when the decision was reported – i.e. when participants pressed either the left or right arrow key. Given that the average response time for the different types of intersections ranged between ~1300msec and 1600msec, the following analyses concentrated on the last 1500msec before the response was reported. This data was then split into 30 intervals each covering 50msec.

For each 50msec interval we calculated the likelihood that participants' gaze was directed towards the (eventually) chosen part of the stimulus. This value ranged from 0 to 1. The gaze bias analysis revealed systematic gaze bias effects. Specifically, for all types of intersections (UU, UX+, UX-) participants demonstrated a gaze bias in the movement direction, reaching its maximum around the time when the decision was reported (see Figure 4).

An ANOVA (factors: time to report decision [50msec intervals from 1500msec before the response until the response] & type of intersection [UU, UX+, UX-]) revealed significant main effects of both time to report decision (*F*(30, 479.1) = 28.52, *p* < .001 , partial – η^2 = .64) and type of intersection (*F*(2, 32.05) = 66.76, *p* < .001 , partial – η^2 = .81). The interaction did not reach statistical significance (*F*(60, 947) = 1.33, *p*=.053, partial – η^2 = .08). The overall gaze bias averaged over 1500msec was stronger at UX+ intersections (mean: .70) followed by UU (mean: .59) and UX- intersections (.43). Pairwise comparisons demonstrate significant differences between all three conditions (all comparisons *p*<.001).

A closer inspection of the gaze bias data (see Figure 4) suggests two distinct phases: In the early phase, there is little dynamic in the gaze bias. Only in the late phase does the likelihood that participants inspect the eventually chosen part of the stimulus change dramatically. We therefore split the data at -750msec and reanalyzed the early phase and the late phase independently.

Early phase (-1500msec – -750msec): An ANOVA (factors: time to report decision [-1500 – -750 msec] & type of intersection [UU, UX+, UX-]) revealed s significant main effect of the type of intersection (*F*(2,32.20)=22.24, *p*<.001, partial – η^2 = .58) but neither a main effect of time to report decision (*p*=.97) nor an interaction (*p*=.96). Specifically, the overall gaze was stronger at UX+ intersections (mean: .61) followed by UU (mean: .50) and UX- intersections (.34). Pairwise comparisons demonstrate significant differences between all three conditions (all comparisons p<.001).

Late phase (-750msec – 0msec): An ANOVA (factors: time to report decision [-750 – 0 msec] & type of intersection [UU, UX+, UX-]) revealed significant main effects of both time to report decision ($F(15, 240) = 96.40$, $p < .001$, partial – $\eta^2 = .86$) and type of intersection ($F(2, 32) = 79.84$, $p < .001$, partial – $\eta^2 = .83$), as well as a significant interaction ($F(30, 480) = 5.17$, $p<.001$, partial – $\eta^2 = .24$).

Separately analyzing the data for the early and late phase demonstrates a stable offset in the likelihood that the eventually chosen option is inspected between all the different types of intersections, but no changes in the temporal dynamics. Only in the late phase does the likelihood systematically increase and differences in the temporal dynamic are observed between conditions.

This is also apparent in Figure 5: At UU intersections, participants distribute their gaze evenly between the two sides of the image until ~800msec before reporting their decision. They then display what we refer to as a positive gaze bias – i.e. a gaze bias in direction of the eventually chosen side. At UX+ intersections, participants display a positive gaze in both the early phase and the late phase. At UX- intersections, in contrast, participants show a negative gaze bias during the early phase – i.e. they spend more time inspecting the part of the image that they do not choose, but that contains the distinctive information needed to identify the current location and thus the required movement choice. Only at the end of the late phase do participants display a positive gaze bias.

Discussion

In this study we investigated gaze bias effects in the context of spatial decision making. Participants were navigated along a route consisting of left or right turns along 18 intersections. Their task was to remember the route and to replicate the turns in a subsequent test phase in random order. Participants' gaze behavior was recorded while they decided which of two path options – left or right – corresponded to the training route. The different intersections could be identified by landmarks – i.e. by images of animals displayed on signs that were mounted to the left and right side of the intersection (see Figure 1). Each intersection featured two landmarks. Intersections of type UU featured two unique landmarks, while intersections of type UX+ and UX- always featured a unique and a non-unique landmark. Identifying a specific UX intersection therefore required attending to the unique landmark. UX+ and UX- intersections differed in the response required at these intersections. Movement was required in the direction of the unique landmark at UX+ intersections and in the direction of the non-unique landmark at UX- intersections.

The behavioral results clearly demonstrate that participants could learn the route successfully. In the test phase of the first experimental block participants already reached average performance levels of about 65% correct responses. In the test phase of the third experimental block performance was close to 90%, and above 90% thereafter. While performance increased over experimental blocks, response times decreased from around 2500msec in the first block to just over 1000msec in blocks five and six. However, in contrast to performance, response times differed significantly between types of intersections. Average response time was similar between UU and UX+ intersections but was ~200msec longer on UX- intersections. This difference in response time between intersections is not easily explained by the main theories of route learning. Route knowledge is often conceptualized as a series of recognition triggered responses (Trullier, Wiener, Berthoz, & Meyer, 1997) in which the recognition of a place – for example by recognizing a landmark or a snapshot – triggers a particular movement response such as 'turn left' (i.e. landmarks serve as associative cues).

Waller and Lippa (2007) have recently suggested another route learning strategy in which participants simply recall landmarks that are located in movement direction (beacon strategy). From a memory perspective this strategy requires no explicit learning of a potentially arbitrary association between a landmark and the action, as the movement direction can be derived from the landmark location. While this strategy could, in principle, be also applied in the current route-learning paradigm, it would fail at UX- intersections at which the landmark in movement direction is not unique to the intersection. We did, however, not find a difference in performance between the different types of intersections. It is conceivable that participants relied on the beacon strategy only in cases where that was a sufficiently safe strategy. The present study is not explicitly designed to test strategy shifts in the Waller and Lippa (2007) paradigm. Whether attentional shifts in the gaze behavior for UX- intersections can be tied to such differences in strategies remains an open issue for further studies.

A comparison of participants' gaze behavior at the different types of intersections provides a possible explanation for the observed difference in response times. Participants displayed a gaze bias in direction of the eventually chosen path option – a positive gaze bias – in the last few hundred milliseconds before reporting the response for all types of intersections. This was expected for UU and UX+ intersections as the landmark that was presented on the corresponding side of the intersection was unique, allowing participants to unambiguously identify the intersection along with the required movement response. At UX- intersections, however, the landmark in direction of movement is a non-unique landmark. In order to identify the intersection and retrieve the required movement response, participants had to inspect the landmark situated opposite the required movement direction. This is expressed in a negative gaze bias from 1500msec until ~400msec before responding (see Figure 4 and Figure 5). However, instead of responding while or immediately after picking up the decision-relevant information, participants shifted their gaze in the direction of movement. This suggests that they in fact had to look in direction of (intended) motion. The difference in response time would then simply reflect the process of shifting attention towards the intended movement direction before the response can be given. A number of earlier studies have reported anticipatory gaze behavior in the direction of motion (e.g. Grasso, Prevost, Ivanenko, & Berthoz, 1998; Land & Lee, 1994). In these studies, participants were actively moving through the environment and anticipatory gaze behavior is assumed to be involved in the control of locomotion or steering. In the test phase of our study, however, participants were not actually moving through the environment, they were inspecting static images. So from a perspective of rational analysis of behavior, the attentional shift was not strictly necessary. One might speculate that participants are so used to shifting their attention to the movement direction that they do this automatically, even if it takes additional time. The final attentional shift in UX- does provide the cognitive agent with an opportunity to double-check whether counter-evidence against the associated movement decision is present in the movement direction. Yet the current study does not include such negative cases, and furthermore such a double-check strategy is not found in the UX+ case either.

The observation is also clearly compatible with common coding approaches (e.g. Prinz 1997) which assert that perception and motor actions share core processes and representations. In that sense the final visual shift synchronizes the perceptual input with the anticipated movement direction. Further research is clearly needed to appropriately untangle the reasons for the shift in gaze at UX- intersections.

The results of this study also have implications for visual decision making on a more general level. As mentioned in the introduction, the *gaze-cascade model* for visual decision making states that an orienting bias – i.e. a gaze bias – effectively results in a preference decision for a particular choice based on a positive feedback loop involving exposure and preferential looking (Shimojo et al., 2003), even if the visual stimulus is removed during decision making (Simion & Shimojo, 2007). However, a first analysis of the gaze behavior at UX- intersections in this study demonstrates both negative and positive gaze bias effects. A relatively steady negative bias – directed towards the decision-relevant unique landmark – is observed from 1500msec until ~500msec before the decision. Only afterwards do participants display a positive gaze bias. In contrast, participants display a positive gaze bias during the entire 1500msec period at UX+ intersections. Moreover, the positive gaze bias at UX- intersections builds up much quicker than at UU or UX+ intersections. These results demonstrate that dissociating the decision relevant information from the location to which a response is directed can systematically modulate gaze bias effects.

Conclusion

To summarize, the present study provides new insights into how attentional processes mediate performance in a route memory task. Reaction times for decisions increased when the relevant stimulus information mismatched the required movement direction. Gaze analysis suggests that the reaction time can be broken down into separate processes of stimulus processing and action preparation that require an attention shift in the spatially mismatched condition. While this provides a new piece in the puzzle of understanding landmark processing in route navigation, it also suggests that spatially dissociating relevant stimulus information and the required overt reaction can be used to further scrutinize gaze bias effects and the gaze-cascade model of Shimojo and colleagues (2003).

References

Glaholt, M. G., & Reingold, E. M. (2009). The time course of gaze bias in visual decision tasks. *Visual Cognition*, *17*(8), 1228 – 1243.

Grasso, R., Prevost, P., Ivanenko, Y., & Berthoz, A. (1998). Eye-head coordination for the steering of locomotion in humans: an anticipatory synergy. *Neuroscience Letters*, *253*, 115–118.

Land, M., & Lee, D. (1994). Where we look when we steer. *Nature*, *369*(6483), 742-744.

Montello, D. R. (2001). Spatial cognition. In *International encyclopedia of the social & behavioral sciences* (p. 14771-14775). Oxford: Pergamon Press.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, *9*, 129-154.

Simion, C., & Shimojo, S. (2006). Early interactions between orienting, visual sampling and decision making in facial preference. *Vision Research*., *46*, 3331–3335.

Simion, C., & Shimojo, S. (2007). Interrupting the cascade: Orienting contributed to decision making even im the absence of visual stimulation. *Perception & Psychophysics*, *69*(4), 591-595.

Shimojo, S., Simion, C., Shimojo, E., & Scheier, C. (2003). Gaze bias both reflects and influences preference. *Nature Neuroscience*, *6*, 1317–1322.

Trullier, O., Wiener, S. I., Berthoz, A., & Meyer, J. (1997). Biologically based artificial navigation systems: Review and Prospects. *Progress in Neurobiology*, *51*, 483-544.

Waller, D. & Lippa, Y. (2007). Landmarks as beacons and associative cues: their role in route learning. *Memory & Cognition*, *35*, 910-924.

Wiener, J.M., Büchner, S., Hölscher, C., & Konieczny, L. (under review). Space Perception, Spatial Decision Making, and Wayfinding

Wiener, J.M., Büchner, S., Hölscher, C., & Konieczny, L. (2009). How the Geometry of Space controls Visual Attention during Spatial Decision Making. *Full Paper and Oral Presentation at CogSci*