Environmental motion presented ahead of self-motion modulates the heading direction estimation

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Abstract:

The ability of a moving observer to accurately perceive their heading direction is essential for maintaining balance and effective locomotion. Previous research has identified mechanisms for integrating multisensory signals presented simultaneously, but it remains unclear how observers integrate visual signals collected before and during their own movement to perceive their heading direction. Here we explore the impact of environmental motion presented ahead of self-motion on heading perception. Human observers sat on a platform, viewed visual motion stimuli, and then indicated the direction of their movement after the platform had moved. Our results demonstrate that environmental motion presented before the observer's movement significantly influenced their self-motion perception. We explain this result using an optimal causal inference model that takes into account the causal relationship between visual signals generated before and during observer movement. Overall, our study highlights the crucial role of environmental motion presented before self-motion in multisensory integration and self-motion perception.

Keywords: Bayesian observer model; causal inference; multisensory integration; self-motion; perceptual bias

Introduction

Heading perception is crucial for spatial navigation and maintaining balance. Accurate heading perception becomes especially challenging when the surrounding environment is also in motion, as visual signals collected by the observer may be originating from their own motion or from the motion of the environment (Dokka et al., 2015; 2019; MacNeilage et al., 2012; Sasaki et al., 2017).

For example, consider an observer sitting on a bench watching a passing bus while she stands up. If the motion of the bus on her retina appears to be moving down and to the right while she is getting up, it could be because the observer is moving vertically upwards while the bus is moving to the right, or it could be that the bus is stationary, but the observer is standing up incorrectly and moving to the left. To solve this problem, temporal context needs to be considered. In the real world, buses do not suddenly appear on the road. The bus was probably already moving from left to right before the observer tried to stand up. Therefore, the observer could accurately perceive her heading direction by subtracting the previously presented motion of the bus from the visual signals collected during her rise.

Observers need to appropriately use the visual signals they collected before moving to perceive their heading direction. Numerous previous studies have revealed how observers integrate visual and vestibular signals while they are moving (Fetsch et al., 2009; 2012; Gu et al., 2008), but little is known about whether and how observers use the visual signals collected before they begin to move to estimate their heading direction, if the surrounding environment is already in motion before they start moving. Here, we test whether environmental motion presented ahead of self-motion modulates the heading perception.

Methods

We developed a psychophysical experiment that emulates the situation described in Introduction. Seven human observers each sat on a platform and passively moved for two seconds in one of ten directions from −45° to 45° relative to the vertical upward direction. Their task was to report their perceived heading direction (Fig. 1).

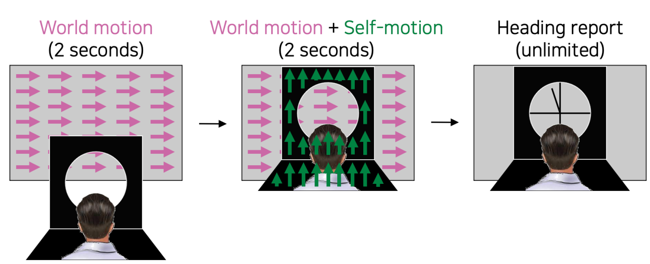

Figure 1: Sequence of events on a trial.

Importantly, visual motion stimuli moving either to the left or right were presented through a circular aperture on the screen, starting two seconds before platform motion and continuing until the end of platform motion (Fig. 1). We tested three different visual motion conditions in which the speed of visual motion presented during the platform motion was the same across conditions (i.e., either 0°/s, ±5°/s, or ±10°/s), while the speed of visual motion presented before the platform motion varied systematically. Specifically, in the acceleration condition, the visual motion speed was zero before the platform motion. In the constant condition, the visual motion speed remained constant before and during the platform motion. In the deceleration condition, the visual motion speed before the platform motion was twice as fast as the visual motion speed during the platform motion.

Results

Human Observer Figure 2A illustrates results of our study, along with three possible strategies that observers may employ. First, observers may rely solely on vestibular information, disregarding visual information entirely (i.e., vestibular strategy). Second, observers may rely solely on retinal motion during self-motion, assuming the world is stationary while they are moving (i.e., momentary vision strategy). Finally, observers may subtract the world motion before self-motion from the retinal motion during self-motion, assuming the world motion remains constant before and during the self-motion (i.e., contextual vision strategy).

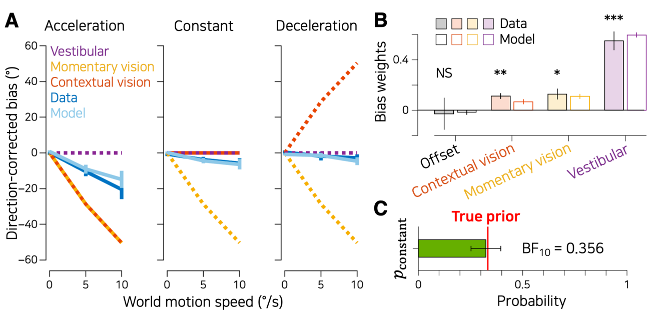

Figure 2: Experiment and modeling results.

The data from human observers is represented in dark blue in Figure 2A, and it is evident that the response bias varies significantly depending on the visual motion conditions. Our findings also demonstrate that observers did not rely exclusively on any of the three strategies. Instead, it appears that they utilized a combination of all three strategies, as evidenced by the significant coefficients of the linear regression analysis (Fig. 2B).

Model Observer To account for the observed pattern of data, we developed an optimal causal inference model that considers two plausible scenarios (Dokka et al., 2019; Körding et al., 2007). The first scenario assumes that the environmental motion is constant before and during the self-motion (i.e., $C = 1$), while the second scenario assumes that the environmental motion is independent before and during the self-motion (i.e., $C = 2$). The model observer combines two estimates, each based on a different scenario, weighted in proportion to their corresponding posterior probabilities:

$$\hat{S}_{\text{self}} = p(C = 1|x_{\text{vest}}, x_{\text{vis}}, x_{\text{vis0}})\hat{S}_{\text{self},C=1} + p(C = 2|x_{\text{vest}}, x_{\text{vis}}, x_{\text{vis0}})\hat{S}_{\text{self},C=2}$$

The estimates are:

$$\hat{S}_{\text{self},C} = \underset{S_{\text{self}}}{\operatorname{argmax}}\, p(S_{\text{self}}|x_{\text{vest}}, x_{\text{vis}}, x_{\text{vis0}}, C) = \frac{\frac{x_{\text{vest}}}{\sigma_{\text{vest}}^2} + \frac{\mu_{\text{K}}}{\sigma_{\text{K}}^2} + \frac{0}{\sigma_{\text{self}}^2}}{\frac{1}{\sigma_{\text{vest}}^2} + \frac{1}{\sigma_{\text{K}}^2} + \frac{1}{\sigma_{\text{self}}^2}}$$

where

$$\mu_{\text{K}} = \begin{cases} x_{\text{vis}} - \dfrac{\sigma_{\text{env}}^2}{\sigma_{\text{env}}^2 + \sigma_{\text{vis0}}^2} x_{\text{vis0}}, & C = 1 \\ x_{\text{vis}}, & C = 2 \end{cases}$$

$$\sigma_{\text{K}}^2 = \begin{cases} \sigma_{\text{vis}}^2 + \dfrac{\sigma_{\text{env}}^2 \sigma_{\text{vis0}}^2}{\sigma_{\text{env}}^2 + \sigma_{\text{vis0}}^2}, & C = 1 \\ \sigma_{\text{vis}}^2 + \sigma_{\text{env}}^2, & C = 2 \end{cases}$$

Both $\hat{S}_{\text{self},C=1}$ and $\hat{S}_{\text{self},C=2}$ are a combination of three sources of information: vestibular, visual, and prior information. The crucial distinction between them is that $\hat{S}_{\text{self},C=1}$ incorporates contextual visual information by subtracting visual motion before self-motion, x_{vis0}, from visual motion during self-motion, x_{vis}, whereas $\hat{S}_{\text{self},C=2}$ only includes momentary visual information that reflects visual motion during self-motion, x_{vis}.

Our causal inference model provides an excellent fit to the psychophysical data (Fig. 2A, light blue). We performed the same linear regression analysis as for human data. All three coefficients were significant, indicating that the model successfully captured the complex interplay of the different strategies (Fig. 2B). Lastly, the best-fitting value of a free parameter representing the prior belief that environmental motion would be constant before and during self-motion was consistent with the prior probability of the experiment (Fig. 2C).

Conclusions

Our findings show that environmental motion presented ahead of self-motion plays a key role in the causal inference of multisensory processing and has a profound effect on heading perception.

Acknowledgments

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