Into the unknown: head-based selection is less dependent on peripheral information than gaze-based selection in 360-degree virtual reality scenes

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Abstract

People naturally move both their head and eyes to attend to information. Yet, little is known about how the head and eyes coordinate in attentional selection due to the relative sparsity of past work that has simultaneously measured head and gaze behaviour. In the present study, participants were asked to view fully immersive 360-degree scenes using a virtual reality headset with built-in eye tracking. Participants viewed these scenes through a small moving window that was yoked either to their head or gaze movements. We found that limiting peripheral information via the head- or gaze-contingent windows affected head and gaze movements differently. Compared with free viewing, gaze-contingent viewing was more disruptive than head-contingent viewing, indicating that gaze-based selection is more reliant on peripheral information than head-based selection. These data dovetail with the nested effectors hypothesis, which proposes that people prefer to use their head for exploration into non-visible space while using their eyes to exploit visible or semi-visible areas of space. This suggests that real-world orienting may be more head-based than previously thought. Our work also highlights the utility, ecological validity, and future potential of unconstrained head and eye tracking in virtual reality.

Introduction

Natural visual orienting typically involves the head and eyes moving together. Yet the vast majority of laboratory research on visual orienting has been conducted with an observer's head constrained by a chin rest, thereby reducing visual orienting to eye movements alone. While these lab studies have made significant contributions to vision research, the exclusion of head and body movements fails to recognize that visual perception is embodied within an active system of effectors that are embedded in a dynamic physical world (Clark, 1999; O'Regan & Noë, 2001). Coordinated movement of the eyes, head, and trunk are essential in order for visual selection to occur naturally, yet save for some notable exceptions (e.g., Land, 2004), they are rarely studied together, leading to concerns regarding their ecological validity (Smilek et al., 2006). Indeed, when participants are able to freely move their eyes, head, and body in mobile eye tracking research, it becomes clear that head-free visual orienting differs from head-fixed orienting. For example, when asked to watch a video of someone walking to get a coffee, participants' eye movements explored the whole range of the video image, with particular focus on the people in the videos. When the eye movements of the walkers themselves were analyzed, they tended to keep their eyes roughly in the center of their heads, selecting objects such as other pedestrians with their head and eyes rather than with their eyes alone (see Figure 2 in Foulsham et al., 2011).

In many normal everyday situations, the eyes and head are tightly coordinated (Einhäuser et al., 2007; Freedman, 2008; Land & Tatler, 2009). However, their coordination does not appear to lead to identical means in how they select information. For example, the eyes and head seem to differ in how they trade 'knowledge in the head' for 'knowledge in the world'. Eye movements

are a relatively inexpensive way of collecting task-relevant information and reducing the demands on working memory, compared to the more energetically expensive head and body movements (Ballard et al., 1995). Indeed, search locations are revisited less often when searchers must move their whole bodies rather than just their eyes (Gilchrist et al., 2001). Researchers have also found evidence to suggest that the difference in energetic costs between the eyes and the head is enough to lead to different tradeoffs between their reliance on working memory. In one recent study, Solman and Kingstone (2014) compared search that was yoked either to participants' eye movements (eye-contingent), or head movements (head-contingent). They found that head-contingent search, in comparison with eye-contingent search, led to greater reliance on memory when re-examining a previously perceived visual image.

Recent work has suggested that in head- and gaze-contingent settings, the head may operate in service of the eyes, bringing new information to the eyes for more detailed inspection for the eyes to exploit. Using eye- or head-contingent viewing, and windows that were either horizontally or vertically elongated, Solman, Foulsham, and Kingstone (2017) investigated this hypothesis for effector-specific changes in behaviour. They found that eye movements had a clear bias towards making horizontal movements over vertical movements in free viewing. However, when the elongated window was yoked to eye movements, the bias was modulated such that eye movements were more likely to move in the direction of visible information (i.e. vertically for vertical windows, horizontally for horizontal windows) In contrast, when viewing was yoked to the head, eye movements were more likely to move perpendicular to the window (i.e., horizontal for vertical windows, and vertical for horizontal windows) as if to inspect the new information brought about from movement of the head. This suggests that when

peripheral visual information is obstructed people prefer to use their eyes to move into visible space, and they prefer to use their head to move into nonvisible space thereby providing the eyes with new visual information to explore.

Collectively, these data suggest that freeing the head (and body) to move beyond the information delivered on a computer screen can alter the manner in which the eyes acquire information. Specifically, they suggest that the head and eyes operate in a complementary manner, with head movements supporting visual exploration by the eyes. For instance, when one is free to explore the visual world, the eyes remain largely centered in the head. Thus, if the eyes move, the head quickly follows, thereby providing the oculomotor system the full range of directions for a future movement (Freedman, 2008). Similarly, for head contingent windows, the head moves to provide the eyes with the maximum amount of new information to explore (Solman et al., 2017).

It should be noted that in the above studies, the relationship between the head and eyes was often measured crudely, at best. For instance, in the Foulsham et al. (2011) study, head position was determined post hoc from a scene camera that was attached to a mobile eye tracker. In the Solman and Kingstone (2014), and the Solman et al. (2017) studies, head position or eye position were measured separately. Thus, for example, how the eyes responded to the movement of a head-contingent window was inferred but not directly measured.

The aim of the present study was to address this fundamental gap by concurrently measuring head and gaze position while participants explored a 360-degree panoramic scene while fully immersed within a virtual reality (VR) environment. All participants viewed these

scenes freely, and through a head- or gaze-contingent window. In all three conditions, participants were not confined or restrained to a chin rest but were able to move their head, eyes, and whole trunks around like they would in everyday life. Using a similar paradigm to Solman and Kingstone (2014), participants viewed these scenes freely, or through a circular window that was yoked to their gaze (gaze-contingent) or to their head (head-contingent). To encourage exploration of the scenes, participants were asked to remember the scenes for a later recognition task; and though recognition performance was not the focus of this investigation, a memory test was provided to avoid any appearance of deception. In sum, this paradigm enables us to investigate how the head and eyes may respond to a lack of peripheral information while freely exploring scenes. This is of critical importance for understanding the many everyday situations of when our peripheral information may be limited by the task at hand; for example, changing lanes while driving, straining to see through a crowd, or being screened as a goaltender in net.

In sum, we expect to find that since the head and eyes work in a complementary manner as a pair of nested effectors (the eyes are nested in the head), there will be a strong degree of correspondence between them, particularly during free viewing. However, as separate effectors in the oculomotor system, the head and eyes each have different physical characteristics. Therefore, we expect the head and eyes to respond differently to the perturbations introduced by the head- and gaze-contingent windows compared to the baseline of free viewing. Specifically, we hypothesize that as the head prefers to provide new information to the eyes (e.g., Solman et al., 2017), it should be impacted less by the lack of peripheral information than the eyes.

Methods

Participants

Twenty-four participants (mean age = 20, range = 18-23, 20 females) with normal or corrected-to-normal vision were recruited from the University of British Columbia. The sample size was determined by using the minimum number of participants (20-30) per grouping variable for having sufficient power to find medium-to-large effects in a within-subjects design (Wilson Van Voorhis & Morgan, 2007). However, the actual power was likely much higher than that given the high number of observations per participant (3517) and the total number of observations (84 415). Participants were compensated with course credits for 1 hour of their time. This study was approved by the ethics board of the University of British Columbia (H10-00527).

Equipment

The stimuli were viewed using an HTC Vive virtual reality head-mounted display (HMD) with an SMI eye tracker (SensoMotoric, 2017), controlled by a custom-built desktop computer (PC with Intel i7-8700K CPU @ 3.70GHz, 32 GB RAM, Nvidia GeForce GTX 1080 Ti, 1TB Samsung SSD). The HTC Vive headset (Vive model 2PU6100) has a resolution of 1080 x 1200 pixels per eye with a 110-degree horizontal and a 113-degree vertical field of view, a refresh rate of 90 Hz, and a weight of 635 grams. The SMI eye tracker was fixed onto the HTC Vive's lenses, sampled at a rate of 250 Hz via multi-threading, and was programmed to automatically calibrate every 30 trials. The manufacturer-claimed accuracy is typically 0.2 degrees. Head movements (movements of the HMD) were tracked via two infrared base stations (60 Hz) located on opposite

corners of the testing room. Participants were seated in a swivel chair in the center of the room and responded via a standard QWERTY computer keyboard. The experiment was built using Unity (version 2017.1.7f1), which is a popular engine for designing 3D environments and video games.

Stimuli

A total of 150 images were presented to each participant across two phases (the encoding phase, and the recognition phase). The content of each image was either an indoor or an outdoor scene. Indoor scenes included offices, museums, and transit stations, among others. Outdoor scenes included fields, forests, and coastal scenes. In each phase we selected an equal number of indoor and outdoor scenes. The images were retrieved from the SUN360 database (Xiao et al., 2012), which have been previously altered so that when they are projected onto a sphere they form convincing panoramic 360 degree scenes (see Figure 1). The images had a resolution of 2048 x 4096 pixels with 90 images presented in the encoding phase and 60 (30 old, 30 new) presented in the recognition phase. During encoding, 30 images each were viewed in the head-contingent, gaze-contingent, and free viewing conditions. During the head-contingent condition, participants' head movements were yoked to a uniformly grey sphere with a window directly in front that was 20 degrees of visual angle in diameter. Thus, participants would move their head around to explore each scene (somewhat like looking around in a dark room with a headlamp). During the gaze-contingent condition, the window size was again 20°, but yoked to the position of the eyes in the head. Note that we call this a gaze-contingent window (rather than an eye-contingent window) because when the head is free to move, the position of the eyes within the head are sensitive to changes in head position. During the free viewing conditions, images were

viewed without the use of a window. Stimuli were counterbalanced such that across sets of 3 participants, each image was presented in each of the viewing conditions. In the recognition phase, participants viewed each scene freely (i.e., without a head or gaze-contingent window). For greater clarification, see Figure 1.

Procedure

Participants were briefed on the experimental procedure and asked to give their informed consent. They were then seated comfortably in a swivel chair in a room set up with an HTC Vive and its external trackers. Participants put on the headset after being familiarized with the equipment which was adjusted by the experimenter to fit their head while they were given the keyboard and shown the response keys. Participants were given detailed written instructions in the headset, followed by a 5-Point eye-tracker calibration sequence requiring participants to follow a moving red dot. Upon successful calibration, and between each image presentation, a grey screen with a fixation cross appeared. Participants were asked to press the keypad 'Enter' key to move to the next image. After every 30 images (before the start of each new condition), the eye-tracker calibration was repeated. The order of conditions was counterbalanced between participants. Once all 90 images were displayed, an instruction screen would appear indicating that the encoding phase was over, and that the participant could remove the headset and take a brief (2-3 minute) break. Participants were then given instructions on the recognition phase and asked to put the headset back on. Each old and new image was presented in a random order. After freely viewing each image for 10 seconds, a new screen appeared with the instructions requesting participants to press the left 'Ctrl' key if they recognized the image that they just saw, and the right keypad 'Enter' key if they did not think they had previously seen the image. After

responding, a grey screen with a black fixation cross was presented and participants were required to press the spacebar to move to the next trial. They were given no feedback and no prior information about the probability of a new image having been seen before. After 60 recognition images, a final screen appeared, thanking the participant for taking part in the study, and asking them to take off the headset. Participants were then debriefed and given course credit.

Data handling

Unfortunately, there is substantial confusion in the eye-movement field regarding the definition of fixations and saccades, and in particular, when eye movements are combined with free head movements (see e.g., Hessels et al., 2018). As such, we take care in specifying our definitions following suggestions from Bischof et al. (in press) and Hessels et al. (2018).

In this study, participants viewed panoramic scenes with free head movements from approximately the center of a stimulus sphere that the panoramic scenes were projected on. For our measures below, we chose to derive them with respect to the stimulus sphere to allow for the expression of eye and head measures, and their comparison, with respect to a common coordinate frame. The main gaze analyses refer to the gaze vector in a world-coordinate frame, which combines the head direction and the gaze direction within the head. A gaze hit point, or 'gaze point' for short, is defined as the intersection of the gaze vector with the virtual sphere on which the panoramas are projected. It is defined in world coordinates, with longitudes in the range $[-180, 180]$ degrees and latitudes in the range $[-90, 90]$ degrees. Torsional eye movements (or ocular counterroll) were ignored, given that we were unable to measure them using our system (see e.g., Chandrakumar et al., 2011; Schmid-Priscoveanu et al., 2000; Schor, 2011). Fixations are defined

as stable gaze points and are extracted from the unfiltered gaze data using the IDT algorithm (Bischof et al., in press; Blignaut, 2009; Komogortsev et al., 2010; Salvucci & Goldberg, 2000), using a minimum duration of 80 milliseconds and a maximum dispersion threshold of 3° . Gaze shifts are defined as angular differences between successive fixations and are calculated using the great circle distance between successive gaze points on the virtual sphere. The great circle distance is the shortest distance between two points on a sphere or globe which is always an arc. It is analogous to how a flight path may be calculated to find the shortest distance between two cities on the earth but in the present case the positions are successive gaze points on the stimulus sphere.

With respect to the head, we define head pitch (achieved through neck extension and flexion), head yaw (achieved through lateral neck rotation), and head roll (achieved through lateral bending of the neck). Head roll is measured counter-clockwise from the vertical head orientation. The head hit point, or 'head point', is defined the intersection of the vector pointing forward from the face with the virtual sphere and is also defined in world coordinates, i.e., longitude and latitude on the virtual sphere. Analyses of head movement have demonstrated that head movements are fairly slow and continuous and do not share the characteristics of fixations and saccades. As such, we adopted the convention of defining head positions relative to each recorded fixation determined by our IDT script such that a head fixation is defined as the average head hit point position during that fixation (Bischof et al., in press). Head shifts were measured as the angular distance between successive head fixation positions on the virtual sphere and were also calculated using the great circle distance. An acknowledged consequence of this definition is that the contribution of the vestibulo-ocular reflex (VOR) is not taken into account. During a gaze

fixation, the VOR could be acting to stabilize gaze position during a head movement which in our definition of a head fixation would be averaged (Bischof et al., in press). See Figure 2 for a 2D visualization of head and gaze hit points on the stimulus sphere.

For all our analyses we used R (Version 3.5.2; R Core Team, 2018) and the R-packages *afex* (Version 0.27.2; Singmann et al., 2020), *dplyr* (Version 0.8.5; Wickham et al., 2020), *emmeans* (Version 1.4.6; Lenth et al., 2020), and *papaja* (Aust & Barth, 2020). All analyses of variance (ANOVAs) are reported with their effect sizes using generalized eta squared, and all repeated measures ANOVAs are reported with sphericity corrections to the degrees of freedom using Greenhouse-Geisser corrections (Bakeman, 2005).

Analyses and Results

The principle aim of this study was to compare concurrent head and eye measures in response to perturbations (head- and gaze-contingent windows) affecting the amount of peripheral information available for visual orientating. We use measures of central tendency, head and gaze shifts, and eye-head divergence to investigate our hypotheses. We also recorded the mean number of fixations and the mean duration of fixations as general measures of scanning behaviour. These are reported below. Recognition performance was not our interest, though we note here that performance overall was well above chance (81.3% correct).

General eye scanning behaviour

In order to determine whether viewing condition had any impact on general eye movement measures, we calculated the average number of fixations and average fixation duration for each viewing condition. The number of fixations was defined as the average number of fixations within a trial, across each condition for each participant. These are presented in Table 1. A within-subjects ANOVA was conducted to compare the effect of viewing condition (free viewing, head-contingent viewing, and gaze-contingent viewing) on the mean number of fixations per trial. No significant effect was observed, $F(1.96, 43.22) = 2.12$, $MSE = 11.35$, $p = .133$, $\hat{\eta}_G^2 = .031$. An ANOVA was also conducted to compare the effect of viewing condition on mean fixation duration (for each subject, condition, and trial). There was a significant effect of viewing condition, $F(1.71, 37.63) = 3.88$, $MSE = 173.79$, $p = .035$, $\hat{\eta}_G^2 = .040$. However, follow-up Bonferroni-corrected pairwise comparisons revealed no significant differences between conditions (all p 's $> .05$).

Eye-head divergence

In order to determine how closely the eyes and head worked together during encoding, we calculated eye-head divergence. We computed this measure as a way of quantitatively interpreting the relationship between head and eye movements during the same time series. The eye-head divergence directly compared the positional proximity of gaze and head positions for each fixation and was calculated by taking the great circle distance (in degrees) between gaze and head positions on the sphere for each recorded fixation (see the black lines in Figure 2). Figure 3 shows the eye-head divergence for each viewing condition. A one-way repeated measures ANOVA with 3 levels (viewing condition) revealed that there were significant differences between viewing conditions on eye-head divergence, $F(1.05, 23.02) = 129.00$, $MSE = 144.69$, $p < .001$, $\hat{\eta}_G^2 = .775$. Bonferroni corrected pairwise comparisons were then conducted. Gaze-contingent viewing resulted in significantly greater divergence than head-contingent viewing, $t(44) = 15.55$, $p < .001$, and significantly greater divergence than free viewing, $t(44) = 11.26$, $p < .001$. Head-contingent viewing resulted in significantly less divergence than free viewing, $t(44) = -4.29$, $p < .001$.

The eye-head divergence data indicate that there was significant impact of viewing condition on how the head and eyes operated. During free viewing, as we would predict, there was a strong degree of correspondence in that the positions of the head and eyes tended to diverge by less than 20 degrees. More interestingly, we found that gaze-contingent viewing increased the amount of eye-head divergence, while head-contingent viewing decreased the amount of divergence. This suggests that changing the means by which the oculomotor system

can explore visual scenes, radically alters the means by which the head and eyes typically work together. In this case, becoming more tightly coupled in head-contingent viewing, and less tightly coupled in gaze-contingent viewing.

Central tendency of head and gaze positions

In order to determine how participants explored with their head or gaze movements, we computed their central tendency. The central tendency of the head and gaze positions was calculated by comparing the end position point (head/gaze direction) on the sphere to the initial position at the start of each trial using the great circle distance, with the results displayed in Figure 4. A 3 (viewing condition) by 2 (selection system: head or gaze) repeated measures ANOVA revealed a significant main effect of viewing condition on central tendency, $F(1.62, 35.65) = 81.67$, $MSE = 131.96$, $p < .001$, $\eta_G^2 = .384$, and a significant main effect of selection system, $F(1, 22) = 94.31$, $MSE = 36.04$, $p < .001$, $\eta_G^2 = .108$. There was also a significant interaction between viewing condition and selection system, $F(1.04, 22.93) = 25.75$, $MSE = 75.25$, $p < .001$, $\eta_G^2 = .067$. Follow-up Bonferroni corrected pairwise comparisons were conducted across viewing conditions within each selection system. For the head, gaze-contingent viewing had significantly lower central tendency than head-contingent viewing, $t(72.45) = -10.72$, $p < .001$, and free viewing, $t(72.45) = -13.14$, $p < .001$, but head-contingent viewing was not significantly different compared to free viewing, $t(72.45) = -2.42$, $p = .054$. For gaze, gaze-contingent viewing had significantly lower central tendency than head-contingent viewing, $t(72.45) = -3.39$, $p = .003$, and free viewing, $t(72.45) = -8.38$, $p < .001$, and

head-contingent viewing had significantly lower central tendency compared to free viewing, $t(72.45) = -4.99, p < .001$.

Our data demonstrate that excluding peripheral information in the window conditions decreases exploration compared to free viewing (main effect of condition). Our data also suggest that overall observers explored more with their gaze than their heads, which converges with the idea that it is more energetically expensive to move the head than to shift gaze. Interestingly, exploration was more similar to free viewing in the head-contingent viewing condition than in the gaze-contingent viewing condition. However, unlike head behaviour under head-contingent viewing, gaze behaviour in head-contingent viewing stayed closer to the center of the image than gaze behavior in free viewing. An additional difference was found in how the head and gaze responded differently to the viewing conditions. Head central tendency was much lower in the gaze-contingent condition, but relatively unaffected by the head-contingent condition, whereas gaze central tendency was much lower in both head- and gaze-contingent conditions. This demonstrates that people explore scenes differently with their head and gaze when peripheral information is excluded.

Head and gaze shifts

Figure 5 displays the effects of the different viewing conditions on head and gaze shifts. Head and gaze shifts were measured by computing the amplitude between each recorded head or gaze position. A 3 (viewing conditions) by 2 (selection systems) repeated measures ANOVA revealed a significant main effect of viewing condition on mean shifts, $F(1.95, 42.81) =$

32.49, $MSE = 2.00$, $p < .001$, $\hat{\eta}_G^2 = .306$, and a significant main effect of selection system, $F(1,22) = 303.52$, $MSE = 0.49$, $p < .001$, $\hat{\eta}_G^2 = .344$. There was also a significant interaction between viewing condition and selection system, $F(1.15,25.29) = 71.56$, $MSE = 0.87$, $p < .001$, $\hat{\eta}_G^2 = .200$. Follow-up Bonferroni corrected pairwise comparisons were conducted between viewing conditions for each selection system. Gaze shifts did not differ significantly between gaze-contingent viewing and head-contingent viewing, $t(65.21) = -1.43$, $p = .471$, but gaze shifts in gaze-contingent viewing, $t(65.21) = -11.55$, $p < .001$, and head-contingent viewing, $t(65.21) = -10.12$, $p < .001$, were smaller than gaze shifts in free-viewing. For head shifts, there were no differences between any conditions, all t 's < 1.79 , all p 's $> .234$.

Our data demonstrate that there are differences in gaze and head shifts across conditions. Overall, head shifts were smaller than gaze shifts, which supports the idea that the head is more energetically expensive. Gaze shifts were reduced equally, and significantly, by introducing a head- or gaze-contingent window. In contrast, head shifts were unaffected by the window condition, indicating that reducing the peripheral information with a head- or gaze-contingent window had no measurable impact on the execution of head shifts relative to free viewing.

Discussion

In the present work, we recorded simultaneously the head and eyes, and systematically introduced perturbations (head- and gaze-contingent windows) during immersive 360-degree scene viewing in virtual reality. These windows limited the visual information from the periphery that was available to the observer. The window was yoked to either the head or gaze of participants, or participants viewed the images without a window. One aim of this work was to expand on the work of Solman et al. (2017) and Solman and Kingstone (2014) by simultaneously recording both eye and head movements in a fully immersive environment. Critically, we compared how closely the head and eyes correspond, how the different selection systems were used to explore the scenes, and the amplitudes of head and gaze shifts. Overall, we found strong evidence for the commonplace idea that the head and eyes are tightly coordinated. However, we also found strong evidence that the head and eyes differ in how they are coordinated when the peripheral information in visual scenes is limited (see Figure 6). In such a situation, people rely more on their head than their eyes to move into new regions of unseen space. Below both of these points are discussed in detail.

Selection by head and gaze is tightly coordinated

There were robust data to support the notion that the head and eyes are tightly coordinated. Critically, we directly analyzed and compared the eye-head divergence between viewing conditions by taking the positional proximity of gaze and head positions on the sphere for each fixation. During free viewing, we found that the angular difference between the position of the head and the position of the eyes was only about 18 degrees. This fits with other research

indicating that the eyes tend to stay centered in the head such that fixations between items of relevance in a scene require smaller muscular deviations in the eye (Tatler, 2007). This also supports the work done by Freedman (2008) demonstrating that the eyes tend to stay centered in the head, enabling the oculomotor system to benefit from a full range of directions for planning future movements. It is also interesting to note that gaze and head were more tightly coupled in head-contingent viewing compared to free viewing. In head-contingent viewing, the divergence between gaze and head positions was even smaller than the window size yoked to the head. This suggests that limiting peripheral information and limiting the means by which the oculomotor system can actively select information, as we did with the windows, can radically affect the amount of coordination between head and eyes. Where head-contingent viewing led to much tighter coupling of the head and gaze, gaze-contingent viewing significantly decreased coupling.

Selection by head and gaze is different

We also found strong evidence demonstrating functional differences between the head and gaze as selection systems. Specifically, we found evidence to support the hypothesis that people prefer using their head to move into nonvisible space, and they prefer to use their gaze to exploit visible space. Limiting peripheral information had different effects on gaze and head exploration. Unlike gaze, exploration with the head was not affected by the head-contingent window, where central tendency was quite similar to that in free viewing. This suggests that how people visually select with their head is less dependent on visible information. Furthermore, while gaze shift amplitudes were reduced significantly by introducing a head- or gaze-contingent window, head shift amplitudes were unaffected by the window conditions. This again suggests that people rely less on peripheral information for selection with the head compared to selection with their gaze,

aligning with previous work (Solman et al., 2017), and suggesting that people prefer to use their head to move into nonvisible space and their gaze to exploit visible space.

Further evidence for the idea that people opt to use their head to explore nonvisible space and their gaze to exploit visible space comes from comparing how head- and gaze-contingency differed relative to free viewing. In general, gaze-contingent viewing was more perturbing than head-contingent viewing. That is, observers' movements during head-contingent viewing looked more like free viewing, than movements during gaze-contingent viewing (see, for example, Figure 4). In the gaze- and head-contingent conditions, gaze shifts tended to occur within the window (~10 degrees – see Figure 5), while head shifts remained stable (~7.5 degrees) across conditions. This dovetails with the notion that head-contingent viewing looks more like free viewing because people use their head as they normally would - to move into nonvisible space; and they use their eyes to exploit the visible information produced by the movement of the head.

Another key finding was that the head had smaller amplitude shifts between fixations and remained more central (i.e. explored less) relative to gaze, regardless of viewing condition. Essentially, people were more constrained with their head movements compared to their gaze movements. This fits with the idea that the head is more energetically expensive when compared to the 'cheaper' ballistic eye movements (Ballard, Hayhoe, & Pelz, 1995). This difference was, if anything, amplified by the weight of the VR headset. Thus, our results may overestimate how much more conservative people are in moving their heads compared to their eyes. Nonetheless, these data are line with the important idea that how people select with their eyes and head is influenced by the relative differences in costs for selection. Furthermore, our data indicate that people will move both their head and eyes to explore scenes when given the option to do so,

which complements previous work indicating that visual selection is more head-based than previously considered (Foulsham et al., 2011; Solman et al, 2017).

Overall these lines of evidence generate substantial support for the notion that the functional consequences of visual selection by the head and eyes differ in critical ways, and that by restricting peripheral information during viewing, as we did in the window conditions, reveals that the head and eyes behave like nested effectors, such that the head serves the eyes by leading them towards regions of nonvisible space. This is consistent with the idea that the eyes prefer to exploit visible information while the head tends to explore unseen space (Solman et al., 2017). Furthermore, this builds off previous results (e.g., Solman & Kingstone, 2014) that perturbations to the visual information provided by the eyes and head is a profitable method for revealing key aspects of their dynamic relationship.

Conclusion

Everyday visual behavior involves the coordination of the eyes and head, yet the vast majority of research into scene viewing and visual orienting has focused on understanding the neural and behavioural mechanisms of eye movements while the head is constrained. Yet, we are discovering that there is a strong and complementary relationship between selection with the head and eyes, and how observers recruit their head and eyes differ in predictable ways. We found strong support for the hypothesis that people prefer to use their head to explore or move into nonvisible space and to use their eyes to exploit visible space because gaze-based selection is more dependent on visible information than head-based selection. By using a novel approach with unconstrained head and eye movements and controlled virtual reality environments, we

demonstrated the efficacy of this methodology for probing the complementary nature of head and eye movements. Indeed, the fertile and largely unexplored terrain of virtual reality promises to become an increasingly productive tool for revealing the cognitive and behavioural mechanisms of visual orienting in everyday life.

Table 1

Descriptive statistics of general eye scanning behaviour.

	Viewing Condition	Mean	Median	SD	Min	Max
Fixation duration						
	Gaze-contingent	185.49	181.15	22.71	139.69	239.09
	Head-contingent	176.93	176.06	20.22	146.09	225.67
	Free	176.71	174.19	18.70	141.56	213.05
Fixation number						
	Gaze-contingent	51.61	52	3.69	41	60
	Head-contingent	51.96	52	3.98	43	58
	Free	50.26	50	2.61	45	55

Note: Fixation durations are reported in milliseconds.

Table 2

Descriptive statistics of recognition results (proportion correct).

Viewing Format	Mean	Median	SD	Min	Max
Gaze-contingent	0.75	0.75	0.18	0.50	1.00
Head-contingent	0.79	0.80	0.16	0.50	1.00
Free viewing	0.79	0.90	0.20	0.30	1.00
New images	0.93	0.97	0.07	0.80	1.00

Figure 1

2D Representation of a Participant Viewing a 360 Scene Through a Window in VR

Figure 2

Plot of an Individual Trial's Head and Gaze Positions on the Stimulus Sphere Remapped to a 2D Representation

Note: Orange squares are head points and blue circles are gaze points on the virtual sphere. The length of these lines represent the correspondence in head and gaze positions. The central tendency of head and gaze positions towards the center of the image represent a measure of how much of the image was explored. Head and gaze shifts are distances between successive head and gaze positions.

Figure 3

Plot of Eye-Head Divergence Between Conditions

Note: Error bars represent 95% within-subjects confidence intervals.

Figure 4

Plot of the Central Tendency of Head and Gaze Positions Between Conditions

Note: Error bars represent 95% within-subjects confidence intervals.

Figure 5

Plot of Head and Gaze Shifts Between Conditions

Note: Error bars represent 95% within-subjects confidence intervals.

Figure 6

Exemplar Trials from Each Viewing Condition

Note: Orange squares are head points and blue circles are gaze points on the virtual sphere.

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