Stimulus Sampling with 360-Videos: Examining Head Movements, Arousal, Presence, Simulator Sickness, and Preference on a Large Sample of Participants and Videos

Hanseul Jun*, Mark Roman Miller*, Fernanda Herrera*, Byron Reeves, and Jeremy N. Bailenson

***Abstract*—As the public use of virtual reality (VR) scales, understanding how users engage across various sources of VR content is critical. 360-video is popular due to its ease of both creation and access. There are, however, few studies of 360-videos, and they suffer from three limitations. First, most studies rely on small and homogeneous samples of participants. Second, they tend to examine only a single 360-video, or a handful of them in a few exceptional cases. Third, very few studies trace participants' VR use over multiple experiences. The current study examined a large sample of participants (511) and a large set of 360-videos (80). Each participant experienced 5 of the videos, and we tracked head movement in addition to self-report data on presence, arousal, simulator sickness, and future use intention for each video. This design allowed us to answer novel questions relating to individual differences of participants and changes in experience over time, and in general to present results of VR use at a scale not seen before in the literature. Moreover, the results suggest that looking at patterns across stimuli provide unique insights which are missed when looking only within a single piece of content.**

***Index Terms*—Stimulus sampling, 360-videos, virtual reality**

I. INTRODUCTION

USE of virtual reality (VR) headsets is gaining traction, with recent reports showing more than 1 million people use VR each month [1]. While researchers have spent decades studying the psychological responses to VR, most of these studies involve small, and homogeneous, samples of participants (see [2] for a recent review). Moreover, participants are typically only exposed to a single VR experience in each study. Hence, we know very little about how individual differences among people shape VR use, and even less about how these individual differences are reflected across different types of VR experiences. Consider the medium of television. One would never ask an affluent 18-year-old college freshman to watch one single episode of The Simpsons, and then generalize the results across participants and stimuli. In other words, few would claim that the experience of a teenager watching an animated fantasy show would elicit the same types of perceptual and psychological processes and effects as a 60-year-old watching local news. In media studies research, while some scholars are starting to examine large samples of participants, it is far less common to find studies that examine a large sample of media content (i.e., different videos, games, etc.), as pointed out by Reeves, Yeykelis, and Cummings [3].

A lack of attention to stimuli makes the sampling of them a critical issue, no less important than design issues related to random sampling of study participants. Stimuli are often given cursory treatment in media experiments, and especially in meta-analyses. In VR experiments, researchers rarely qualify results as applicable only to the particular experience used in the research. The external validity of subject samples is often mentioned, but there is less expectation that results will be evaluated based on the external validity of stimuli. The problem of stimulus sampling has received considerable recent attention in psychology (e.g., [4], [5], [6]) but the issue is perhaps even more worrisome in VR because the stimuli, more so than is often the case in psychology, are generally more complex and variable in content, media genre, and length.

One type of content typically viewed in these headsets is 360-videos, which allows users to turn their heads around and see a video scene from all angles. The benefit of 360-videos—as opposed to scenes crafted in computer graphics—is both their photorealism as well as the ease of capturing them, which is simply filming a scene with a special camera. On the other hand, 360-videos lack interactivity due to their predetermined nature. Moreover, visual cues such as motion parallax are difficult to create, and even if one allows a user to translate through a video sphere there is no way to "look behind" objects.

There have been a few dozen studies examining how people engage with 360-videos in VR. In these studies, researchers are examining the medium of 360-videos, developing methods for assessing behavior during use, as well as manipulating and testing various technological affordances which are intrinsic to the medium. Moreover, VR headsets with 360-videos have been studied in many application areas, including education (e.g., [25]), inducing empathy (e.g., [14]), journalism (e.g., [31]), shopping (e.g., [11]), sports training (e.g., [23]), and tourism (e.g., [15]). Table I lists all VR 360-video studies we could find which have manipulated or selected an independent

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Reference	Number of Participants	Number of Videos
Barreda-Ángeles, 2019 [7]	36	3
Calvert, 2019 [8]	53	1
Chang et al., 2018 [9]	44	N/A
Elsey et al., 2019 [10]	95	9
Feng, 2018 [11]	198	2
Fraustino et al., 2018 [12]	81	1
Fremerey et. al., 2018 [13]	48	20
Kandaurova and Lee, 2019 (Study1) [14]	85	1
Kandaurova and Lee, 2019 (Study2) [14]	53	1
Kelling et al., 2017 [15]	20	1
Kim and Ko, 2019 [16]	137	2
Li et al., 2017 [17]	95	73
Makransky et al., 2020 (Study1) [18]	131	1
Makransky et al., 2020 (Study2) [18]	165	1
Meyer et al., 2019 [19]	118	2
Muntean et al., 2019 [20]	43	1-6
Narciso et al., 2019 [21]	128	1
Nasrabadi et al., 2019 [22]	60	28
Panchuk, et al., 2018 [23]	20	10-12
Rupp et al., 2016 [24]	63	1
Rupp et al., 2019 [25]	136	1
Shin et al., 2019 [26]	44	1
Simon and Greitemeyer, 2019 [27]	60	2
Singla et al., 2017 [28]	30	6
Stupar-Rutenfrans et al., 2017 [29]	35	3
Sun et al., 2018 [30]	324	4
Sundar et al., 2017 [31]	129	2
Ulrich et al., 2019 [32]	81	1
Vettehen et al., 2019 [33]	83	1
Yoganathan et al., 2018 [34]	40	1

TABLE I: A List of 360-video studies in which there were at least 20 participants in an empirical study which manipulated at least one independent variable.

variable, studied outcome measures with at least a total of 20 participants, and also have been published in a peer-reviewed academic forum.

Notice in Table I, that a few exceptional studies have samples larger than 100 participants or 10 videos. But strikingly, even the exceptional studies only examine either a large participant sample or a large video sample—none do both.

In the current research, we aim to address this issue by having large sample sizes for both participants and videos. Each of 511 participants experienced 5 different 360-videos, and across participants, 80 videos were experienced. For each participant and for each video, we examined head movements, self-reported arousal, presence, simulator sickness, and preference. For each person, we can compute a global score by averaging a given measure across all the videos that person experienced. Similarly, for each video we can compute a global score for a given measure by averaging across participants. We can then compare the global scores to more specific instances (i.e., a behavior of a subset of participants on a subset of videos) to answer novel questions regarding the interaction between person and environment in VR.

A. Novel Questions about the Psychology of 360-Video

1) VR Discovery Over Time: One of the most salient features that makes VR unique is the ability to move one's head and have the scene respond naturalistically. There have been studies that examine how people explore content in 360-videos by moving their heads. For example, De Abreu, Ozcinar, and Smolic [35] observed how people discover 360 still images with VR headsets, plotted saliency maps, and reported the patterns of the saliency maps. Fremerey and colleagues [13] conducted a study on 360-videos and virtual reality headsets with 48 participants, each of which experienced 20 videos, and presented visualizations of participant head rotation and exploration over time. More than half of their participants explored more than 330 degrees of the videos in terms of head rotation yaw. Also, for 90% of the time, their head rotation pitch remained between -30 to 30 degrees. We seek to expand these previous works with a larger sample, and to develop additional analyses of how exploration behaviors change over time.

2) Correlation of Head Movements and Preference: Scene exploration should have an impact on subjective preference. For example, one can imagine that moving one's head back and forth often can be a proxy for enjoyment, in that they were engaged with the video and wanted to look around. On the other hand, 360-video is a fairly new medium, and designers might be bringing production strategies from traditional film, with focal points or narrators designed to capture one's attention in a particular spot. Those types of videos might show that truly engaging experiences would have small amounts of scene exploration as the viewers attend to the designated spot. Li and colleagues [17] conducted a study on 360-videos and VR headsets with 73 videos. With data collected from 95 participants, using videos as the unit of analysis, they found a correlation between valence and standard deviation of head rotation yaw, such that people who moved their heads more rated videos more positively than those who moved less. Previous studies have leveraged head rotation as a proxy for a number of outcome measures in interactive, computer graphic-based VR scenes (see Bailenson [36] for a review). However, the current study further tests this relationship with a large sample of participants and video content.

3) The Relationship Between Presence and Arousal: Lee [37] defined presence as "a psychological state in which virtual objects are experienced as actual objects in either sensory or nonsensory ways." Presence is a central psychological construct for describing the usage of immersive media such as VR [38]. There has been a general assumption among many scholars that physiological arousal is one of the main mechanisms that produce presence. For example, Diemer and colleagues [39] present a theoretical framework in which arousal acts as a filter between technological immersion and presence outcomes. However, as Slater (2004) notes, the constructs are very hard to pin down with questionnaires, and many questions in scale might seek to measure one while they are actually measuring another (i.e., presence questions function as a proxy for other constructs such as arousal).

Many studies include physiological arousal as an outcome measure and use it as a proxy for presence (e.g., [40]). But there is an assumption behind this argument that the experience itself is designed to be arousing. Some VR is designed to produce the opposite effect, for example applications built for meditation and relaxation. Freeman and colleagues initially presented this argument. For example, when presenting stimuli designed to be relaxing on 2D screens, the relationship between presence and arousal disappears [41], [42]. What has not been tested, to our knowledge, is a direct comparison between videos designed to be high and low in arousal, or any such comparison in immersive VR, which one would predict a higher relationship between presence and arousal for videos which are arousing, compared to ones which are not. While Freeman and colleagues derived their statement from a study with arousing videos and another study with not arousing videos, given our study includes various videos across the levels of arousal, instead of a two-group comparison, we reframe their prediction by comparing the correlation between presence and arousal on videos which are high on the global arousal score to those which are low on the global arousal score. In other words, for videos which are arousing, there should be a high correlation between arousal and presence. For ones which are not arousing, this relationship should be smaller.

4) Biological Sex and Simulator Sickness: Most studies simply have not had a sufficiently large sample to examine how different types of people experience VR, though there are some notable exceptions. One area which has received attention is simulator sickness (see [43] for a review). Weech and colleagues [43] assimilated a number of studies and concluded that women are more susceptible to sickness than men. Boyd [44] also suggested that difference of interpupillary distance (IPD) between biological sexes—males have larger IPD than females [45] and the head-mounted displays are designed for the larger IPD—may be responsible for the disproportionate simulator sickness experienced by female VR users. But few of these studies have had the sample size—or heterogeneity—to look at any of these factors definitively.

Age	Sex			Total
	Female	Male	Other	
19-	40	58	0	98
19-25	104	64	1	169
26-45	61	86	1	148
45+	42	54	0	96

TABLE II: The distribution of age and biological sex of participants.

II. METHOD

Participants. A total of 511 participants (247 female, 262 male, 2 other) were recruited. Three hundred seventy eight participants were recruited from a museum in the San Francisco Bay Area and 134 participants were undergraduate students recruited from courses or paid for participation. There were 23 African American, Black; 4 American Indian, Native American; 48 Chinese; 9 Filipino; 31 Hispanic or Latino; 51 Indian; 6 Japanese; 10 Korean; 24 Mexican; 9 Middle Eastern; 14 Southeast Asian; and 220 White, Caucasian, Non Hispanic participants. Seventeen participants declined to state their race, 42 participants stated they belong to more than one race; and 3 participants did not know their race or did not report their race. One hundred ninety participants did not have prior VR experience, while the other 321 participants had. Table 2 presents the age and biological sex distribution of the participants. The recruitment and experimental procedures were approved by the Institutional Review Board of Stanford University, IRB-43879.

Videos. A total of 80 videos were prepared. These videos were 20-second-long clips chosen from 71 original videos that were all longer than 20 seconds. We attempted to find videos that spanned the emotional space, that is, ones which we determined qualitatively to be either high or low in arousal, and high or low in valence. Five of the original videos provided two distinct clips each and one original video provided five distinct clips for this study. We only collected videos which were recorded with a stationary camera and without scene jumps to avoid simulator sickness. Videos were coded to be "People", "Animal", "Nature Scene", "Underwater", and "Other". If there was a single person in the scene, even if that person was in nature or around animals, the coding was given "People" (33 videos). "Animal" (32 videos) had at least one mammal or bird (fish were not included). "Nature Scene" (10 videos) had no people or visible animals in the scene. "Underwater" (5 videos) were filmed completely underwater. Anything not fitting those categories received "Other". All video creators affirmed their ownership of copyright and consented to the use of these videos in current and future research, and the videos themselves are available online, along with the corresponding mean self-report ratings and movement metrics for each video. Researchers who want to use VR experiences to conduct other studies can find our videos and their ratings at https://github.com/vhilab/psych-360.

Apparatus. Participants wore the HTC Vive VR headset with 90 Hz refresh rate with a resolution of 1080x1200 per eye. The field of view of the HTC Vive headset is about 110 degrees. Participants used HTC Vive hand controllers with the headset. The headset and the hand controllers had 6 DOF

Fig. 1: A participant watching a video and answering a questionnaire. Top-left and top-right screenshots are the ones corresponding to the photos below them. Bottom-left is the participant watching a video, and bottom-right is the participant answering a questionnaire.

sensors tracking their position and rotation. The software was built for Windows PCs using Unity3D. We used PCs that were able to render the videos in 90 Hz. For example, one had a 3.6 GHz Intel i7 CPU and an Nvidia GTX 1080 GPU.

A. Procedure

The experiment lasted approximately 15 minutes. Before the experiment, participants were asked pre-screening questions to determine whether they were eligible for the experiment. The pre-screening questions checked whether participants had health issues related to VR headset usage, such as epilepsy or seizure disorder. While it would be ideal to know the number of excluded participants, this was not collected during the experiment. For the rest of the experiment, the participants wore a VR headset and there was no interruption from the experimenter. In VR, the participant was asked demographic questions. Then, the participant watched 360-videos. Each of the videos were 20 seconds long and was followed by a questionnaire assessing affect, presence, simulator sickness, and future intent. Figure 1 provides an example of a participant watching a 360-video and answering a question in VR. Participants recruited from the museum watched 5 videos to limit the amount of time required for the experiment. Other participants who were recruited to a lab environment watched 8 videos because there was less of a time constraint. While we collected data from the 8 videos, we will only use the first 5 videos from those participants in our analysis for consistency across locations. Participants from both locations saw a subset randomly chosen from the 80 videos.

B. Measures

1) Demographic Variables: Using the hand controllers, participants answered questions inside the virtual environment about age, biological sex, race, and the amount of prior VR experience. The wording of questions and the breakdown of demographic responses are shown in Appendix A.

2) Self-Report Measures: After watching each video, participants answered a questionnaire in VR. The questionnaire measured the level of arousal, presence, dizziness, nausea, willingness to recommend the video to others, and willingness to continue watching the video. Appendix A presents the full questions.

Arousal. Arousal was asked on the Self-Assessment Manikin [46] with a range from 1 to 9 following the previous work of Li and colleagues [17]. The mean value of arousal of the sessions was 4.82 ($SD = 2.29$). Because the Self-Assessment Manikin has five figures, our extension to 9 points meant the figures were shown above points 1, 3, 5, 7, and 9.[1]

Presence. Presence was measured through three questions on 5-point Likert scales asking the level of presence the participants have felt. The mean values of each of the questions were 3.47 ($SD = 0.98$), 3.61 ($SD = 0.94$), and 3.46 ($SD = 0.99$). The Cronbach's alpha for the scale between the questions was 0.89. In our analysis, we used the average score from these three questions. The mean value of the average score of the questions was 3.51 ($SD = 0.88$).

Simulator Sickness. Participants were asked questions about the level of dizziness and nausea whose mean values were 1.37 ($SD = 0.74$) and 1.23 ($SD = 0.63$) on 5-point Likert scales. Since they were highly correlated to each other ($r = .69$, $\alpha = .81$) they were averaged into *simulator sickness* ($M = 1.30$, $SD = 0.63$).

Preference. We asked participants how much they are willing to recommend ($M = 3.47$, $SD = 1.16$) and continue watching ($M = 3.33$, $SD = 1.24$) the video on 5-point Likert scales. Given the strong correlation between them ($r = .73$, $\alpha = .84$), they were averaged into *preference* ($M = 3.40$, $SD = 1.12$).

3) Tracking Data: The tracking data of the VR headset and the hand controllers were collected during the studies. 6-DOF (position and rotation) tracking data were collected in 90 Hz. Though we collected tracking data of the hand controllers, we did not include them in the current analysis. Our analysis is based on Euler angles. Positive yaw value indicates rotation to the right side, and the range of yaw is from -180 to 180 degrees.

Exploration Range. Exploration range is measure we introduce to quantify exploration of virtual environments. As people show an equator bias—not looking upward or downward for most of the time—watching 360-videos [47], we focus on yaw and call the range of yaw explored throughout the video exploration range. Exploration range is 0 to 1, from no horizontal rotation to the full exploration (360 degrees) of the horizontal directions. Notice that this measure does not include the field of view, thus no horizontal rotation does not correspond to a certain non-zero measure but zero.

III. Results

In the current study, we are demonstrating results that are largely descriptive. No findings are associated with formal

[1] Valence was also asked on the Self-Assessment Manikin [46]; however, it was not included in our analysis given its small variance.

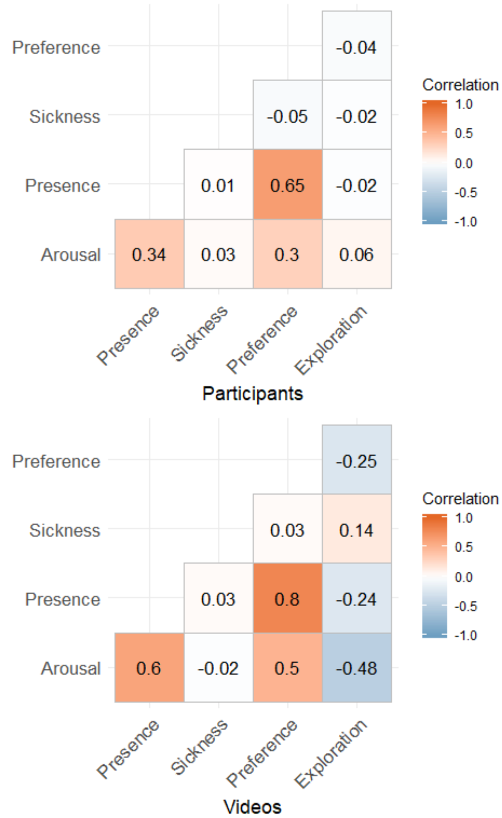

Fig. 2: Correlation coefficients between self-report measures, and exploration range while using participants as the unit of analysis (top) and videos as the unit of analysis (bottom).

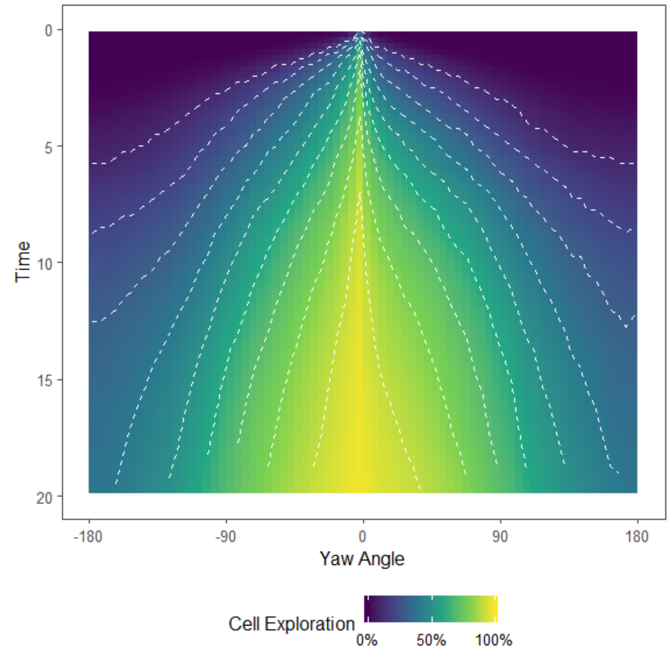

Fig. 3: The exploration pattern along head rotation yaw over time with contours of 10% intervals. The color of each cell is for the ratio between the number of sessions that participants explored the yaw angle at the corresponding time to the total number of sessions.

hypotheses, although some of our findings do echo previous research, for example the relationship between sex and simulator sickness. Our strategy is to show an overall effect, for example, correlation or a t-test. Then, we break down that effect by showing how it works when applied to individual videos, or groups of participants. In these subsequent tests we attempt to provide measures of variance such as confidence intervals. We then interpret descriptive patterns across those videos. However, we are careful not to draw specific conclusions about significance based on these tests as there are likely issues with family-wise errors. For some analysis, we use more traditional test of significance—for example mixed effects models in the instance of examining order effects.

In total, our analysis includes 2555 sessions collected over all participants and videos. For each video, there was an average of 31.94 ($SD = 6.38$) participants who experienced it, with a maximum of 48 and a minimum of 17. Figure 2 shows the correlation coefficients between self-report measures, and exploration range over participants and videos. See Appendix B and C for the means and standard deviations of variables across the demographic groups, prior VR experience, and order of videos.

A. Exploration of the 360-Degree Scene

1) Exploration over Time of Each Video: Exploration of the 360-videos is plotted in Figure 3. For this analysis, we divided yaw angles into 72 steps—5 degrees between each step—and time into 80 steps—0.25 seconds between each step. In total, this led to 5760 spatiotemporal cells. For a given time and given yaw direction, the cell's value is the percentage of participants who had looked in the given yaw direction at some time before the given time. Dotted lines represent contours of 10%. By the end of the video (bottom of graph) about 40% of users had looked all the way behind from where they started (bottom left corner, bottom right corner.) These results corroborate the finding of Sitzmann and colleagues [47] that it takes about 20 seconds for the average person to fully explore a scene. By ten seconds in, about 50% of participants had looked to the right 90 degrees. In the common case where a video producer wants almost all viewers to have seen some focal point, natural exploration will take a significant amount of time when the focal point is far from the initial direction. However, many participants explored the scene quickly, and so there is a large variance on when a viewer may look in a given direction.

2) Exploration over Order of Videos: To further investigate the effect of order of videos on exploration with two of our variables, prior VR experience and the order of videos, we conducted an analysis using a mixed effects model with participants and videos as random effects. The random effects were added, for instance, to mitigate the imperfect random assignment of videos to participants. See Figure 4 for the result.

Two key features of the graph are visible. First, the effect of the order of videos on exploration is not linear, but rather

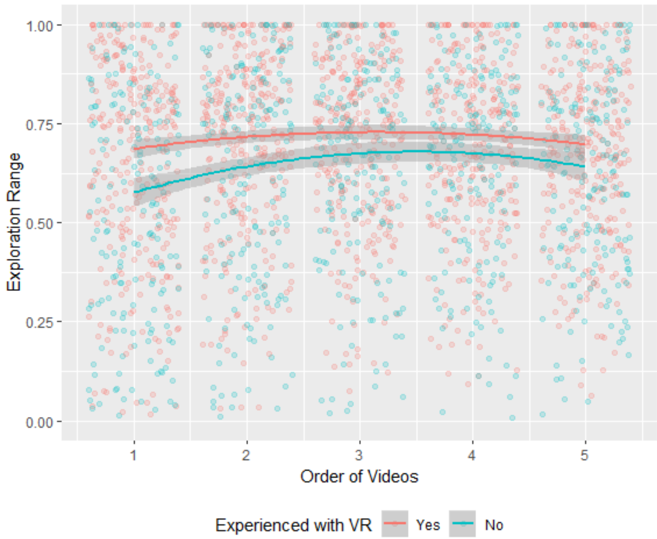

Fig. 4: The effect of prior VR experience and order of videos on exploration range. Each point represents a session.

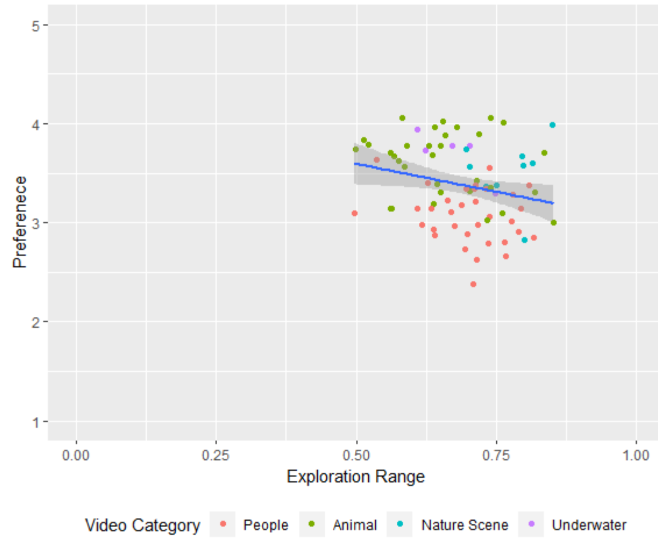

Fig. 5: The relationship between exploration range and preference. Both exploration range and preference are the mean values of each video across the participants who watched the video. Color indicates the categories of the videos.

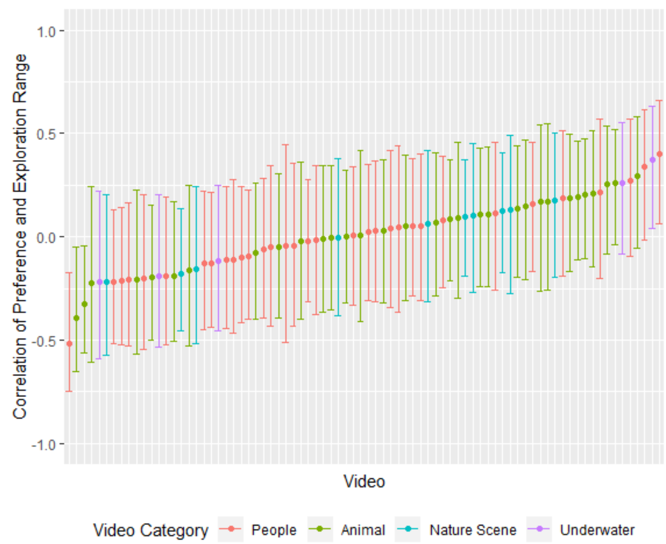

Fig. 6: The correlation between preference and exploration range of each video. Color indicates the categories of the videos.

quadratic. In our comparison between a mixed effects model with prior VR experience, order of videos, and the interaction between them as fixed effects and participant and video as random effects to the model with the quadratic term of the order in addition, we found that the model with the quadratic term was more accurate ($\chi^2(2) = 44.05$, $p < 0.001$). Second, first-time VR users explored less than experienced VR users ($t(315.65) = 3.66$, $p < 0.001$).

In the mixed effects model with a binary fixed effect of VR experience and a quadratic fixed effect of order and random effects of video and participant, all terms were statistically significant. Prior experience ($b = 0.17$, $t(2478) = 4.83$, $p < .001$) and order of the video ($b = 0.120$, $t(1987) = 6.31$, $p < .001$) were positively associated with exploration range. The square of order ($b = -0.017$, $t(1988) = -5.40$, $p < .001$) and the interaction between prior experience and order ($b = -0.061$, $t(1991) = -2.55$, $p = .01$) were negatively associated with exploration range.

Based on our post-hoc interpretation of the quadratic term as the combination of a learning effect within the first one or two videos and a fatigue effect after the initial set of videos, participants without prior experience were more responsive to the learning and fatigue effects compared to the participants with prior experience. Anecdotal accounts noted that sometimes participants were surprised and disappointed when the 20-second video finished the first time. After a video or two, some participants learned they could explore the scene to look in any direction. The visible difference in the first session between first-time users and experienced users lends more evidence to interpreting the initial effect as a learning effect.

B. Exploration and Preference

In this dataset, the relationship between exploration and preference is nuanced. The first thing to point out is the wide range of exploration values. Descriptively, the nature scenes which don't have a dedicated focal point (i.e., no animal or person in the scene) induced larger exploration range compared to others ($t(16.92) = 4.72$, $p < .001$).

Figure 5 shows the relationship between a video's exploration and its average preference value. Each point in the scatter plot is the average preference rating by exploration when averaging across all participants who saw that video. The relationship is negative ($r = -.24$) and significant ($p = .028$) such that videos that had on average more exploration were preferred less. Second, in Figure 6, we plot the correlation between exploration and preference within each video individually, investigating whether some videos had different relationships than others. Each of the lines in the graph represents the correlation between exploration and preference for only the participants who saw that video. While there is not a clear statistical interpretation for a plot like this, we note two important features. First, the mean of all these correlations is about zero—there is no general effect within a video of exploration on preference. Second, there are about as many "significant" correlations within each video as would be expected by chance. The fact that 5 of 80 of the 95% confidence intervals don't overlap with 0—and that they are on opposite sides—is consistent with a true effect of zero.

These two figures seem to contradict each other: in the first, it appears exploration and preference are negatively related, and in the second, it appears there is no relationship at all. To reconcile them, note that the first aggregates by video while the second looks only within video. Consider that some feature of the video—perhaps whether it has a key focal point—influences both exploration and preference. A focal point means users find it and continue watching it, and therefore have lower exploration. A focal point also means there is some part of the video that draws and keeps attention, which is likely a preferred experience. When controlling for video by looking only at one video at a time, one would expect exploration and preference to be independent, as is in Figure 6. However, when aggregating by video, one would expect the relationship between exploration and preference to be present, as is in Figure 5. The take-home message here is that if one only examines a single piece of content, relationships that emerge when one looks across many pieces can be missed.

C. Higher Correlation between Presence and Arousal for Arousing Stimuli

Freeman and colleagues [41] stated that arousing stimuli show correlation between presence and arousal, while non-arousing stimuli do not. We examine this statement with a reformulation their comparison between groups of arousing and non-arousing stimuli into a correlational analysis over arousal. Figure 7 shows the result of this correlational analysis with the 80 videos as the unit of analysis. The correlation between presence and arousal per video was positively correlated ($r = .29$, $p = .01$) confirming the statement of Freeman and colleagues [41]. In Figure 8, we plot the correlation between presence and arousal within each video. With 43 videos having their 95% confidence interval above zero, this shows the consistency of the positive correlation between presence and arousal across individual videos.

D. Biological Sex and Simulator Sickness

The most direct way to test this question like this is a simple t-test by biological sex between participant's average simulator sickness scores over the five videos. This test was marginally significant, $t(502.95) = 1.74$, $p = .08$, with women having more simulator sickness than men.

Applying the within video approach, in Figure 9, there were only two videos whose confidence interval of the effect size of biological sex to simulator sickness did not overlap with zero.

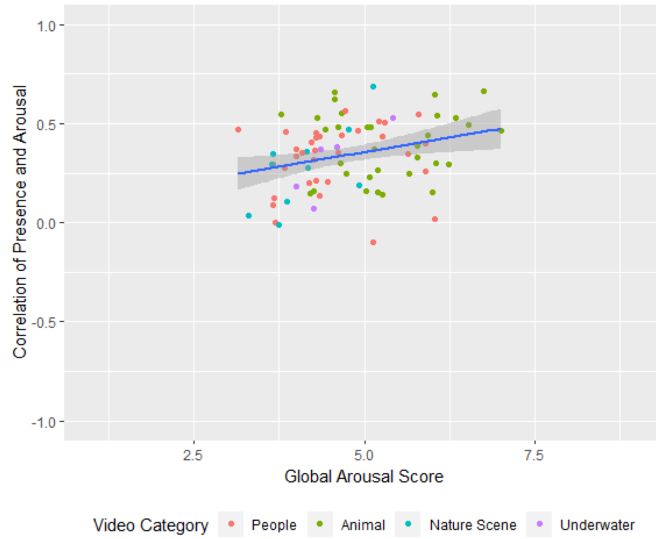

Fig. 7: The correlation between the global arousal score of the videos and the correlation between presence and arousal of videos. Color indicates the categories of the videos.

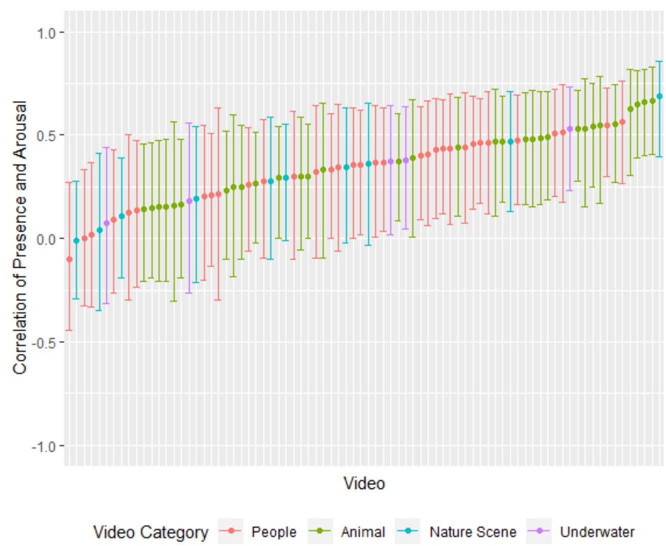

Fig. 8: The correlation between presence and arousal of each video. Color indicates the categories of the videos.

While this result did not support the link between biological sex and simulator sickness, the discrepancy between this result and the marginally significant result between videos led us to notice the videos with significantly positive effect sizes. The two videos with the largest effect sizes, that caused the between video analysis to have marginal significance, were a video with skateboarders and a video taken from a hotel balcony high enough to induce fear of heights.

To explore this interaction further, note that overall, participants reported low simulator sickness. In fact, 229 of the 505 participants (45%) reported the lowest amount of simulator sickness statistically possible ("None at all", ranked as 1), on both simulator sickness questions across all 5 videos. Given we used hardware with low latency and excluded videos which

Fig. 9: The effect size of biological sex to simulator sickness of each video. Color indicates the categories of the videos.

had any camera movement, this low rate of simulator sickness is not surprising. To address the lack of response variance, we ran a post-hoc analysis, binning participants into two categories based on whether their reported average sickness was above or below "Slightly" (ranked as 2). In this analysis with Fisher's exact test, women (31 out of 214), compared to men (14 out of 246), were more likely to feel simulator sickness ($p = .005$).

IV. Conclusion

In this work, we explored and examined VR 360-videos with demographic information of the participants, self-reported measures, and tracking data that measured participants' physical movements. We examined the research questions that were driven by existing theories and anecdotal observations. Since 360-videos, and VR experiences in general, cannot be fully seen without head rotations, we investigated how people explore (i.e., rotate their heads) when they are watching 360-videos. We first looked at how long it takes for people to horizontally explore the 360-videos. In 20 seconds, about 40% of the participants fully rotated to see the entirety of the scene, and about 70% of the participants rotated to explore more than half of the scene. Additionally, we found that there is a quadratic pattern between exploration range and the order of videos; exploration range increases for the first few videos then starts to decrease.

In our analysis on head movement and preference, we found that exploration range were negatively associated with preference when using video as the unit of analysis, while there was no significant correlation between them when looking at the videos one at a time. We find this relationship, which is puzzling at first sight, might be explained by the role of focal points in 360-videos. In other words, when people find interesting points inside a 360-video, they keep looking at that point, and these focal points might be a feature that is associated with videos that are preferred in general, hence the negative correlation comes from the between video analysis. Supporting this argument, in the within video analysis, when different participants were looking at the same video, the correlation between exploration range and preference disappeared.

Inspired by Freeman and colleagues [41], after reformulating their cross-study approach into a correlational hypothesis, we found a positive correlation between the global level of arousal of videos and the correlation of presence and arousal within the videos. With an analysis over individual videos and the correlation within the videos, we showed the consistency of the positive correlation between presence and arousal across individual videos.

Utilizing the demographic information and simulator sickness data of our study, we examined the effect of biological sex on the level of simulator sickness. The direct comparison between female and male participants showed a marginally significant effect of biological sex in the direction of female participants experiencing more simulator sickness than male participants. In an analysis that binned participant based on whether they felt simulator sickness or not, given that many of our participants reported the lowest amount of simulator sickness, we found that female participants were more likely to feel simulator sickness than male participants.

A. Limitations

To improve the representativeness of our video samples, we aimed to have videos widely distributed in terms of valence and arousal. However, there was no videos in our sample with a low level of valence (i.e., negative videos). This is in part due to a general paucity of videos which are very low in valence available to the public, and in part a failure by overestimating, during our qualitative process of examining videos for the study, the negative valence of the videos in our sample.

On simulator sickness, our study suffered from having a very low mean value, indicating that there might have been a floor effect. While this may suggest that new devices are better at rendering content based on head movements and mitigated simulator sickness, it is unclear what caused the low mean value in our study as we did not use older devices.

Given we were working with a public museum to recruit participants, we needed to keep the total amount of time spent in VR per-person to a minimum to be able to include all guests who wanted to participate in the study. And given it was essential to our design to include multiple videos per participant, we needed to limit the length of the videos to 20 seconds to maximize the number of participants. Moreover, we prioritized avoiding simulator sickness given these were museum guests in a public place, and the short length of the videos was also designed to minimize simulator sickness found.

For the exclusion of subjects due to our pre-screening procedure, we do not know how many were excluded, which does limit our ability to generalize our results to the entire population. In future work we will ensure to record this data.

Additionally, we attempted to widen the age of participants by diversifying our recruitment processes, for example word of mouth at the museum. But still, a large portion of the participants were relatively young with more than half of them being under 26 years old. In future studies, we hope to have enough variance in age in order to look at interactions between age and gender.

B. Future Work

While we explored many research questions in our current study, our approaches are mostly exploratory and descriptive. We designed our experiment to become one that is scientifically general-purpose, being able to answer many research questions. In the future, more specific research questions should be addressed with experiments designed for specific purposes. For example, with our study, it is impossible to examine the causal directions between head movement and preference due to the lack of experimental conditions. Work on education demonstrates another potential direction (e.g., [48], [19], [18]). Also, in future work we plan on utilizing longer videos to provide better insights, especially in regards to simulator sickness.

C. Implications

As our study dealt with a popular form of VR, there are implications relevant to future researchers, VR designers, and content providers. From our observation on the exploration pattern of participants, when the experience is expected to last longer than tens of seconds, it is understandable to expect participants to find objects placed even behind them. Based on our analysis on head movement and preference, exploration range and preference were negatively associated, showing that participants explored the preferable videos—which were likely to have attention grabbing focal points—less than other less preferable videos. The relationship between presence and arousal implies that arousing VR experiences (e.g., roller coasters and horror movies) should be arousing to induce higher level of presence, while this is less important to less arousing VR experiences (e.g., peaceful sceneries and mediating videos).

Most striking from the current work is the wide range of responses which occur on different pieces of content. Most VR studies examine only a single piece of content and infer some causal effect about the medium from that single piece of content. As research progresses it is critical to generalize research findings across various VR experiences.

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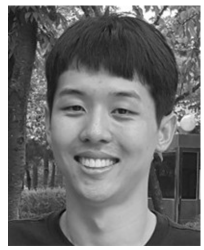

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APPENDIX A
QUESTIONNAIRE

A. Demographic

1) How old are you?
   - 15-18
   - 19-25
   - 26-35
   - 36-45
   - 46-55
   - 56-65
   - 65+
2) What gender do you identify as?
   - Female
   - Male
   - Other
3) What is your racial background?
   - African American, Black
   - Indian
   - Southeast Asian
   - Mexican
   - Chinese
   - Japanese
   - White, Caucasian, Non Hispanic
   - American Indian, Native American
   - Filipino
   - Korean
   - Hispanic or Latino
   - Middle Eastern
   - More than one race
   - Unknown or not reported
   - Decline to answer
4) How many times have you used VR before?
   - This is my first time using VR
   - 1-2
   - 3-5
   - 6-10
   - 10-15
   - 15+

B. Survey

1) Valence

2) Arousal

3) To what extent did you feel like you were actually inside the virtual experience?
4) To what extent did you feel surrounded by the virtual world you saw?
5) How much did it feel as if you visited another place?
6) Indicate how much dizziness affected you during the virtual experience.
7) Indicate how much nausea affected you during the virtual experience.
8) How likely are you to recommend this virtual experience to someone?
9) To what extent would you would have liked the virtual experience to continue.

APPENDIX B
STATISTICS ON DEMOGRAPHIC VARIABLES

Age	19-			19-25			25+			Total
Biological Sex	Female	Male	Total	Female	Male	Total	Female	Male	Total	
Participants	40	58	98	104	64	168	103	140	243	509
Arousal	4.70	4.61	4.65	5.08	4.89	5.01	4.75	4.76	4.75	4.82
	(2.38)	(2.39)	(2.39)	(2.21)	(2.20)	(2.21)	(2.29)	(2.32)	(2.30)	(2.29)
Presence	3.69	3.64	3.66	3.62	3.26	3.48	3.47	3.49	3.48	3.52
	(0.88)	(0.80)	(0.83)	(0.86)	(0.90)	(0.89)	(0.95)	(0.82)	(0.88)	(0.88)
Sickness	1.34	1.27	1.30	1.34	1.21	1.29	1.34	1.28	1.31	1.30
	(0.64)	(0.57)	(0.60)	(0.68)	(0.46)	(0.61)	(0.64)	(0.67)	(0.66)	(0.63)
Preference	3.54	3.66	3.61	3.33	3.24	3.29	3.35	3.42	3.39	3.40
	(1.13)	(1.04)	(1.08)	(1.14)	(1.09)	(1.12)	(1.16)	(1.10)	(1.12)	(1.12)
Exploration Range	0.71	0.70	0.70	0.74	0.73	0.74	0.63	0.65	0.64	0.68
	(0.25)	(0.23)	(0.24)	(0.23)	(0.22)	(0.23)	(0.27)	(0.26)	(0.26)	(0.25)

TABLE I: Mean values (and standard deviations) of the demographic groups.

APPENDIX C
STATISTICS ON VR EXPERIENCE AND ORDER OF VIDEOS

Order	1			2			3			4			5			Total
VR Experience	Yes	No	Total	Yes	No	Total	Yes	No	Total	Yes	No	Total	Yes	No	Total	
Participants	321	190	511	321	190	511	321	190	511	321	190	511	321	190	511	511
Arousal	4.45	4.72	4.55	4.77	4.93	4.83	4.91	4.89	4.90	4.83	4.99	4.89	4.80	5.15	4.93	4.82
	(2.14)	(2.35)	(2.22)	(2.28)	(2.34)	(2.30)	(2.30)	(2.30)	(2.30)	(2.37)	(2.29)	(2.34)	(2.29)	(2.26)	(2.28)	(2.29)
Presence	3.23	3.43	3.30	3.50	3.69	3.57	3.57	3.65	3.60	3.54	3.59	3.56	3.47	3.65	3.54	3.51
	(0.79)	(0.82)	(0.81)	(0.84)	(0.79)	(0.83)	(0.87)	(0.85)	(0.86)	(0.92)	(0.91)	(0.92)	(0.94)	(0.94)	(0.94)	(0.88)
Sickness	1.26	1.39	1.31	1.23	1.38	1.28	1.23	1.41	1.29	1.23	1.42	1.30	1.25	1.41	1.31	1.30
	(0.54)	(0.64)	(0.58)	(0.54)	(0.73)	(0.62)	(0.57)	(0.69)	(0.62)	(0.58)	(0.75)	(0.65)	(0.62)	(0.73)	(0.67)	(0.63)
Preference	3.23	3.59	3.37	3.41	3.59	3.48	3.40	3.47	3.42	3.28	3.52	3.37	3.27	3.48	3.35	3.40
	(1.13)	(0.94)	(1.08)	(1.12)	(1.01)	(1.08)	(1.15)	(1.05)	(1.11)	(1.22)	(1.03)	(1.15)	(1.22)	(1.07)	(1.17)	(1.12)
Exploration Range	0.68	0.58	0.64	0.72	0.65	0.69	0.73	0.67	0.71	0.72	0.68	0.70	0.70	0.64	0.68	0.68
	(0.26)	(0.30)	(0.28)	(0.23)	(0.28)	(0.25)	(0.22)	(0.26)	(0.24)	(0.23)	(0.25)	(0.24)	(0.22)	(0.26)	(0.24)	(0.25)

TABLE II: Mean values (and standard deviations) across prior VR experience and order of videos.