The Geometry of Storytelling: Theatrical Use of Space for 360-degree Videos and Virtual Reality

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ABSTRACT

UPDATED—January 23, 2017. 360-degree filming and head-mounted displays (HMDs) give recorded media a new sense of space. Theatre practitioners' expertise in manipulating spatial interactions has much to contribute to immersive recorded content. Four theatre directors led teams of three actors to stage the same scene for both immersive theatre and for 360-degree filming. Each team was recorded performing the scene at least six times, three in each condition, to extract actors' coordinates. This study establishes how to quantify theatre practitioners' use of spatial interactions and examines the spatial adaptations made when transferring these relationships to 360-degree filming.

Staging for a 360-degree camera compared to staging for an audience member had shorter distances from the camera and between performers, along with fewer instances of the camera being in the middle of the action. Across all groups, interpersonal distance between characters and between the audience/camera dropped at the end of the scene when the characters come together as a team, suggesting that elements of Proxemics may be applicable to narrative performance.

ACM Classification Keywords

J.5 Computer Applications: Arts and Humanities, Performing arts; H.5.1 Information Systems: Multimedia Information Systems

Author Keywords

Virtual Reality; Narrative; Theatre; Performance; Cinematic VR; Interpersonal Space; Head-Mounted Display; Workflow; 360-degree video

INTRODUCTION

The first head-mounted display (HMD), nicknamed 'Sword of Damocles' because of the bulky and alarming apparatus precariously perched above the viewer, was developed in 1968 [27]. Nearly 50 years on, our HMDs are light-weight and relatively comfortable to wear with Google Cardboard [1], Samsung Gear [2], HTC Vive [8] and Oculus Rift [10] all commercially available. For creators of entertainment and games in Virtual Reality (VR), the new accessibility of VR content makes the stakes for immersion much higher. The commercial implications of a satisfactory VR experience could be considerable. In the first two months of 2016, $1.1 billion were invested into VR companies, films and initiatives [5], leading to a plethora of techniques aimed at hijacking the human senses. To fully immerse the viewer, VR developers are exploring techniques as varied as allowing the user to navigate the virtual space as they walk through their viewing space [8], using dynamic spatialised sound to keep sound sources consistent in the virtual world as the user moves their head [10, 26, 8] and even providing tactile feedback to the user through a vibrating body suit [22]. Competition is fierce to find the most convincing content, the most realistic journey into an imaginary world and the most emotional connection between user and virtual content.

Narrative, immersion and control in VR

For the first time creators of recorded content have the possibility of using a sense of space as a narrative tool. Like VR, theatre is a fixed-point 360° experience in which the audience is free to look anywhere, so expertise in theatre can inform VR cinematography. Traditional film techniques manipulate a sense of space by changing how the viewer's gaze is framed. While VR has thus far struggled to reconcile narrative control with audience relationship and interactivity, theatre has an established practice of combining all of these elements through the careful orchestration of physical spaces and spatial relationships. The expertise of theatre practitioners lies not only in their presentation of narrative through spatial cues, but also in their management of the complex spatial relationship between audience members, the physical action on the stage and the narrative of the imagined world of the play. VR commentators and content creators seeking solutions to VR's narrative challenges have come to think of theatre as offering possible answers [12, 25] and in August 2016 the National Theatre founded its first VR Studio [15]. Sound principles lead VR creators to expect answers from theatre. Experienced theatre practitioners can spatialise narratives for different audience configurations, negotiating complex layers of spatial relationship between audience, actors and characters.

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This study examines how theatre practitioners with no experience of VR develop spatialisations of narratives and what adjustments they make when transferring these stagings for viewing on a HMD. This paper will first establish the parameters theatre practitioners use when approaching a narrative and whether different practitioners approaching the same script share any common spatial tactics. Secondly, it will examine how staging is adapted for filming on a 360-degree camera and playback on a HMD. By analysing the quantitative differences in spatial arrangements, as well as the discussions between actors and director in rehearsal, this study aims to provide insight into the narrative use of space in theatre and how this can be applied to VR content creation. The focus of this research is the process and artistic use of new technology and does not engage in assessing the quality or audience-friendliness of creative outputs.

RELATED WORK

This section reviews theories of how spatial relationships are interpreted in social settings, their effect in virtual environments and use in performance.

Theories of Interpersonal Space: Distance and Orientation

How people stand, sit and move in relation to one another and the space surrounding them informs the way we experience social dynamics. Interpersonal distance, the distance between those taking part in an exchange, and orientation, the direction that interactants are looking and turning their bodies towards, are two key factors that impact how we interpret spatial interactions. Spatial relationships are so key to social interactions that the interaction itself can be defined in spatial terms, relying on the ways in which two or more people arrange themselves when interacting. Kendon [21] defines a unit of social interaction by the presence of an *F-formation*, in which two or more people mutually orient towards a shared space between them that they all have access to, called the *O-space*, which all members of the F-formation are orienting towards (Fig. 1). The F-formation is not dependent on these spaces maintaining a particular shape (such as a circle or a rectangle) or even involving the same people. As a unit of social interaction, the F-formation's shape is in flux as its interactants shift to accommodate new members or members who leave; it is defined solely by the group maintaining the shared O-space, which is not directly accessible to those outside the F-formation.

The social dynamics of an interaction also affect the way in which they are spatially organised. During a cooperative activity two people are more likely to stand next to one another or at a 45° angle, maintaining a shared orientation to the task at hand. A competitive activity is more likely to involve interacting pairs to sit opposite one another [21]. When someone gives directions, they usually stand next to the person they are giving directions to, which gives both parties a shared orientation and facilitates indicators like 'left' and 'right' [23]. The status of participants in an interaction is also signalled by use of space: the person with the most speaking rights tends to have more space within their group, so an unequal spread of participants can indicate unequal speaking rights [21].

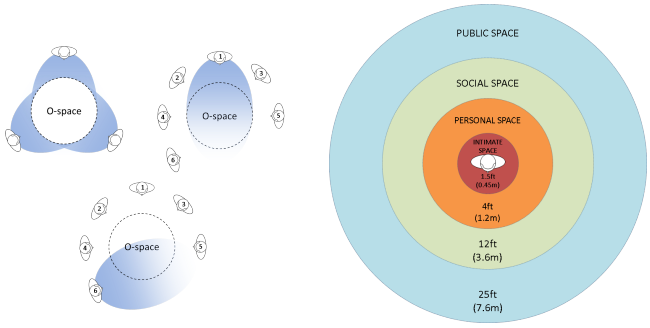

Figure 1. Diagrams of F-formations (left) and Proxemics (right), based on [6, 11]

Interpersonal distance is integral to *Proxemics*, the theory that suggests that there are concentric circles of personal space around the body, like bubbles: intimate space, personal space, social space, and public space [19] (Fig. 1). Hall suggests that though the dimensions of these spaces differ according to physical environment, culture and personality, we are sensitive to social violations of these boundaries and react to them.

Interpersonal Interactions in Virtual Environments

The importance of interpersonal space to our experience of social interactions extends to digital and virtual environments. In virtual environments (VEs) people respond more strongly, measured by skin conductance, when they approach a humanoid figure than when they approach a cylinder of the same size [13]. They will also come closer to a humanoid figure not making eye contact [13]. These findings indicate that the principles of Proxemics hold in virtual environments, despite the fact that the humanoid figures within the environment were not particularly realistic.

The complexity of our relationship to virtual agents is illustrated by the fact that when participants believe virtual agents to be avatars of human beings they maintain a greater interpersonal distance than if they believe those figures to be computer generated [14]. Changes in spatial behaviour generated by the presence of others is at the heart of live performance, from using spatial relationships to understand the meaning of characters' interactions to the spatial relationship between audience and performers.

Spatial Configurations in Performance

Theatre practitioners are required to have a keen sense of space. First, there are a wide range of physical configurations possible in a performance space. Each staging places different technical demands on the creative team who develop 'blocking', the final on-stage positioning of the cast. Blocking takes into account the presence of on-stage objects, or 'props' (short for 'theatrical property'), as well as the physical placement of the audience. During the rehearsal period, the process of blocking is a negotiation of visibility for the audience, anticipating the practical demands of on-stage placement and suitable narrative actions. If an actor needs to refer to a drink they have in their hands, the blocking needs to ensure that they will reliably be near that tray that holds the drink in time to say the line. Those timings and placements will be altered by the physical

dynamics of the character (the object might need to be closer if the character is old and slow) and the physical capabilities of the actor (if an actor has a broken arm, the objects may need to be placed on their 'good' side).

Actors have a spatial obligation to their audience. They 'cheat out' towards the auditorium, a theatrical term that refers to the actors' orientation towards the audience. Even when speaking to another actor on stage, an actor is rarely in profile, instead 'cheating' their orientation to a three-quarter profile, with their legs and pelvis facing the auditorium, so that the audience can see their expressions and hear them clearly. As well as the pragmatic need for this type of spatial manipulation, maintaining lower body orientation with the audience keeps audience-members within an actor's F-formation. Lower-body orientation is more stable than upper-body orientation (movement of the head and shoulders) and is typically used as an indicator of engagement and interaction between people rather than the more fleeting upper-body orientation [21, 18, 23].

Actors constantly negotiate spatial needs with the technical demands of lighting and sound in real time while performing. Blocking is most commonly used to preserve a sequence of spatial relationships, such as "near the tray, facing towards the audience but opposite the table," rather than to state the exact on-stage placement of the cast members. The importance of spatial relationships in theatre is such that theatre practice has its own navigational terms to avoid confusion. 'Stage left' refers to the left-hand side of the stage when viewed from the performer on stage, a key point of clarification particularly when the director or choreographer is providing advice from the auditorium.

The process of blocking is also one of the most important parts of conveying the identity and relationships of characters on stage. As social beings, people are finely attuned to interpersonal space, gaze and orientation, reading them fluently in their everyday lives. The overlap between research into space in social interactions and rehearsal practices in theatre is striking, though unsurprising. For example, high status characters tend to be given more physical space around them, tallying with findings that show that the person with the most speaking rights has more space around them [21]. Imagine a classic film where a pauper throws off their rags to reveal the glimmering outfit of a queen: the other characters cower away in awe, physically providing more space to the person whose status is now raised. The scene would be decidedly underwhelming if the queen's reveal led to no movement from the other characters.

For the first time, 360-degree filming and VR make it possible to harness the power of spatial relationships and configurations for recorded media. Rather than manipulating space in a fixed frame, such as close-ups and wide shots, actors can manipulate spatial relationships between one another in a way that is familiar in theatre and in everyday life.

Analysing Interpersonal Space in Performance

This study applies computational methods to further the understanding of spatial techniques in narrative. While no research on actors' use of space appears to exist, group formations and interpersonal distances have been successfully analysed using computational approaches. Interpersonal distances extracted from bird's eye view footage of two sessions, with six and seven people interacting respectively, were sufficient for a computational analysis of participants' status and intimacy based on Proxemics [17]. Interpersonal distances have been shown to have a significant effect in VR and have been successfully used for computational analysis of social dynamics.

This experiment examines how theatre practitioners approach the use of performance space when telling a story for an audience member or for a 360-degree camera in the centre of the stage. Interpersonal distances, distance from centre (the camera or audience member) and the maximum angle between performers on stage were measured to analyse actors' spatial configurations. Clear narrative shifts and characterisations in the script provide a test for the basic ways in which theatre practitioners might spatialise stories. One would expect a character to physically move away from the others when they are excluded and for characters to come closer together when they are on more intimate terms. The same interpersonal dynamics may also hold true in the relationship between the audience member in the centre, with characters who are empathetic to the viewer closer to the centre than those who are not. Based on F-formations, one might also expect that actors would include the audience member in their F-formations when trying to connect them to characters or moments in the narrative, whereas placing them in the centre of an F-formation has a more alienating effect that makes the viewer the spatial focus of the actors' action. By first testing whether these principles hold true in theatre staging, then tracking their evolution when groups produce the same piece for 360-degree filming, this study aims to gain a better understanding of the narrative spatial techniques theatre practitioners can contribute to VR.

METHODOLOGY

Experimental Design

The aim of the experiment was first to examine how creative teams use spatial configurations to establish relationships between characters and with audience members, and second how these spatial configurations change when staging for a live audience member compared to a 360-degree camera. Four creative teams, each composed of one director and three actors, were asked to rehearse the same scene for two creative briefs. At least three recordings of the scene were taken for each creative brief in each group (Table 1). Groups were asked to stage the scene for a single audience member seated on a swivel chair in the centre for the immersive theatre brief, while during the 360-degree brief groups staged the scene for a 360-degree camera in the centre of the stage. Of the four groups to take part, two began with the 360-degree brief and two began with immersive theatre; neither had any knowledge of the second brief they were asked to complete during the second part of the experiment. The order in which groups undertook the creative briefs was counter-balanced in order to control for the effect of rehearsal on staging. By asking all teams to fulfil both briefs (described in more detail below), it becomes possible to examine how the same team's stagings differed between the two briefs as well as to compare stagings between groups.

	Group 1	Group 2	Group 3	Group 4
Morning	Theatre x 3	360-filming x 3	Theatre x 3	360-filming x 3
Afternoon	360-filming x 3	Theatre x 3	360-filming x 3	Theatre x 3

Table 1. Experimental Conditions

Designing an Experimental Script

A professional writer was commissioned to write a three-person scene to be used as the basis for this experiment. Copyright-free scripts were generally poor quality and three-person scenes where all parties have roughly equal speaking parts are rare. The writer was known to the experimenters and had previously worked with the BBC on a short film, in addition to having worked as a scriptwriter for narrative games.

The writer was asked to write a short theatre scene that fulfilled the following criteria:

- A three-person cast with roughly equal speaking parts
- Little to no reliance on objects to tell the story and no stage directions
- No actors leave or enter the scene for the duration of the script, and it is treated as a 'curtain up, curtain down' scene with self-contained action
- Strongly stylised (either melodrama or comedy) to encourage movement
- At least one change of social dynamics in the storyline

Based on the criteria above, the writer created a six- to seven-minute scene during which three colleagues are in a corridor waiting for a meeting with their employer (see *Leverage* in Supplementary Materials). Two colleagues Brian and Alice are half-heartedly comforting the third, Cathy, who fears she may be about to lose her job. Brian is confident the he will not be fired as he has "leverage" over the employer. Alice undermines the value of the leverage Brian believes he has, which leads Brian to believe he will be fired and to attack Alice by citing her poor appraisals. Alice then becomes convinced she is the one who will be fired. Finally the three come together, deciding that while each of them may be disposable, all three of them cannot be fired if they stand united. During the scene it becomes clear that the three characters are in fact elves and that their employer is Santa.

The text was written in a comedic sketch-show style. It had the benefit of not requiring strict casting, which gives the directors greater freedom in selecting their cast. Other than having gendered names, the characters did not require actors of any particular age, ethnicity or physical mobility.

Participants

Four directors were recruited to take part in the experiment who in turn recruited three actors each. Two of the directors were recruited from prior involvement in the experimenters' projects. All directors had been working professionally for at least seven years and had been affiliated with established theatres. Two and a half weeks prior to commencing the study, directors were provided with a draft script to assist them in the selection of appropriate performers for the roles.

The participants in the study had a diverse range of experience in theatre and all had participated in non-traditional staging for live performance. The 16 participants were aged between 26 and 60, with a mean age of 34. 15 of the 16 participants had taken part in productions that were immersive, interactive or ensemble-based. 94% reported between 5 and 20 years of professional experience in theatre, with 56 % reporting between 10 and 20 years of experience. They had all previously included audience participation in at least one live production with 87.5% reporting that they directly engaged audience members at least half of the time in their staging. 93 % participants had no experience creating work for 360-degree filming, video games or VR, though 69% had watched a 360-degree video and 56% had viewed content a head-mounted display.

Creative Briefs: Theatre vs 360-degree filming

One week before their involvement in the study, directors were provided with a short document outlining the creative brief they would be asked to direct in the morning, which differed depending on the experimental condition to which they were randomly assigned. Both creative briefs required staging the scene around a central point which contained either an audience member or a 360-degree camera. In neither condition were participants allowed to change the placement of the camera or audience member so that each group's spatial staging could be directly compared. The immersive theatre brief asked directors to stage the scene for one audience member seated in the centre of the space in a swivel chair. This brief was designed to simulate the viewing requirements of non-interactive VR without involving its technical elements. The audience member in the immersive theatre scenario is physically able to turn to follow the action, much as VR viewers wearing a Head-Mounted Display (HMD) are able to do. The VR brief asked directors to stage the scene for a 360-degree camera placed in the centre of the space and explained that they would not be expected to have any prior technical knowledge of the 360-degree filming process.

VR Training and Use of 360-degree Technology

The VR training delivered to all creative teams was a combination of documentation and hands-on experience of a HMD. Prior to training, all team members were asked a series of screening questions to ensure that they were physically and mentally fit to experience a film on a HMD and willing to do so. Participants were informed that their ability to use the HMD in no way affected their involvement in the study. All participants passed the screening questions. One person opted not to view the content during training though they later decided to view the footage from their shoot. The HMD used, a Samsung Gear, uses a Samsung S7 phone as a screen, which plugs into the headset [2].

During training participants were provided with a basic explanation of how 360-degree films are created by 'stitching' together two or more angles to capture a scene in 360°. They were shown the Ricoh Theta S camera they would be using throughout their 360-degree brief, with particular attention to the two lenses mounted on the camera [3]. They watched Cirque du Soleil's 360-degree video *Zarkana* [16], chosen for its relationship to staging a live performance, on a Samsung

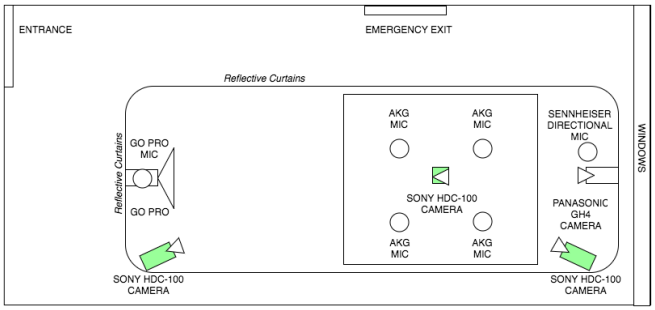

Figure 2. Diagram showing the placement of recording equipment

Gear [2] to familiarise participants with navigating around a 360-degree film. The 360-degree camera was then placed in the middle of the room on a tripod at a height of 1m20, or eye-level of a seated viewer in a swivel chair. Participants were told that they review recordings of their performances on the available HMD. An experimenter organised this transfer, which involved moving the file from the camera, rendering it into a HMD-friendly file and transferring it onto the Samsung phone that was being used in the Samsung Gear. This process took roughly 20 minutes for a video of the entire scene, which varied between five and eight minutes in length. All participants were warned that reviewing the footage would involve delays due to file transfers.

Room and Recording Set-up

Data was collected in three ways: video to record the coordinates and timing of actors' movements, audio to document their discussions during the process and in interviews and questionnaires to provide information on the participants' prior experience. A clapper board was used during recordings to help synchronise camera footage and audio recordings. The available 'stage space' for the teams was determined by the amount of space covered by the overhead camera, which led to a 3.5m by 3.5m space being taped off in a room that was 5m by 11m. A circle roughly 50cm in diameter was taped off in the centre of the stage space so that a swivel chair or a tripod could be placed there. In order to minimise their effect on the rehearsal process, experimenters remained in a separate viewing gallery during the study and observed the video feeds in real-time. Both morning and afternoon sessions were recorded using five cameras. Three cameras were primarily used to capture actor movement: one directly over the centre and two diagonally facing the actors from a height of roughly 3.5m (Fig. 2).

Extracting Actor Coordinates from Video

There are two parts to extracting the positions of the actors from the footage from the three 'data cameras.' First, the 2D position of the actors in the video picture provided from each of the cameras was determined; second, the positions from the three cameras were combined for each actor to determine their 3D position. The 2D position of the actor was determined by using software that analysed the video frame by frame, looking for an area of distinct colour within the picture using chroma-keying on the actors' distinctly coloured T-shirts and choosing the centre of that region. We then found the 'centroid,' or mean position of all the pixels that were inside these two regions, and chose the largest regions to exclude the odd pixel in the scene that may match the right colour. We recorded this centroid for each actor for every frame as their 2D image position. This was repeated for all three cameras recording the scene.

In the second stage we converted the 2D positions to 3D by using our knowledge of the positions of the cameras to triangulate the actor's position. Before any recording began, the three camera positions were calibrated to establish their positions and orientations in the real world. Once we had the positions of the actors in 2D in the camera's image we could use software to calculate the vector produced by 'shooting' a line of sight or ray out from the camera's centre, through the 2D point in the image and out into the 3D world. Three rays, one from each camera, were taken for each actor. Each of these rays was compared with the others to determine the positions in 3D where they passed nearest to one other. The measurements had some inaccuracy so the rays were likely to pass each other without touching. Once every ray had been compared to each other ray we had three possible positions of the actor in 3D. The median of the three positions was deemed to be the 3D position of the actor. The median is useful as it allows for the exclusion of results that are furthest away and likely to be wrong. This was repeated for every frame and for every actor and the results were written out for further processing.

Questionnaires and Qualitative Data

Participants were asked to fill in questionnaires about their professional experience and training, VR and 360-degree filming experience and demographic information. These questionnaires were administered on laptops using Qualtrics. Experimenters present in the gallery during the experiment noted timestamps of discussions about space, 360-degree filming, and relationship to camera/audience member, which were later transcribed from recordings. The number of chairs was tracked by reviewing the video footage. Each team was interviewed following both the morning and afternoon sessions and a debrief interview was conducted with the four directors individually in the week following the study.

RESULTS

In total 25 run-throughs were recorded: six for each group (three in theatre and three in 360-degree, with an additional recording in 360-degree for Group 4, described in more detail at the end of this section). The length of the recordings varied significantly. The longest recording was 8m20s, while the shortest was 5m48s with a mean length of 6m57s. The data on interpersonal distances, distance from centre and the size of angles between characters extracted from each video frame (25 per second, to a minimum number of 9250 measurements per recording) was analysed using the Kruskal-Wallis analysis of variance test for independent samples of non-parametric data to establish whether the mean ranks of groups, characters, sessions and experimental condition were significantly different using MATLAB [9]. The test findings were then examined using MATLAB's multcompare tool in the Statistics toolbox,

which used the Tukey-Kramer range test to establish which mean ranks were different to the others above standard error.

Narrative and Spatial Configurations

Anchoring the Space: Audience, Obstacles and Places

Each group was given the option of using three chairs, one for each character. The script was designed to minimise the need for props but chairs were provided after two of the four directors asked if chairs would be made available ahead of the study. The placement of the chairs was important in determining the floor patterns the actors traced and provided spatial anchors to which they gravitated or avoided. After watching a run-through on a swivel chair, a director remarked that "we need another chair over there because the chair has a gigantic gravitational pull of the focus," noting that both their gaze and the actors' movement were being disproportionately affected by the chair. The chair or chairs were also used by three of the four directors as places for characters to go to when they realise that they are at risk of being fired. Two groups used the term "*oh shit* chair" in rehearsal because each character exclaims "oh shit" when they realise their vulnerability.

As well as using physical objects to anchor the space, all directors quickly communicated representations of place to their casts. They all indicated the direction of Santa's office, an important narrative point as the characters in the scene are waiting to see Santa. For the purposes of data visualisation the coordinates of performances were rotated so that Santa's office was on the same side of the stage (right hand side). Another representative place that was brought up by creative teams was the direction characters had just entered from, while other spatial representations such as lift doors and high windows (from which escape might be possible) were also used.

Character Relationships and Staging

In order to test the theory that the relationships described in the script reliably affected the physical staging of the piece, the interpersonal distances between dyads of characters were compared across all groups. Each group developed its staging completely independently, so significant differences between characters' interpersonal distances that remain consistent across groups would suggest that creative teams were spatialising relationships in systematic ways based on the script. Applying Proxemics, one would expect smaller interpersonal distances to indicate intimacy between characters while greater distances suggest more formal relationships.

The scene used was designed to have clear dynamic changes that would impact spatial configurations. In the scene, three characters (Blue, Green, and Red) are waiting to see their employer. At the beginning of the scene Red (Cathy) is convinced she will be fired, as are her colleagues Green (Brian) and Blue (Alice). Each character has a distinct and archetypal personality: Red is warm and bumbling, Blue is cold and mean, and Green is well-meaning and condescending. As Blue half-heartedly reassures Red, and Green actively tries to make Red feel better, it emerges that Green's sense of security is unfounded. When Red and Blue mock Green's confidence, Green lashes out at Blue, revealing that she is detested by the rest of the staff, which makes her most likely to lose her job. The scene resolves when Red brings Green and Blue together, suggesting that they go in as a team and refuse for any one of them to be fired. The script can be thought of in four phases: during the first three, each character in turn believes themselves to be at risk, and during the fourth they become a unit.

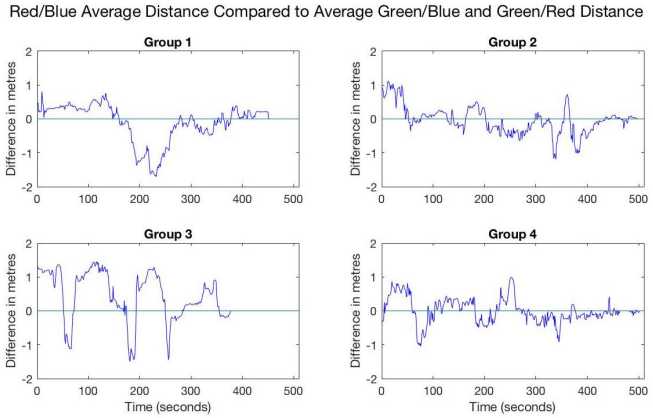

Figure 3. Distance between Red and Blue characters compared to the average distance between Green/Blue and Green/Red dyads

The ranking of interpersonal distances between dyads of characters was significantly different across all groups ($\chi^2 = 142.89, p < 0.01$). The distances between Blue and Red were the longest, suggesting a consistency with the narrative in which Blue and Red are at odds with one another for most of the scene. Fig. 3 plots the difference between the Red/Blue distance versus the mean of the Green/Blue and Green/Red distances for each group (averaged over all performances). While the trend is subtle, the curves are above 0 more often than not, especially for Groups 3 and 4. Note that the noise in Fig. 3 and the two subsequent figures is due to a few factors. The plots combine the coordinates of actors during six or seven performances, each of which have different timings and sometimes narrative choices. Also, the actors were constantly in motion, which means that their spatial relationships were also changing constantly. The narrative expressed through spatial interactions can be seen in more tangible ways. All four groups placed the three characters in close spatial formations at the end of the scene at the moment where the characters decide to work as a team, often linking arms or physically touching, again reflecting social dynamics in their use of space. Towards the end of the scene, all groups showed a drop in interpersonal distance, indicating that the characters moved closer together (Fig. 4).

Audience Relationship and Staging

Across all four groups, the sympathetic Red character was significantly closer to the centre ($\chi^2 = 121.48, p < 0.01$). This suggests that as well as expressing relationships between characters spatially, theatre practitioners may use distance from the audience to express the narrative function of a character. Fig. 5 shows how the distance from the centre for Red varied in comparison to the mean of the distances for Green and Blue.

In general, the curves in Fig. 5 stay below 0, especially for Groups 1 and 2.

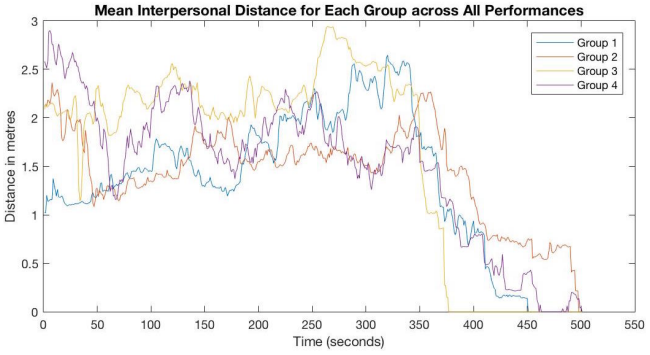

Figure 4. Mean interpersonal distance between dyads for each group over time

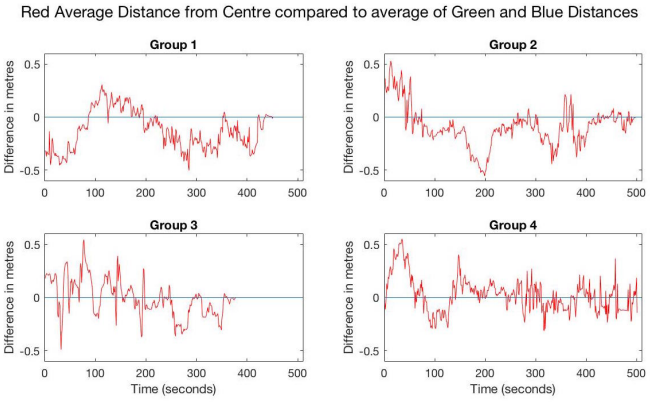

Figure 5. Distance between Red character and centre compared to the average distance from centre of Blue and Green characters

During their first recording, 3 of the 4 groups did not use direct address while in their last recording 3 of the 4 did use direct address, suggesting that over the course of the day those groups decided to emphasise interaction with the audience. Direct address is a theatre term for an actor speaking directly to an audience member and breaking the imaginary fourth wall that exists between stage and auditorium in traditional proscenium arch theatre. The last line of the piece "This is so much worse than working for the Easter Bunny," was delivered directly to audience or camera in 13 of the 25 recordings, with Red turning to face the centre of the space to deliver their line. Direct address was occasionally explored in more depth. One group also had Green's first line, "I don't think she's taking it very well," delivered to the audience. In all groups the issue of direct address was discussed, even when it wasn't used throughout the scene ("Let's do something similar where this [the camera] is just another elf in the room," "maybe next time we'll pretend it's [the centre of the room] an elf"). Two of the groups specifically played with the idea that the viewer was "a spirit" and "invisible," in light of the disembodiment effect that 360-degree recordings on a tripod give the viewer who can't see their body when they look down.

The centre of the stage was occupied with either a tripod or swivel chair, which presented a logistical problem for all groups. The script was designed as a traditional theatre script, but the physical positioning of the viewer/camera led all teams to tackle the presence of a third party in the room as it affected how they could move within the space. Group 1 experimented with placing different representations in the centre of the space (initially a fish tank and later a large Christmas tree) to help justify the unnatural circular movement demanded by the stage. All groups also discussed the possibility that the audience member or camera was in fact another character in the scene: all groups suggested that the audience might be another elf waiting to find out about their employment and one group added the possibility of the viewer being Santa's receptionist. Group 3, after discussion, decided not to make the viewer another character, but Groups 1, 2 and 4 all placed the viewer firmly in the position of another elf by the end of the day. During rehearsal the semantic meanings were given to the space ("come towards the centre when you feel intense emotions" during one exercise) and the stage space was placed within a wider spatial context by improvising the workshop that the characters usually worked in and their journey to the final set of the scene "at the heart of Santa's complex" (Group 2).

Groups 1 and 2 physicalised the audience's membership to the characters' group by placing their three chairs in a line next to the centre point of the space, as if extending the row of chairs to include the viewer seated in their chair watching on a HMD or in the physical space. This simple staging device implies that the viewer is in the same situation as the three characters, placing them in the same space and physical context.

Spatial Configurations in Theatre vs 360-degree filming

The Process of Working with 360-degree Technology

The recordings were only placed on one HMD and the significant length of the recording compared to their available rehearsal time meant that it was difficult for all participants to watch one recording in full and impossible for all participants to watch all three 360-degree recordings in full. The overall decision as to who would watch how much was taken by the director, though actors' opinions were voiced and taken into account. The HMD playbacks were primarily used to check the effects of particular configurations, which then influenced staging choices. In three of the four groups, the director watched a large proportion of the recordings while actors watched smaller segments. One director remarked on the difficulty of taking notes on the performance they were watching on the HMD as they couldn't see their pen and paper. In their feedback on the use of 360-degree technology in rehearsal, several people remarked that they would have preferred more ability to playback their recordings.

87.5% of participants reported that they felt somewhat to extremely creatively satisfied while working with 360-degree technology during the study. Swapping between an audience member and a camera facilitated use of 360-degree: "It felt like it was easy to integrate into the rehearsal process as opposed to a usual camera when you have to be concerned about eye lines / frame etc" and "switching between a real person sitting in for the camera and the camera made the camera less

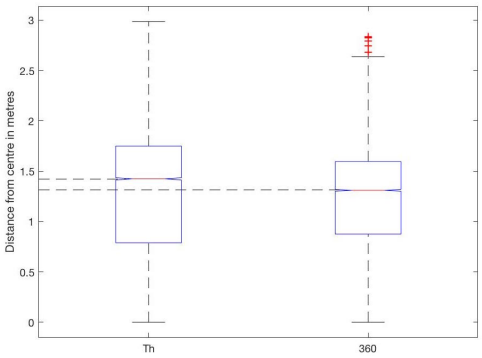

Figure 6. Mean ranks of distance from centre in theatre and 360-degree

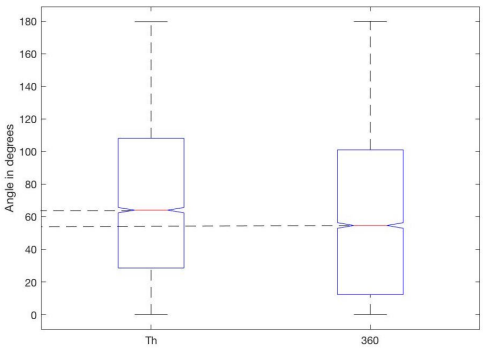

Figure 7. Mean ranks of angles in staging for theatre and 360-degree

abstract and our decisions towards it more conscious." Factors that contributed towards the challenges of working with 360-degree were discomfort with the HMD, the traditional nature of the script which had no explicit direct address and the period of time needed to adjust to the new technology.

Differences between Spatial Configurations in Theatre and 360-degree Filming

All groups, regardless of whether they began or ended with the brief for theatre, used the actors' distance from the centre differently when staging the script for theatre or 360-degree filming. When staging for theatre, actors were further from the centre ($\chi^2 = 383.35, p < 0.01$)(Fig. 6), used wider angles ($\chi^2 = 115, p < 0.01$)(Fig. 7) and were more likely to place the audience member in the centre of their interaction (Fig. 8). The finding that distance diminished with 360-degree filming chimes with theatre practitioners expressing that they felt they could get closer to the camera than they could to an audience member ("I'd like someone to be able to walk through the middle of the camera"). Coming closer to a camera than a person may be due to the extra sensitivity that the actors would have felt in coming close to a person, invading their personal space.

The reduction of angles when staging for 360-degree is likely due to the reduction of field of view that occurs when using the head-mounted display, which has a field of view of only 96° as opposed to our usual field of view of roughly 180°. One actor expressed that "one of the things that really annoyed me was when you were looking at someone you couldn't see someone else. (...) If you're inside 180 degrees, but only just, you can only see a bit of both people. (...) So what you want is for them to come closer together."

When staging for a 360-degree camera, the viewer was less likely to be placed in the midst of the actors' interactions. Staging for theatre was more likely to include instances of actors being on either side of the audience member and placed in the middle of characters' interactions. This finding overlaps with the differences identified in actors' use of angles, as smaller angles between performers correlate with more compact action. However, viewing this data through the lens of F-formations reflects whether the audience member or camera was placed in between actors. F-formations are a unit of social interaction where all participants spatially orient themselves towards a central space, as during group discussions where interactants face one another with what is referred to as an O-space between them. In 360-degree staging, there were fewer instances where the viewer was placed inside the O-space, hinting that staging for 360-degree filming might include more instances of actors including the viewer in their F-formation rather than placing the audience in their shared area of orientation. While this reflects a more naturalistic, embodied way of engaging in a group in real life, it may also be a reflection of the restrictions field of view places on such spatial arrangements (Fig.8).

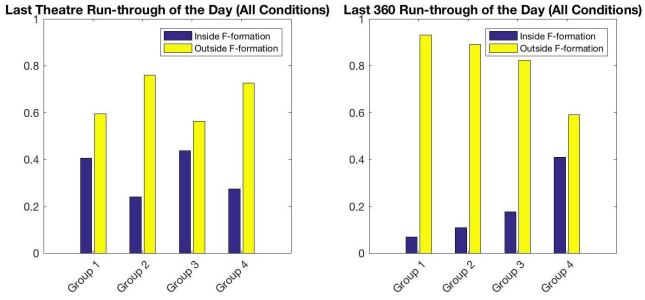

Figure 8. Normalized instances of audience being inside or outside the actors' F-formations

Case Study: Direct Transposition from Theatre to 360-degree Filming

Group 4 filmed seven run-throughs rather than six. As this group started with 360-degree staging, they specifically requested re-staging for 360-degree filming at the end of the day. A repeat staging for 360-degree at the end of the theatre session in the afternoon was not part of the experimental design in order to avoid the suggestion that staging should be different.

However, Group 4's request made it possible to directly compare the changes made when transitioning from theatre to 360-degree staging. The director's advice to the actors was to "emulate as much as possible a person being in the middle. Just remember about keeping the focus and changing the focus around. Although you can't see that person swinging around, you can kind of remember those moments when you're being the centre of attention and when you're supporting that person being the centre of attention." The director then went on to

address distance to camera by highlighting moments where the actors could come close to the camera and use effects unique to 360-degree filming (see Fig. 9). The group had used a huddle above and around the camera during their morning 360-degree session but decided to abandon that piece of blocking for theatre because "that's so intrusive with a person," changing it to a huddle that physically included the audience member. Group 4 purposefully manipulated the 'flaws' in 360-degree filming with the basic lenses of the Ricoh Theta, which warp dimensions close and far from the camera as it is composed of two fish-eye lenses, for creative purposes. The two chairs used in this staging were moved closer to the camera to increase use of space near the centre [1].

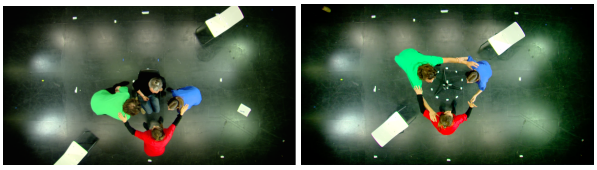

Figure 9. Group 4's 'huddle' in theatre (left) and 360-degree (right)

LIMITATIONS

360-degree Training

Peripheral awareness was reported to be an important factor in directors' decisions to restrict angles when staging for 360-degree filming. During the study, spatialised sound was not recorded or played back to teams. Sound plays an important role in peripheral awareness and the addition of this dimension may have diminished how much directors restricted angles when staging for 360-degree filming. The nature of 360-degree training evolved throughout the course of the four-day experiment, which may have inadvertently impacted the results of this study. Two main problems brought up in the first two days were addressed directly in the third and fourth day: the height of the camera and its initial orientation. The height of the camera was lowered on Day 1 from the initially planned 1m30 in response to the director's request. It remained at 1m20 throughout the rest of the study. The director on Day 2 requested that the image that people start with when using the 360-degree HMD be specified. Orientation of the camera was then provided to all subsequent participants. The content and quality of the 360-degree footage itself is not part of this study, so the effect of these changes is negligible.

F-formation: Out or In?

The coordinate data extracted from videos of the study participants did not include any information on the orientation of the participants themselves. A good approximation of lower body orientation could be made by adding vectors based on the direction of feet from the centre of the body mass (captured during the current data extraction). This could be done quite simply by using white strips of tape on the feet or shoes of performers and replicating the chroma keying used in this study on aerial footage. Without knowing who is facing whom, the analysis of whether the viewer is inside or outside F-formations is rudimentary. For example, two characters might be talking amongst themselves on one side of the stage while a character on the other paces back and forth. By examining only the aerial X and Y coordinates of the three actors, it would appear that the viewer is being placed in the O-space of the three characters' F-formation. The reality might be much more complicated: the viewer may be part of the F-formation with either group or none. Which group they are spatially included in may have important narrative implications.

Bias and Sample Size

The resources necessary to involve professional theatre makers, set up multi-camera recording and conduct the debrief interviews made it impractical to increase the study beyond a concentrated four-day period. As well as impacting generalisability, the small sample size exacerbates the impact of errors in experimental protocol. For example, the director of Group 4 did not read or receive the creative brief to plan for staging in 360-degree ahead of the day of the experiment itself. While the quantitative analyses do show a significant difference between the 360-degree filming condition and immersive theatre condition, the true nature of this relationship may have been affected by the different experiences that the two directors in the 360-degree filming condition had. However, Group 2 and Group 4 did not significantly differ from one another in terms of interpersonal distances. Participating in an experiment in blocking, as it was described to the directors, naturally appeals to theatre directors with an interest in experimenting with theatre craft. The self-selection bias is borne out in the study participants' principally immersive and non-traditional theatre backgrounds. Observation bias is also a risk with this study, as the participants were aware that they were being filmed throughout the day.[2] This may have affected their dynamics in the rehearsal room as well as their way of working. Finally, the experiment was not conducted blind and the same experimenter trained and interviewed the participants, which may have introduced experimenter bias.

FUTURE DIRECTIONS

Replicating this study with a different HMD with a wider field of view, such as the Oculus Rift which has a field of view of almost 180° as opposed to Samsung Gear's 96°, would be an interesting test of whether the reduction in angles during 360-degree filming was due to the limitation of the viewing technology or was an active narrative choice on the practitioners' part. The creative teams in this study were specifically requested not to place the audience member or camera anywhere other than the centre, though all were eager to experiment with camera placement. This extra variable was outside the scope of this experiment but would provide further insight into how theatre practitioners communicate audience relationship and spatial relationships through staging. No studies have yet been done to establish the nature of the spatial expertise of theatre performers and the methodology of this study opens the door to direct comparisons between the work of theatre practitioners and non-experts.

[1] An animated visualisation of actors' positions in both of these conditions can be found in auxiliary materials

[2] Short animations comparing actor coordinates within and across groups can be found in the auxiliary materials

Distance to centre and interpersonal distance could be usefully analysed through their sequentiality: do the distances to camera and between characters evolve in roughly the same order in each group? If so, one would expect that the most narratively isolated character would be further from the other characters and from the viewer. A time series analysis might provide insight into the similarity of different spatial sequences but was beyond the scope of this study. Running a similar study with film and TV practitioners might yield important insights into how spatial configurations are used in traditional recorded media. Finally, analysing spatial configurations in existing 360-degree and VR films would also provide useful information into choices that content producers have made.

DISCUSSION

While judgments of performance or film quality are beyond the scope of this research, it is interesting to note that whatever the brief, all groups addressed questions that are considered vital to VR content: Who is the viewer? Why are they there? Should they be addressed directly? The findings of this research chime with the work of filmmakers and researchers working in VR. Jessica Brillhart, Google's Principal VR Filmmaker, addresses the importance of the audience member's presence in the VR space in her research [20]. Another VR expert who conducts experiments in VR filmmaking, Michael Naimark, found in a case-study that reduced angles between two parties having a conversation in a 360-degree film was preferable [24]. The addition of theatre techniques, along with a consideration of the importance of interpersonal geometry between characters, may further enrich the work of VR filmmakers.

360-degree video creators can borrow the spatial approaches used by theatre practitioners in this study: using physical objects and architectural features in ways that change relationship to audience and movement between characters, using a semantically loaded space and exaggerating spatial dynamics in rehearsal, for example. Using the spatial expertise of theatre makers may help create narrative immersion. But that is far from the only lesson that theatre has to offer recorded immersive content. In theatre, the multiplicity of space on stage and in the auditorium is used to create a collaborative suspension of disbelief. Makers of VR could gain a great deal from considering the types of narrative device, all based on spatial tensions, harnessed in theatre on all its levels: in the world of the play, between the actors, between actors and audience and between the audience members themselves.

CONCLUSION

Interpersonal distances in live performance operate on several levels: first between characters on stage, second between actors on stage, third between actors and audience, and potentially also between audience members. Spatial configurations in theatre are chosen to meet practical, narrative and technical demands simultaneously. Theatre practitioners in this study adapted the widest angle between performers, distance from the centre and distances between characters when they staged for 360-degree filming rather than for immersive theatre, though the viewer or camera was in the same position. Despite the spatial adjustments made to accommodate the two different viewing experiences and the variety of staging choices between the four groups, there was consistency in the ranking of interpersonal distances between characters as well as each character's distance from the centre. Spatial configurations were adjusted to respond to practical considerations but this study suggests that the narrative function of these formations remained intact when moving from one medium to the other. Theatre practitioners with no previous VR training applied their spatial expertise to the unfamiliar medium of 360-degree filming using techniques that could be useful to VR content creators.

This study strongly suggests that theatre-makers use space for narrative purpose in ways that align with how spatial configurations inform our everyday lives. Computational approaches that have been used to identify social dynamics from interpersonal distances and orientations seem to apply to the study of the performing arts. The complex ways in which theatre directors approach space, as a technical challenge and semantically loaded space, have much to contribute to the emerging art form of immersive recorded media. The technique used in this study for experimental purposes, rehearsing for immersive theatre as if for an audience member in the centre of the space, may prove a useful tool in preparing theatre directors for blocking 360-degree films. The central role of the script on spatial configurations also points towards the development of a new craft of scriptwriting for VR. The way the script is written, and perhaps even formatted, needs to place the audience member at the heart of the story and to address the audience's role, spatial relationship to others and relationship to the environment.

The applications of these findings extend beyond the current capabilities of commercial VR and look towards developing technologies that have ever more complex uses of space. Microsoft is currently developing HoloLens [7] technology to allow for real-time VR interactions between people while techniques for volumetric capture [4] may soon make it possible for audiences to move around inside a recorded performance. Recorded media will increasingly rely on space as part of its fundamental language and as it does, it will call more and more on spatial storytelling techniques.

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