Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Stats On-Site — Sports Spectator Experience Through Situated Visualizations

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ARTICLE INFO

Article history:
Received April 23, 2025

Keywords: Situated Visualization, Augmented Reality, Sports Spectating

ABSTRACT

With recent technological advancements in sports broadcasting, remote spectators are presented with an enriched experience. These enriched experiences include additional content such as statistics and graphics that support game understanding. However, these technological advancements are often not accessible to on-site sports spectators. In this paper, we explore the opportunities of using situated visualization to enrich on-site sports spectating. Situated visualization techniques allow us to display information in a spatial context to its physical reference and have the potential to close the gap between on-site spectating and content access. With regards to this, we developed a framework for situated visualization focusing on sports spectating. We identified components needed for such a use case and developed two novel situated visualization approaches based on the proposed framework: (1) situated broadcast-styled visualization and (2) situated infographics. To evaluate the visualization approaches and explore user preferences, we conducted a lab study and a subsequent on-site study in a stadium.

1. Introduction

Sports spectators attending live sports events have the advantage of experiencing the on-site event atmosphere and being part of a community event. However, they often miss out on additional content accessible to remote spectators in broadcast and online media. This is despite game understanding being vital for the enjoyment of live sports spectating [1] and could be one of the factors contributing to a decline in numbers for on-site sports spectating [2, 3]. To access similar information as in sports broadcasts, spectators would need to look up information from sports statistic websites[1] or mobile applications[2]. However, information obtained from mobile sports applications or websites is usually limited to box-score data (statistical summary of a game) or game meta-data (such as weather or team kit) [4] which provides little to no temporal or spatial context for the spectators.

In contrast, sports broadcast has seen major technological advancements in recent years. From automatically selecting optimal broadcast camera angles [5], home sports broadcast AR experiences with the Hololens [6] to augmentation of virtual graphical elements in sports broadcast [7, 8], lots of research and commercial development have been done in order to provide better experiences for television or online sports broadcast spectators. An option to bridge the gap between on-site spectating and remote broadcast experiences is to use augmented reality (AR). There were already almost one billion AR-compatible (AR-kit and AR-Core) mobile devices in 2018, with the numbers predicted to triple by 2022 [9]. However, aspects of using augmented reality for live sports spectating are still underexplored. Soltani et al. discussed current applications of AR in sports [10], ranging from education, spectating, and training using a variety of different AR approaches. Examples of other research in this area are focused on computer vision techniques to recognize a player from an input image to output basic player

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[1]https://www.espn.com.au/rugby/

[2]All Blacks Official, OneFootball

profiles [11] or using non-real-time broadcast-based systems focusing on post-processing [7]. While there are some interest from commercial companies, to date there is no on-site mobile AR system available where spectators could get AR visualizations by pointing their devices towards the field (of action).

One of the reasons for this could be that the aspect of how to visualize content in such a scenario has not been explored so far. Situated visualization [12] seems to be a promising solution. Situated visualization displays information in a spatial context to its physical reference and could as such support a spectator in understanding the actions on the field. But up until now, it remains unclear if spectators would benefit from such on-site visualizations and what is the best way to implement them. In this work, we address this gap by proposing a conceptual framework describing components of situated visualization for on-site sports spectating. We designed our framework in a way that is applicable to most sports, particularly team sports, but our scenario primarily focuses on rugby (Rugby Union). We use the framework to develop and evaluate two situated visualization approaches, namely situated broadcast-style visualization and situated infographics.

We then ran user studies both in a controlled lab environment and on-site in a stadium. Our findings show positive responses towards the concept of on-site situated infographics and an improved game understanding without any increase in mental demand compared to on-site spectating without assistance or with traditional infographics. The reported user experience of the proposed visualization methods was also positive. However, improvements can be made to make it more inclusive for spectators of all knowledge groups, which we are planning to incorporate into our future prototypes. To replicate the live event experience, we also explored the use of indirect AR [13] for the sports spectating scenario, for both testing and actual on-site usage purposes.

2. Related Work

In previous work, researchers focused on identifying visualization approaches for AR in general and visualization frameworks. In this section, we will discuss types of situated visualization and explore relevant frameworks. We will also discuss visualization approaches for sports data and highlight the gaps for on-site sports data visualization.

2.1. Situated Visualization

White and Feiner introduced situated visualization as a concept of visualizations in a spatial context [12]. Later on, Willett et al. [14] introduced the concept of data referents. These are the two most popular definitions used in past literature according to a survey by Bressa et al. [15]. Both describe visualization techniques that are relevant to the location or physical context in which they are displayed. However, situated visualization is still a general term. Hence, we discuss some related concepts below.

Embedded visualization is considered as a part of situated visualization where the visualizations are on the referent itself [14]. This means that information is visualized with direct spatial reference to the object of interest. Thomas et al. [16] mentioned that for embedded visualization, the presentation elements need to be aligned to their corresponding referents.

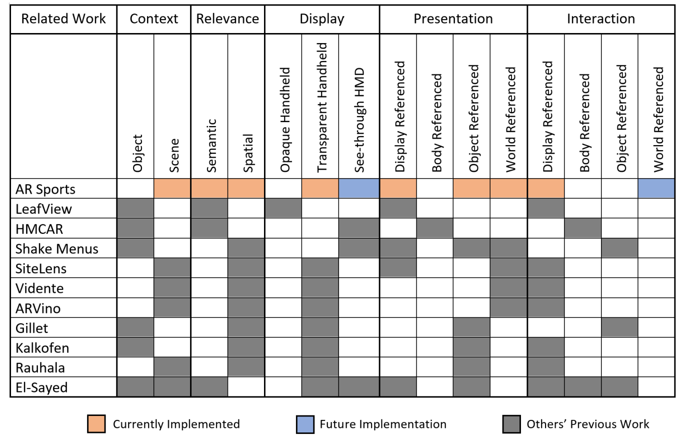

Fig. 1. Characterization of our application using White et al.'s classification framework. The table is obtained from White et al.'s technical report [12] with the addition of our proposed work and the work of El-Sayed et al. [18]

Temporally situated visualizations are visualizations that are related to a region of time close to the time the visualization is presented [16]. This means that the visualization shown is in real-time and not as a summary of the past. For on-site sports, temporally situated visualizations are important as some information shown is time-sensitive and would not make sense if not shown at a specific time.

Situated Analytics combine Visual Analytics (VA) [17] and AR to embed visual representations into the physical environment [16]. This object-centered approach uses the concept of embedded visualization and is interactive and data-oriented. The main goal is to support users navigating a multi-dimensional database, including ranking, filtering, and locating physical objects based on queries. Situated Analytics also deal with similar challenges like situated visualizations including clutter management and intuitive interaction methods [18]. In the example given by El-Sayed et al., users on mobile devices explore the nutritional value of different cereals based on what they select. So far, most Situated Analytics applications require lots of input from the user and there is no large environment implementation that would be necessary for our stadium use case.

2.2. Taxonomy and Frameworks of Existing Situated Visualization Concepts

A visualization framework is an important base to reliably and effectively create similar visualizations in the future. There are a few frameworks relevant to our goal of supporting on-site spectators in a stadium environment. One of them is the AR-CANVAS framework for embedded visualization [19]. This framework discusses key terms, parameters, and challenges that should be considered when designing an embedded visualization. Zollmann et al. developed a visualization taxonomy and framework for Augmented Reality in general [20]. White et al. also developed an AR visualization framework in which various

AR applications are characterized based on context, relevance, display type, presentation, and interaction [12].

We extended White et al.'s classification with our target application for on-site sports spectating (Figure 1). Our implementation involves an entire stadium environment for integrating content. According to White et al.'s classification, our implementation includes the scene context and uses both semantic (the players on the field) and spatial relationships (related to where events happen on the field). Our research also aims to provide a world-referenced interaction, using the environment to interact with the data, which is a first according to White et al.'s classification. In addition, we added an entry on Situated Analytics[18] as it also involves situated visualization and explores multiple objects in a scene. However, Situated Analytics focus on a smaller scale and require more complex user input rendering it unsuitable for our scenario.

2.3. Sports Visualizations

In recent years, sports visualization for broadcasting and web-based applications advanced considerably. Perin et al. compiled a list and reviewed recent sports data visualization work based on the sports data classification of box-score data, tracking data, and meta-data [4]. Applied to an example in our rugby use case involving a player scoring a penalty, the box-score would be the scoring itself and previous penalty stats, the tracking data could be the position the kick was made and the meta-data could be the expected performance of the player (prediction). However, most of the current work done is of analytic nature and is not in real-time, let alone on-site AR. These types of visualizations are more suitable for a tabletop AR scenario or a virtual experience where graphs and charts could be drawn and explored in 3D space, such as by using the DXR toolkit [21] or the Immersive Analytics Toolkit (IATK) [22]. There are also more general data classifications such as the basic classification by nominal, ordinal, and quantitative [23] and the multi-dimensional classification by Shneiderman [24].

There is also a growing interest in AR situated visualizations for sports [25, 26]. SportsXR [26] identified the potentials for coaches, fans, and even the players themselves in terms of training, but also mentioned some technical challenges such as data collection and visualization design. Stein et al. provided several examples of visualizations that could be implemented for soccer matches [8]. Companies such as Immersiv.io[3] and Nexus Studios[4] showcased on-site AR applications for soccer and basketball. However, besides demo videos and showcases, there is not much more information available publicly yet. Our observation is that the research area of on-site AR in sports spectating is still emerging and there is only a little previous work, with most of them done in terms of coaching and training rather than the spectators' experience.

Previous AR-based sports application research mostly focuses on player identification via image processing [11, 27], off-site AR-based broadcasting [7] and off-site AR used concurrently with live broadcasting [6]. There is also research on using AR for gamification and social reaction sharing in sports [28]. However, what is missing overall is a conceptual framework for situated sports visualization as most researchers are focusing on a certain technical implementation. Our work focuses on providing a basis for all sports situated visualization from where to place content to how to display it.

[3]https://www.immersiv.io/

[4]https://nexusstudios.com/work/samsung-ar/

3. A Conceptual Situated Visualization Framework for On-site Sports Spectating

The main goal of developing situated visualization for on-site sports spectating is to elevate user experience through better game understanding. However, in addition to creating sports statistics, we emphasize specific considerations as visualizations are spatially relevant. Previous AR frameworks [12, 19] are often too general, lacking in sports-specific contexts such as the different types and temporal components of sports data, the involvement of the user as a spectator, and the identification of where one should place content. Therefore, based on previous work, we conceptualize the three components which we dub the Three 'C's that are essential pillars for developing AR situated visualizations in sports spectating. The three components are **canvas**, **content** and **context**. We will discuss how these components are formed and their relevance. In the following, we will refer to White et al.'s visualization framework [12] as FW1 and the AR-CANVAS framework [19] as FW2.

3.1. The Three 'C's

To better fit our sports spectating scenario, we decided to build on FW1 to incorporate elements of sports spectating while taking inspiration from other works such as FW2 and the 5'W's and 1'H' user-centric concept (who, where, what, when, why, and how) [29]. The three components dictate where a visualization should go (canvas), when should it appear (context), what should it visualize (content), and why we visualize something. Under each component, there are sub-components and attributes which allow us to further specialize in different AR sports visualization approaches. These main components are crucial and are present in all cases of situated visualizations in sports spectating while the sub-components and detailed attributes are optional. We will discuss the components of the framework (Figure 2) in detail in the following.

3.1.1. Canvas

The canvas is a dynamically assigned and positioned plane or surface that visualizations could be anchored on to provide spatial relationships to otherwise non-spatial data. FW1 discussed the concept of the *locus of presentation* while FW2 discussed the location of canvases. In our framework, we bring these two sub-components from FW1 and FW2 together, integrating the different types of presentations that exist with either a manual or an automated approach of canvas identification.With reference to FW1, the presentation of data consists of display, body, object, and world-referenced visualizations. It covers the spectrum from screen-based visualization to scene-based visualization. Display-referenced visualizations are visualizations that take place on the screen space itself, regardless of where you

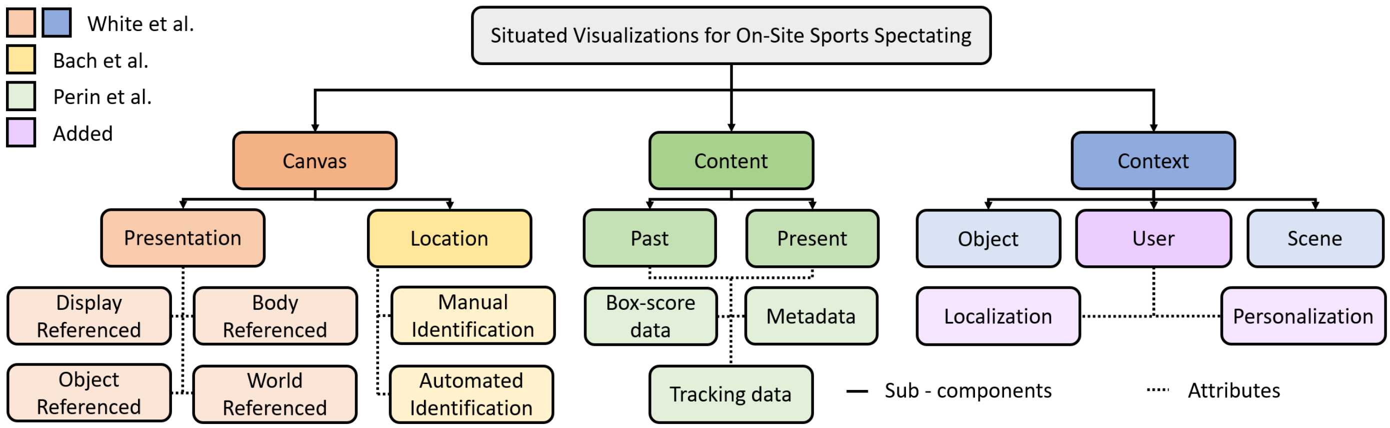

Fig. 2. Our proposed situated visualization concept for on-site sports spectating depicting the three main components: Canvas, Content, and Context. We highlighted the adapted components from previous work [12, 19, 4] as well as new components with different colour codings.

are looking. Body and object-referenced visualization are anchored to an object, in the case of body-referenced, the users themselves. World-referenced visualization uses the surroundings as an anchor, not necessarily attached to a specific object.

Events where situated visualizations for sports spectating are relevant often take place in known environments such as a stadium environment. For large venues like this, 3D models of the environments are often available. In such cases, a manual approach to identifying static canvases can be applied where canvas options can be defined by an app developer or designer using such a model of the venue. The manual approach, although it usually involves more resources, yields better results than automatic approaches as there will be a lower rate of placement errors and visualizations are more custom fitted. Automatic approaches include plane detection methods that identify flat surfaces in the physical environment [30], image space analysis [31] as well as using geographic information systems (GIS) [32]. GIS data can be combined with image analysis to obtain more accurate representations of a structure and make it better suited for real-time implementation [33].

3.1.2. Content

Once canvases are identified, we need to identify the content that should be displayed on those canvases before placing the visualization. FW2 classified all content into a general context data category, while FW1 was inspired by the basic classifications of nominal, ordinal and quantitative data [23]. Since our framework focuses specifically on sports visualization, we based our content component on Perin et al. sports data classification of *box-score data, tracking data* and *meta-data* [4]. We also have a categorization of past and present data to highlight the temporal characteristics of the data.

Box-score data is the most common form of sports data. Originating from the box-like format of score-taking on paper, it features the recording of discrete events that happen in the game, such as scores, fouls, substitutions, etc. Tracking data involves more dynamic data, such as player positioning and ball placements which allows for the generation of dynamic canvases and the creation of real-time embedded visualizations, often used for sports performance analysis [34, 35]. Lastly, meta-data comprises all other data that is not directly related to the game, from historical facts such as previous match-ups, venue history to dynamic data such as crowd emotions and engagements.

The reason why the type of information matters in our framework is that different information can be displayed in different formats, times, and places. Traditionally, box-score data and tracking data are shown when the game is ongoing, requiring real-time processing. Tracking data by itself requires auto-generated visualizations as there is no time for broadcast operators to annotate the visualization unless it is a replay of past events. Some meta-data would be shown mostly pre-game and could be prepared in advance, such as at what venue the game is held, previous match-ups, and weather details. Unlike in sports broadcast, player and game statistics would require a real-time information transfer so that visualizations shown are up-to-date and relevant to the current scene for situated sports visualization. Finally, meta-data is useful to provide additional context to the game and to enrich the user experience, such as allowing the expression of emotions by the spectators.

3.1.3. Context

The context component ensures visualizations appear at the right time and place when and where the user wants to see them. Context is used to describe the situation an entity is in [36]. With reference to FW1, we adopted the concept of an object-based and a scene-based context. Object context mostly refers to details from a specific object, such as visualizations attached to a specific player. Scene context is mostly environmental context such as occurring events and positions of players in the scene. As the user plays a crucial role in many applications we extended FW1 with the user's context.

To make sure visualizations appear at suitable positions, tracking of both the spectators (user localization) in the stadium as well as players on the field is essential (scene context). Unlike pre-calibrated broad-cast systems [8], we cannot rely on pre-calibrating the spectators' position in the stadium as even if they are seated, the actual position and orientation of their devices vary a lot. Visualizations will not make sense if they are misaligned from the referent (canvas) they were referring to, especially since the actions are at a reasonably far distance. Thus, model-based localization combined with real-time tracking is a suitable solution for computing the spectator's pose [37, 38]. For player tracking, computer vision-based tracking is an option to compute player positions from wide-angle cameras installed around the venue. Other options are wearable technologies, specifically, those made for sports analytics [39]. Examples would be the sports wearable by KINEXON[5] and ChyronHego[6] that track players' 3D coordinates and measure multiple sports metrics all while having a low latency (e.g. around 20ms for KINEXON).

Upon getting accurate positioning of the user, which is the localization sub-component, we would then need to know when and what to show. This is a combination of both scene context (when to show) and user context (what to show) alongside the content component to determine the type of data and visualization to be shown. FW2 uses user localization which they referred to as "navigator" but lacks the personalization of each user. However, every spectator can have their own preference of visualizations, therefore, in our framework personalization is listed under the user context sub-component where spectators could tailor their profile according to what they want to see. This is related to the level of understanding each user has towards the sport. A seasoned viewer would probably choose to see more player stats while a spectator new to the sport would appreciate visualizations explaining what the referee is signaling. Other examples of personalization include the highlighting of specific players on-field, level of detail of event descriptions, penalty scoring predictions, etc. Interaction methods (how to control) also fall under this category of user context alongside the scene context.

3.2. Applications and Limitations

This conceptual framework is designed primarily to support on-site sports spectating in a known environment. This covers many different sports from individual sports such as track and field, swimming to team sports such as basketball, soccer, and many more, including our use case — Rugby. Different sports will interpret the framework differently, for example, in a swimming scenario, the canvas would mostly be the pool. A useful past content data would be on pacing, possibly the previous world record pace visualized in a line, so spectators could get scene context of how fast the current swimmer is in comparison with the world records. For basketball, the court and the whole indoor stadium could be the canvas, content could be ball path of free throws, where it provides a spatial context of how the ball entered the hoop.

This framework is designed to be a guide in the early conceptual design process of situated visualizations for on-site sports spectating. It however does not include the actual design phase detailing how a certain visualization should be designed given a certain format. For example, if we have ball possession data of a game, we would already have the content, which is a combination of past and present data. Designers then have to use the canvas component to determine where a visualization should be attached, either by a manual identification or an automated plane detection approach for example. If designers wanted the visualization to be in a spatial environment, then it would be a world-referenced canvas, due to the data type where it is not attached to a single-player nor the screen space. This framework also views canvas, content, and context from separate viewpoints, mostly coming from where we place content at the appropriate time. Further research could be done to investigate the relationships between different components and how it affects each other.

[5]https://kinexon.com/technology/player-tracking

[6]https://chyronhego.com/products/sports-tracking

4. Implementation of Situated Visualization for on-site sports spectating

Our goal is to explore visualization approaches that would benefit sports spectators in the stadium and to evaluate our conceptual framework. We achieved that by implementing two different situated visualization concepts for sports spectating, where the three 'C's are guiding our implementation so that we can attach content onto canvases in the right context. We are focusing on mobile devices as it is the most accessible option with the opportunity to be ported to an AR head-mounted display (HMD) when the technology is mature enough for long-term use. We developed two situated visualization options, one based on a standard TV broadcasting style (Situated Broadcast-style Visualization (SBV)) and the other in the form of an in-situ AR visualization (Situated Infographics (SI)). These two options allow us to explore different aspects of familiarity from traditional broadcast and the spatial awareness AR situated visualization can provide.

Although the system infrastructure is not the focus of the study, we will first give a brief overview of how the system works as it is relevant to get a better understanding of the overarching approach. Most of our visualization evaluation and development is done within the application itself. However, we implemented an overall system consisting of player tracking cameras at the stadium, an on-site content server for providing data, and lastly the mobile AR clients similar to the approach described by Zollmann et al. [25]. The content server receives player positioning details through a computer vision tracking module as well as scoring data input from commercial sports data providers. The content server then connects to the AR client where the player tracking data and scoring data gets translated into visualizations to be displayed in a comprehensible format.

4.1. Situated Broadcast-style Visualization

The motivation behind the situated broadcast-styled (SBV) visualization option is to provide a visual layout on-site that is familiar to spectators from the traditional broadcast. In this visualization approach, the users are presented with a live video stream of the actions on the field from their perspective. This is combined with visualization elements that are presented in screen-space, following the layout of commonly seen television broadcasts where a game timer appears on the top left corner,

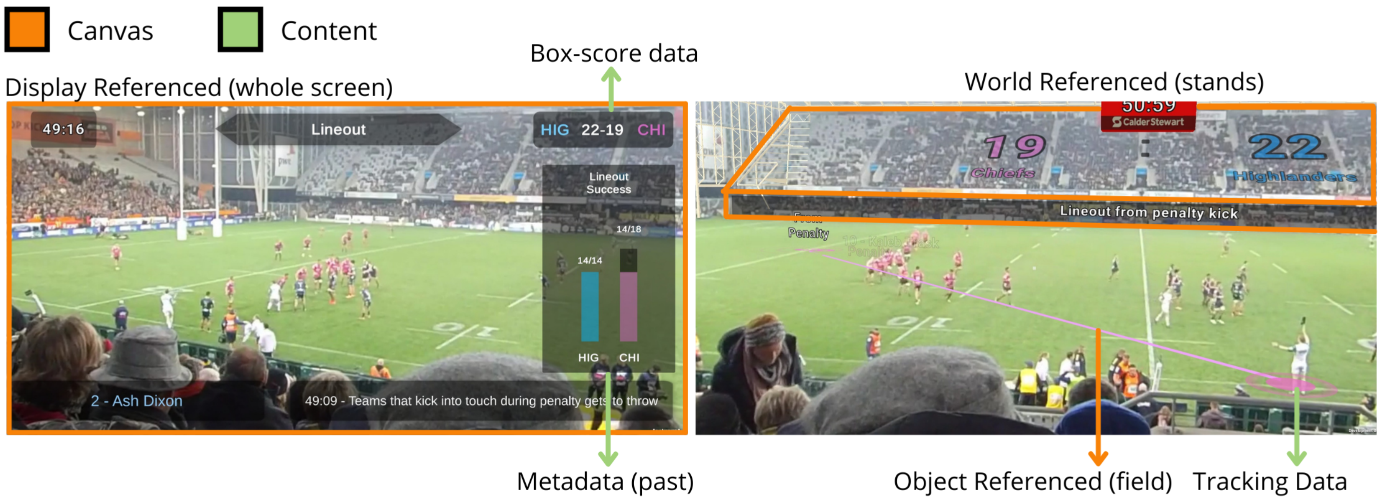

Fig. 3. An example situated broadcast styled visualization (SBV) and situated infographics (SI) alongside references of the canvas (in orange) and content components in the proposed framework (in green). We are unable to visualize context here, but visualization shown are based on user localization and scene context of the game. Left: SBV. Right: SI.

scores on the top left or right corner, and additional details appearing as a banner at the bottom of the screen. With that said, the layout mentioned above is just a guideline and is flexible to be customized. The core concept is to visualize data in a two-dimensional format on a graphical user interface. We used the three components of situated AR visualization for sports to design this visualization approach.

Within the situated broadcast-style visualization, the visualizations are limited to the screen space of the device, similar to the head-up displays (HUD) of games. Therefore, it is a *display referenced presentation* under the **canvas** component in our proposed concept. The small screen size limitation is prone to information clutter which could impact the user experience [40]. Thus, visualizations must be thoughtfully planned and often positioned at the borders of the screen to not block the action on the field. For our implementation, we placed the timer on the top-left corner and the scores on the right, which is the norm for most sports broadcasts. The bottom left corner will only show the player name and number which is involved in a certain event while the description of the event appears at the bottom right corner. Because of the similarity to traditional broadcast, spectators are likely to be already familiar with such a layout or able to quickly adapt to such a visualization layout as elements remain in place throughout the game. The only exception would be during special events such as game breaks where some charts and visuals are brought up on the screen without disrupting the viewing experience (Figure 3, left).

Due to its limited screen space, the **content** will mostly be presented in text or icon form. The canvases are display-referenced and mostly presented as rectangles that are suitable to show *box-score data and metadata* from the past and present as text-based representations. Some player or game-based statistics could still be visually represented depending on the **context**. Despite not needing any tracking of spectator poses and players on the field for visual alignment (no *identification component* required), the context is still vital for the broadcast-style visualization, especially the *scene context* for appropriate timing of full-screen visualizations. For example, while showing stats during the break, it is possible to fully utilize the screen space and set the whole screen as the canvas. The same could not be done if there is still action happening on the field, and therefore would require some smart placement of the canvases.

4.2. Situated Infographics

The second visualization approach we developed is an in-situ AR-style visualization which we call situated infographics. Situated infographics unlock the limitations of restricted screen space as the whole surrounding environment can be the canvas for visualizations. Situated infographics work similarly to embedded visualizations where visual elements are transformed into a 3D visualization and visualized in a 3D space, aligned to their referents. The main goal of situated infographics is to visualize complex information coherently and related to the users' environment in real-time. In a nutshell, situated infographics is a world-centric visualization method that takes the context around it into consideration. It can be seen as a form of a WorldBoard [41] concept implementation where information is placed in the environment as if it belonged in the real world (Figure 3, right).

The **canvas** for situated infographics is important to ensure visualizations have somewhere to anchor on in the environment. This is either in form of a static canvas (*world-referenced presentation*) such as attached to the field, the stands, but also in form of dynamic canvases (*object-referenced presentations*) as each player on the field can be a canvas on their own. The **content** is similar to the content in SBV but contains more elements that are suitable for graphical representation and that even have an additional dimension of a spatial element. Situated infographics utilize the *tracking data* to better illustrate past and present events on-field. All information is adaptive to the canvas and personalized to the viewpoint of the spectator watching it.

Fig. 4. The three prototypes developed during the development process. Left: The Lab AR prototype we use to view different visualizations from different angles in the stadium in a minified replication of the stadium in a lab setting. Middle: The Indirect AR prototype used to simulate being in the stadium. Right: The actual Stadium AR prototype for on-site usage in the stadium showing the position and frequency of tackles that happen in the game.

The **context** is essential for situated infographics. Without the *user context of localization*, most visualizations would not work and any misalignment in the graphics would cause more confusion than assistance. Without context awareness (*scene context*), visualizations might not appear at the right time and distract spectators from their experience. Dynamic canvases require anchoring to the players on the field. Personalization and user localization are part of the *user context* component. For an information-rich, situated infographics implementation for on-site sports spectating, spectators should be able to choose (automatic and/or interactive) what level of information they want to see. Visualizations then should also adapt to the environment, depending on what is going on nearby and the perspective of the spectator.

5. Prototypes

Throughout the development of the situated visualization approaches, we wanted to experiment and test out various visual elements, including formally conducting user studies. For this purpose, we developed three different prototypes (Figure 4). 1) A Lab AR prototype that is used for in-lab multi-perspective viewing of visualizations, demonstrations, and testing. 2) An indirect AR prototype that simulates being in the stadium in a particular spot, useful for off-site development and testing. 3) A Stadium AR prototype for on-site testing where visualizations are shown in an actual stadium through VST AR.

Since our canvas is based on a 3D model and we are working with AR, we opted for the Unity game engine as our implementation platform. Vuforia[7] is used for extended tracking and image target tracking for the Lab AR and Stadium AR prototype. Each prototype is made to overcome challenges faced in other prototype versions and they share the same standardized fundamental visualization concept and global coordinates. Visualizations can be transferred from one prototype to the other.

5.1. Lab AR

The Lab AR prototype (Figure 4, left) is developed for off-site testing and development. It is approximately 1:100 scale to the actual stadium environment, giving the user a birds-eye view of the stadium model and visualizations with the flexibility to move around with ease. It uses an A0-sized printed pitch which is used for tracking via Vuforia image target tracking to display a virtual stadium. The image tracking is done by using the logos of sponsors on the field. For selected positions, a transition mode is implemented to the indirect AR prototype if the users enter that proximity in the Lab AR stadium model.

The Lab AR prototype is helpful to determine the visibility and usability of some augmented visualizations from different points in the stadium by just moving the smartphone around. This prototype is also used in our user studies and demonstrations as it is a controlled environment and provides a feel of what AR can provide to the users. However, this prototype's localization is done differently from the on-site implementation, therefore it does not represent the actual localization method. It is also possible to miss out on smaller details as the birds-eye view might be too small to highlight some issues spectators might face when viewing a visualization on-site.

5.2. Indirect AR

We developed the indirect AR prototype (Figure 4, middle) simultaneously with the Lab AR prototype with the same goal of off-site development and testing in mind. Instead of being a video see-through (VST) AR application, the indirect AR is comprised of panoramic image data rendered as a texture on a sphere (or skybox), overlaid with graphical elements. When the users rotate their mobile devices, the viewing direction updates accordingly in the indirect AR environment, creating the illusion of the user being at the stadium. This simulates what could be seen if they were there in a specific spot in the stadium. The indirect AR prototype is suitable for off-site evaluation of visualization techniques from a pre-selected viewpoint. We then extended the classical indirect AR approach [13] by replacing the 360-photo with a 360-video. This allowed us to simulate the experience of an actual game by using video capture of an actual match.

The indirect AR prototype has a number of advantages that make it valuable for on-site and off-site visualization studies. Considering graphical content is aligned to the 360-photo or video, there is no need for localization or tracking, a component that often leads to inaccuracies when using traditional AR. Thus, the indirect AR prototype is suitable for controlled user studies by removing the additional confounding variables of localization and tracking fidelity. This prototype also has the ability to use recorded games to simulate the user experience in an actual game with predefined events. However, with the indirect AR prototype, we are limited to specific positions within the stadium where the 360 photo/video is captured.

[7] www.developer.vuforia.com

5.3. Stadium AR

Stadium AR (Figure 4, right) is the prototype that will closely resemble the actual experience and the final product. In this VST prototype, users can see the actual field if they are in the stadium via the camera with situated visualizations overlaid on it. For localization within the stadium, we currently use a user-guided initialization step where the user aligns pitch markings to a shown grid in combination with Vuforia extended tracking [25]. We also explored the use of logo markings on the field and advertisement banners localization but refrained from it due to localization inaccuracies that could potentially lead to a bias in our visualization experiments.

The challenge we faced with this prototype is that development is done off-site and does not take place in the stadium where we could test it out. It is also not possible to simulate games for testing or user study purposes in this prototype as it is showing what is seen on the actual field. Besides that, using this prototype to test out visualization from different perspectives would require the developer to move around quite a bit, and again requires the developer to be on-site to make changes. However, we still used this prototype to investigate if users would perceive a difference between indirect AR and AR experiences within a larger sports venue.

6. Lab Study

Our first goal was to study the general potential of situated visualization within the sports spectating use case. For this purpose, we designed a preliminary user study based on Rugby Union and compared the first design of situated infographics to traditional infographics on a mobile device. We decided to use traditional infographics as a baseline as most people are familiar with the concept and they aim to convey data in a comprehensible way [42].

In a lab-based setting, we applied the Three C's to both forms of infographics: traditional and situated. Different parts of the (virtual) stadium environment served as canvases where the dynamic sports content was put into context. Since this was a lab simulation, we used past data for content.For this user study, no personalization was included yet therefore the user context only consisted of user localization. The user was localized with respect to the lab stadium environment. For the traditional infographics, the canvas was mainly display-referenced whereas for the situated infographics a combined body-world reference model was used.

We were in particular interested to evaluate the user preference of either using situated infographics or traditional infographics. We were also interested in exploring if there are any differences in workload between using traditional infographics vs. situated infographics. This study has received ethical approval from the University of Otago's ethics committee and followed the given requirements (pre-pandemic).

6.1. Design and Apparatus

We designed a within-subject study to investigate the workload when using situated infographics and traditional infographics. The dependent variable is the workload. The independent variable is the visualization method with two conditions: 1) traditional infographics (TI) and 2) situated infographics (SI). In addition, we collected feedback about user preferences with regard to both methods and explored the influence of the visualization technique on spatial understanding.

Fig. 5. A user study participant using the Lab AR prototype. Also seen is the smartphone (hand-held) to view the situated infographics and the other smartphone (on table) displaying traditional infographics.

For this user study, we used a miniature version of a stadium pitch printed as an A0 poster within a controlled lab environment (Figure 5). We presented both TI, as well as SI on mobile phones (Samsung Galaxy S6 and Huawei Mate 20 Pro respectively) to simulate the participants spectating a game in a stadium. In addition, a Microsoft Surface Pro 2017 tablet was used for capturing the answers of the participants. This included marking positions on a photograph of the miniature stadium (captured from the participants' estimated position) as well as answering questionnaires. Historic rugby match data provided by a sports scoring provider was used in order to create a realistic simulation. We used two different sets of data for different scenarios in a controlled randomized order to avoid learning effects while maintaining the same graphical style for both conditions.

6.2. Participants

We recruited participants from the university through advertisements and word of mouth. In total, 30 participants aged between 21 and 38 ($\bar{x} = 26.6$, $\sigma = 4.36$) participated in our user study. 23 of the 30 participants were male and all of the participants had normal or corrected-to-normal vision. Among the 30 participants, only 12 of them stated that they have experienced AR prior to the user study.

6.3. Procedure

After signing a consent form, participants filled out a demographic questionnaire requesting information on age, gender, vision impairments, as well as familiarity with AR. Participants received an introduction of both interfaces, including mentioning the randomized rotation of the field in TI to simulate users sitting on the opposite side of the stadium. Upon familiarization with the interfaces, participants were given three tasks to complete, each using either the TI condition or the SI condition in a controlled randomized order. The tasks were designed in a way

Fig. 6. Lab study: The task here (Task 2) is to mark the position of the orange's team Player 14. Left: Traditional infographic - this version is rotated at a controlled random compared to what the user sees. Middle: Situated infographic - infographics directly on the printed field. Right: The printed field with annotations showing wrong (red) and correct (green) responses by the participants.

that required the participants to understand the infographics and create a moderate workload.

For **Task 1**, we separated the rugby field into five columns and asked the participants to find the area where the most tackles happened during a rugby game. In the TI condition, we showed an infographic with two charts. One chart with colored dots on a 2D picture of a field representing tackles and a second one showing a bar chart with the cumulative tackles for each meter of the field. For SI, we visualized the same dots and bar chart except that the dots are on the field in the AR view with the bar-chart on the side of the field. For both conditions, we asked participants to mark the column of the field with the most tackles on the study tablet.

For **Task 2**, we visualized the initial position of all players on the field while the participants were asked to find the position of a specific player. For TI, the initial positions were displayed on a 2D field (Figure 6, left) while for SI the positions were displayed in AR (Figure 6, middle). Participants had to mark the position of a specific player in a photograph of the rugby field on the study tablet. For the TI condition, the orientation of the TI is randomized to simulate spectators seated at different positions in the stadium. Participants were notified in advance before the start of the study to pay attention to the orientation of the infographics. We decided against rotating the printed stadium as it would be really obvious that the orientation is being changed and thus decided to go with rotating the TI instead.

In **Task 3**, participants had to find the team with the highest numbers of votes. For TI, we visualized six player profile pictures (sorted by team) with the number of votes each of them received next to each other. For SI, the player pictures were displayed as banners sticking out at the side of the field. We asked participants to select the side of the team with the highest voted player in it. Participants were asked to fill in a NASA TLX questionnaire upon completion of each condition per task. We then asked additional questions such as preferences and feedback.

6.4. Results

We analyzed the workload using the NASA TLX. The results were not normally distributed (tested by Shapiro-Wilk, $p<0.05$) except for Task 1 SI overall condition with a mean of 33.39 ($p = 0.16$). Thus, we analyzed the data with the Wilcoxon Signed Rank test and paired t-test for the Task 1 SI overall. We found no significant differences in each category of the TLX questionnaire across the board except for Physical Demand ($p<0.001$). So it seems that participants did not experience a higher workload despite integrating infographics into their field of view adding an additional dimension (Figure 7). This is the case for all TLX categories except physical demand, which we assume is likely due to spectators using the mobile AR to look around.

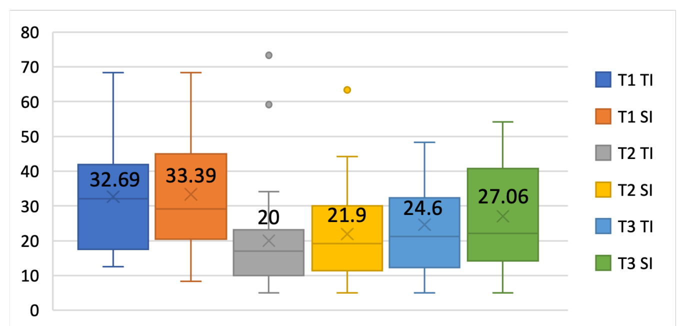

Fig. 7. Overall TLX scores of all tasks in the lab study. Value labels show mean values of the TLX scores.

In addition, we found that there seems to be a lack of spatial awareness while using TI during tasks that require an understanding of the spatial relationship between the data and the user's environment. For instance, for task 2 (asking for the position of the player on the field), only 18.7% of the answers were close to the actual position on the field when using TI. In contrast to 100% correct answers for the SI condition. This is due to the randomized rotation of the infographic to simulate a user on different sides of the field. TI viewed from the opposite side of the stadium would require a diagonal flip instead of just a horizontal flip for the right position. For example, the correct position for orange's team player 14 should be on the bottom left corner instead of the bottom right (Figure 6). There is no such problem with the situated infographics as the spatial relationship is already clearly visible to the user.

Finally, we analyzed user preferences. The majority of participants (90%) favor the SI over the TI (rated ≥ 5 out of 7, $\bar{x} = 5.74$, $\sigma = 1.28$, in which 7 is a preference towards SI). A simple analysis of the participants' feedback shows 26 out of the 30 participants (86.6%) provided positive feedback towards the idea and concept. 15 participants mentioned situated infographics as useful or helpful to them. In terms of some drawbacks mentioned, participants wanted a better-polished front-end implementation, bigger fonts, and simpler infographics.

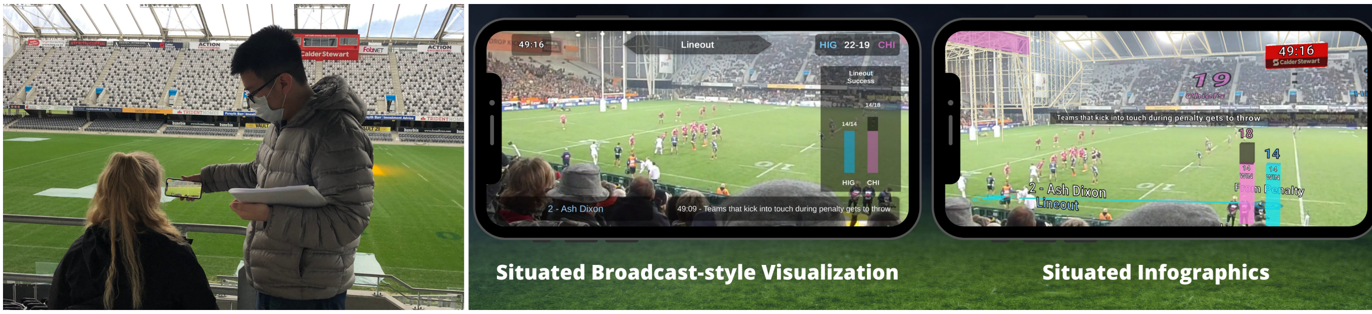

Fig. 8. Left: Explaining the prototype to the participant in the on-site user study. Right: Figure showing the two visualization approach we developed - situated broadcast style visualization and situated infographics.

6.5. Discussion

The preliminary lab study indicated that SI could help with spatial understanding without a significant increase in workload, compared to TI. Considering SI is used in a more complex environment, it brings together more benefits including being able to monitor what is happening on the field in real-time and providing better spatial understanding while still keeping the cognitive load similar to TI. Therefore, our results indicate that albeit similar cognitive load, users are getting more out of it. We also found that participants favored SI in their preferences and emphasized the aesthetics and the easy-to-understand graphics.

7. Formative On-site Study

Our lab study indicated that there is an interest in AR situated visualization sports spectating and that there could be benefits compared to more traditional ways of presenting information on-site. Thus, we ran an on-site user study in a stadium (Figure 8, left) to evaluate situated visualizations on-site (Figure 8, middle and right) as well as user preferences towards different spectating conditions. The experiment was divided into two sessions, an on-site study at the stadium and an off-site session simulating a spectator using traditional broadcast on a TV screen. Following the pilot study, we also focused on Rugby Union for this study, This study has received ethical approval from the University of Otago's ethics committee and followed health and safety precautions (pandemic).

7.1. Design and Apparatus

We designed an on-site study to explore two situated visualization methods - situated broadcast-style visualizations (SBV) and situated infographics (SI) for on-site spectating. Before the user study, we consulted with an expert fan in Rugby Union to walk through our footage of an actual game, explaining the events on the field from a fan perspective to create a consistent visualization and commentary of events. We anticipated that both of these visualization approaches would benefit game understanding and we are interested to find out how they compare against other spectating conditions. Despite being an exploratory study, workloads and preferences were measured with regards to both methods and later compared to a TV broadcast scenario. In addition, we also did a comparative study to determine if the results obtained on indirect AR are transferable to an actual AR scenario. We anticipated that the condition of viewing the visualizations should not be a major factor considering that the visual elements are of equal clarity.

Similar to the lab study described above, all three C-components were applied: Users are actually localized within the stadium environment and match related content (present content) is visualized. For the SI condition, the presentation was driven by a full-fledged combination of world and object references. To make the SBV condition ecologically valid and fair comparison, display referenced data has been combined with scene context, providing visualizations at appropriate timing. Canvas identification was pre-modeled, i.e. a manual approach was used.

The on-site user study is held in the Forsyth Barr Stadium. We decided to run the experiment not during a live match to avoid a bias from an environment and events that are very difficult to control and also due to restrictions with regards to the COVID-19 pandemic. For the on-site visualization, all parts of the study have been performed on an iPhone XR. We captured 360 video footage during a live rugby game for the indirect AR prototype. For the lab session, the broadcast footage of the same game was shown on a 32-inch monitor with participants seated on a sofa roughly 2m away.

7.2. Hypotheses

Based on the design considerations, we postulate the following hypotheses for our on-site study.

- H1: We do not expect a difference in presence and user preference between Indirect AR and AR for our on-site spectators.
- H2: We expect a similar workload for SBV and SI.
- H3: User experience for both situated visualization techniques SBV and SI will be above average.
- H4: Game understanding will be supported by the situated visualization techniques SBV and SI in a similar way to watching a broadcast and will increase compared to watching a game on-site without any support.

7.3. Participants

We recruited participants from the university through advertisements and word of mouth with the requirement of having been to at least one match in the stadium before. In total, 16 participants (11 Male, 5 Female) aged between 19 and 36 ($\bar{x}$ = 24.9, σ = 5.12) participated in our study. Among the participants, 8 of them claimed that they have prior experience with AR, and 4 claimed that they have no experience with AR but know about it, while another 4 have no experience. Four participants majored in sports-related degrees and are deemed as expert users.

7.4. Procedure

Participants were first invited to read the information sheet and were then asked to fill in the demographic questionnaire, COVID-19 declaration, and consent form. We designed the on-site study to consist of two parts.

7.4.1. Part 1: AR and Indirect AR comparison

The first part is a comparison between actual AR and a video indirect AR, which is a prerecorded 360 video of the empty field in the stadium. Both conditions feature the situated visualizations that we used in the pilot study to reduce any confounding variables. Participants were given some time to explore their environment and the visualization for at least half a minute till they were satisfied. They were then presented with a questionnaire consisting of some questions selected from the Igroup Presence Questionnaire (IPQ) and asked if the conditions affect what they were seeing.

7.4.2. Part 2: SBV and SI comparison

Participants then entered the second part of the study with two different situated visualization conditions, both presented in the indirect AR prototype. For this purpose, we used footage of a rugby game we captured on a 360 camera (Insta One X). The first visualization condition is SBV, a broadcast-like overlay visualization, similar to what spectators experience in television with scores, timers, and visualizations being overlaid on the video image. The second visualization condition is an updated version of SI which places the visualization into the environment itself. This means that visuals could appear anywhere, such as the field and the stands (refer Figure 8, right). Participants were given two tasks for each condition. Each task consists of a spatial component and a game stat or game understanding component. Participants were asked to answer questions related to each task after the video clip ended which lasted around a minute and a half. The main purpose of the task is to have the user focus on a task so the NASA TLX questionnaire can be applied later on.

Task 1: Determining where a certain field action (a penalty) occurred and what caused it.

Task 2: Locate the initial position of a certain player and identify the team with higher ball possession.

All the events and related information is presented in the video clip in both conditions. The clips and order of conditions were all in a randomized order. Participants did not view the same clip for different conditions. Participants were also given a hidden task regarding the line-out success rate and roles of players which also appeared in the visualization, but not written in the task list. Participants filled in a NASA TLX questionnaire after each task. They were then presented with both conditions again for the last time and after each condition, they filled in a User Experience Questionnaire (UEQ) to rate the visualization method without needing to focus on any task. The questionnaire continued to ask them about their preferences and experience.

7.4.3. Part 3: Broadcast Footage Viewing Comparison

The last part of the study involved viewing a short snippet of a broadcast game on a different day in the lab after the on-site study. Participants were given a 5-minute broadcast video of the game they saw at the stadium through the video indirect AR in a simulated home viewing setting. They were then asked to fill out a questionnaire about all viewing conditions that they experienced before, from on-site viewing without assistance, SBV, SI, and lastly the TV broadcast. We asked additional questions based on their response to get more feedback.

7.5. Results

In the following, we present and will discuss the results for each of the three parts of the study.

7.5.1. Results Part 1: AR and Indirect AR comparison

For comparing the AR condition with the indirect AR condition, we used a subset of the IPQ test. Only 2 questions passed the Shapiro-Wilk test of normal distribution (p>0.05) which then underwent the paired t-test (p=0.61 and p=0.84). We used a Wilcoxon signed-rank test for the remaining questions (p=0.85, p=0.16, p=0.80, p=0.49, p=0.40). For all 7 questions, we did not find significant differences. Similar findings were captured when asking participants about their preferences. Of the 16 participants, 9 preferred the AR condition and 7 preferred the indirect AR condition. Also when asked if it matters which condition they view the visualizations on, participants rated that it does matter slightly ($\bar{x} = 4.06, \sigma = 1.91$ on a 7 point Likert scale in which higher means it matters more). Some participants said the AR condition felt more realistic (P1, P4), sharper (P2, P3, P8) but some stated that the indirect AR is more pleasing (P5, P10, P14) to look at. These results confirm our hypothesis H1 in that we could not measure a significant difference between AR and Indirect AR for our sample spectators.

7.5.2. Results Part 2: SBV and SI comparison

In the second part of the experiment, we compared the two situated visualization approaches, SBV and SI. We used the TLX test and collected 15 usable data entries for the TLX scores (one participant who rated almost a minimum score for every category was considered an outlier and was discarded). The overall TLX scores passed the test for normal distribution via the Shapiro-Wilk test (p=0.58, p=0.93, p=0.25, p=0.72) and then underwent a paired t-test. Overall TLX results show no significant differences between the two visualization methods (Task 1 p=0.09, Task 2 p=0.44). This confirms our hypothesis H2, indicating a similar workload for both conditions for our samples. However, when separated into normal users and expert users, there is a significant difference in the normal users' overall, mental demand and effort TLX score for Task 1

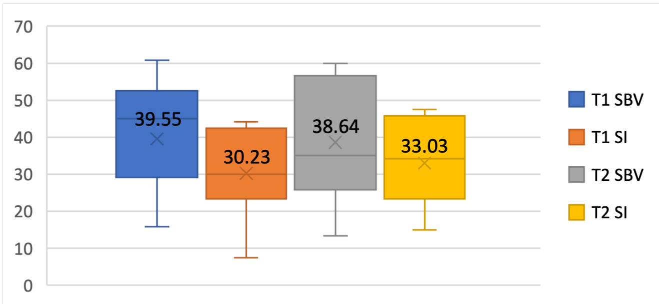

Fig. 9. Overall TLX scores for the 2 tasks (T1, T2) in the on-site study. Value labels show mean values.

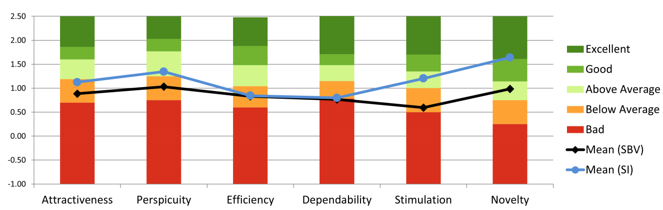

Fig. 10. UEQ benchmark score (version 8) comparison of both visualization approaches, situated broadcast-style visualization (SBV, black graph) and situated infographics (SI, blue graph).

(p=0.03, p=0.03 and p=0.04) with a lower average TLX score for SI (boxplot Figure 9). It is important to note that the workload scores for both conditions are lower than the 50% of previously observed Computer Activities (54.0) and score lower than 75% of previously observed Visual Search tasks (51.06) [43].

The UEQ scored well for both conditions with positive scales on all aspects. Thereby all average scores of SI are higher compared to the ones in the SBV condition. However, we could not measure any significant differences between the conditions across the 6 categories with a two-sampled t-test assuming unequal variances (p=0.53, p=0.37, p=0.96, p=0.90, p=0.06 and p=0.10). We also compared our UEQ scores for both visualization approaches to the benchmark provided by the UEQ Data Analytics Tool (version 4) (Figure 10). It is seen that for SI, a majority of the scores are above average and even scored excellent among the benchmark while the SBV ratings mostly are in the below-average range. The benchmark is a growing collection of all UEQ evaluations which are shared by contributors [44]. According to the latest UEQ handbook (version 8) [45], there are now 452 products in the benchmark with 20190 total participants. The results indicate that we can confirm hypothesis H3 only partly for SI and need to reject it for SBV.

When asked about preferences for on-site spectating, 9 participants preferred SI and 7 participants preferred SBV. Among the reasons for choosing SI are that it is not too cluttered (P7, P8, P12, P13), easy to understand (P4, P10), well-integrated/seamless/realistic (P4, P7, P11) and it is nice to have to information on the field (P6, P12). As for the SBV, participants mentioned that it does not distract from the game as the visuals are not on the field (P1, P14, P16), is more familiar/close to real-life (P1, P2), and is clearer/simpler (P3, P14, P15). There are some contradicting statements among the participants as some said that the broadcast is simpler but some say it is more cluttered.

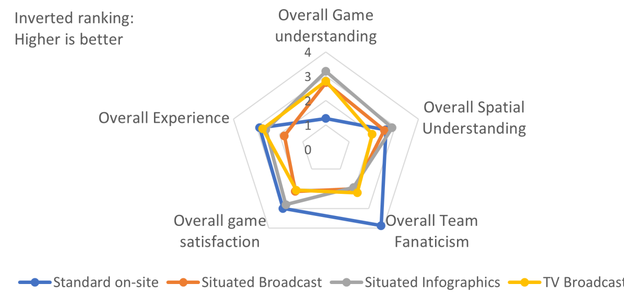

Fig. 11. Ranking of sports spectating method among aspects.

7.5.3. Results Part 3: Broadcast Footage Viewing Comparison

An overall comparison of all methods including off-site spectating indicated that SI is the first ranked condition for game understanding - higher is better ($\bar{x}$ = 1.8, Figure 11). The Friedman Test rejects the null hypothesis showing that differences are found in overall game understanding (p<0.001) and overall team fanaticism (p<0.001). Overall team fanaticism here refers to the feeling of attachment to the participants' supporting team. A further post-hoc Nemenyi test shows that in both overall game understanding and team fanaticism, there are significant differences between unassisted onsite viewing and the rest of the conditions (Game understanding p=0.04, p=0.01, p=0.03, team fanaticism p=0.01, p=0.01, p=0.02). This is in line with almost everyone agreeing that on-site viewing without assistance was the worst in terms of game understanding (12/15 participant, Binomial Test with CI p=0) but the best towards overall team fanaticism (13/15 participant). These results confirm our hypothesis H4, indicating that the situated visualization approaches increase game understanding compared to having no assistance.

7.6. Discussion

Considering that we did not find significant differences in IPQ and ratings varied between the actual AR and the indirect AR, it seems acceptable that indirect AR could be used to represent the actual AR in our setting although more research is needed. When comparing the two situated visualization methods, we found an improved game understanding and promising scores in UEQ, with SI leading ahead SBV. Situated visualizations seem to improve the experience overall except for team fanaticism which is only truly enjoyable without any form of assistance.

However, we found that different users have preferences for different visualization methods. When it comes to SBV and SI, participants' views were mixed. Half of the participants (P4, P7, P9, P10, P11, P13, P14, P15) felt that a personalized view is necessary, with some feeling that there is too little or too much information. Some participants (P5, P13) suggested a hybrid visualization approach, and some mentioned that it would greatly reduce the physical demand as users e.g. do not need to keep moving to the center to see the timer (P13).

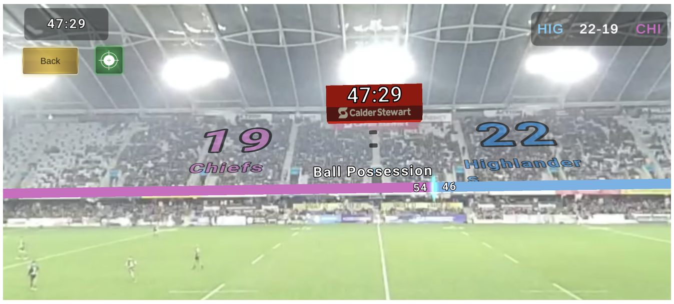

Fig. 12. Hybrid visualization prototype based on the user feedback from the on-site study.

Most participants exclusively focused on the given task. When asked additional questions, the success rate was rather poor. Some participants mentioned that they noticed other visualization elements but did not pay much attention as it was not part of the current task. One participant (P5) said that the line-out visualization for T1 was too quick and clashed with another ongoing event, causing distractions. This also indicates the importance of having interactivity and personalized views.

8. Conclusion and Future Work

We explored situated visualizations in the context of on-site live sports spectating in a stadium environment using rugby games as examples. We presented a new conceptual framework for on-site sports spectating which guided the implementation of our prototypes and the design of our studies. While White's original framework on situated visualization [12] served as a good starting point, our study findings confirm the need for an extended framework considering additional aspects needed for the on-site visualization of sports data. Our framework showed its usefulness when comparing dynamic AR content on different canvases within the stadium scene context where the user is in full view control with the combined approach of a display-referenced canvas for situated broadcast-style visualizations.

We conducted two user studies that support the general feasibility of our approach and found a preference towards situated visualizations compared to just watching on-site games. Spectators are getting more information from SI compared to TI while maintaining a similar cognitive load. We also show that situated visualizations in general assisted in overall game understanding while maintaining the game satisfaction higher than just watching the TV broadcast. An interesting observation is that there is no right or wrong approach when it comes to choosing between SBV and SI as depending on individuals, both are equally favorable. However, we implemented a hybrid prototype that combines SBV and SI (Figure 12) in an attempt to get the best of both worlds as a starting point for future work.

We see three directions for future work: (1) the integration of context-aware interaction with personalized visualizations, (2) the further exploration of the hybrid approach with possible integration of broadcast footage, and (3) the use of crowd engagement to have more socially-dynamic visualizations.

Expert users who are familiar with the rules of the game would prefer more in-depth game statistics. This supports the need for an information filtering step for the next prototype, where personal context considering user preferences and interest comes into play [46]. We are also looking into integrating actual broadcast footage for viewing the game or replays from a different angle, creating a three-phase situated visualization continuum from low spatial relation (broadcast footage) to high spatial relation which is our current prototype.

Lastly, we would like to incorporate more crowd engagement components into our prototype as spectators' participation could help improve the atmosphere of the event [47, 48]. Similar research has been done for live sports broadcast [49] but we want to integrate this into the stadium through sharing of spectator reactions. Extending our current scene context, future work in this could include automated crowd "atmosphere detection" possibly by environmental context-aware sound detection from the microphones of the spectators' devices.

We hope that our work presented here will inspire other researchers to consider situated visualizations in sports and other contexts and to experiment with studies outside of the lab.

Acknowledgments

This project is supported by an MBIE Endeavour Smart Ideas grant. We thank Animation Research Ltd, Forsyth Barr Stadium, the Highlanders, Otago Rugby (ORFU), and OptaPerform for their support. We also would like to thank our participants and our HCI and Visual Computing labs members.

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