A Classification Schema for Designing Augmented Reality Experiences

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Abstract

Aim/Purpose Designing augmented reality (AR) experiences for educational, health or entertainment involves multi-disciplinary teams need to make decisions across several dimensions. We present a comprehensive classification schema and design rationale for AR.

Background Existing schema focus on classification rather than design, or focus on particular dimensions of an AR experience. These schema, combined with analysis of a diverse range of AR applications, form the basis for the schema synthesized in this paper.

Methodology A literature review of existing classifications is used to define the schema. Further analysis of literature is used to confirm that the proposed schema is flexible and comprehensive.

Contribution This analysis and synthesis in this paper results in a schema that can be applied to communicating design considerations and alternative design scenarios where teams of domain specialists need to collaborate to build AR experiences for a defined purpose.

Findings The dimensions of nature of reality, location (setting), feedback, objects, concepts explored, participant presence and interactive agency and style describe features common to most AR experiences. Classification within each dimension facilitates ideation for novel experiences and proximity to neighbours recommends feasible implementation strategies.

Recommendations for Practitioners The schema serves as a design template and is intended to ensure comprehensive discussion and decision making during the design phase for AR experiences.

Recommendations for Researchers A standardized and complete classification schema facilitates classification of experiences and research innovations to more readily identify relevant related work.

Impact on Society Existing AR experiences do not yet fill all regions of the classification schema, suggesting opportunities to deliberately design and evaluate novel forms of AR experience.

Future Research The classification schema can be extended to include explicit support for design of virtual and extended reality applications.

Keywords Augmented reality, interactive experiences, design rationale, classification schema

1 Introduction

When developing augmented reality (**AR**) applications, designers create an assortment of imaginative experiences, utilizing a diverse range of technologies [Schmalstieg and Hollerer, 2016], to support opportunities for engagement, immersion and interaction by the audience [Dey et al., 2018, Milgram et al., 1995]. Continued innovation in the design of such experiences becomes increasingly challenging for designers, particularly where only a small portion of the team may be technology experts [Fenu and Pittarello, 2018]. AR experiences are utilized for many varied purposes including tourism [Weber, 2016, Xu et al., 2016], education [Harley et al., 2016, Radu, 2012, Richardson, 2016, Schneider et al., 2017], and exhibitions [Tsai et al., 2017]. Challenges include: ensuring consensus and common vocabulary within cross-disciplinary teams, achieving consistency and completeness in an AR experience design specification, and in considering the range of opportunities available with AR technologies. In our experience, virtual reality (**VR**) and augmented reality have been used to variously refer to systems involving: use of a head-mounted display, 360°degree video, desktop 3D graphics, or 3D graphics on a mobile device or web browser. Such differences in the most fundamental concepts complicate the design process, despite being technically correct. Other taxonomies [Normand et al., 2012] focus on technical (or techniques) classification, integration with the user, representation of information or interaction strategy. We identify a gap with respect to navigating the design space of applied AR applications.

The goal of this paper is to comprehensively define the design opportunities for AR experiences by developing a classification schema that systematically describes design choices.

To achieve the goal, this paper generates a classification schema specifically focused on supporting the design of AR experiences. This classification schema is derived from reviewing existing literature taxonomies related to extended reality, interactive applications and experience design (section 2). The schema is then validated through mapping of the literature review case studies to the schema (section 4).

2 Literature Review: Classifying realities

The well-known Milgram scale [Milgram et al., 1995] defines a linear continuum of real-to-virtual environments, in which AR is one part of the general area of mixed reality. This can be extended to consider broader application of mixed reality to technologies used, content and user experience [Skarbez et al., 2021]. Mixed reality defines a wide range of applications that situate digital information in the world [Rouse et al., 2015], by simultaneous perception of real and virtual [Skarbez et al., 2021, Normand et al., 2012]. The real-to-virtual continuum classifies applications that aim to alter the user's sense of reality. On one end, virtual environments completely immerse the participant in a synthetic environment [Azuma, 1997]. Whereas AR, defined towards the 'real' end of the continuum, is where the virtual content is overlaid over the participant's perception of the world [Nilsen et al., 2004], but with a tight coupling of graphics to the visual surrounds [Rouse et al., 2015]. Diminished reality [Azuma et al., 2001] is a subset of AR, a reality that removes objects, asking the participant to rely on their senses to mediate the experience. Multimediated reality [Mann et al., 2018] extends previous classification across disciplines, forms of media and sensory experiences. Further to AR and VR, pervasive reality (PR) is that which transcends place and time and can be played in many diverse places and for extended periods of time [Avouris and Yiannoutsou, 2012, Diaconu et al., 2018], exploiting contextual information within the environment [Chatzidimitris et al., 2016, Silva et al., 2016] or making use of situated media [Guven, 2006]. Ubiquitous reality, a subset of pervasive reality, embeds computing technology in the natural environment to support interaction with physical elements [Cheok et al., 2002]. Alternate reality on the other hand provides a mixed reality experience which adds new narratives to the real-world setting [Deterding et al., 2011, Silva et al., 2016]. The precise boundaries of these alternative realities rightly remain vague [Ch'ng et al., 2017]. While we use AR as the primary term throughout this paper as it is often incarnated in highly varied forms, the classification schema is also able to provide greater resolving power in describing the diversity of mixed reality experiences.

AR is more than registration of objects onto locations in the physical setting, and demands consideration of the nature of the interactive experience [Aluri, 2017, Azuma et al., 2001, Collins et al., 2017, Steuer, 1992, Skarbez et al., 2021]. In addition, interactive agency and style should also consider: the social interaction [Dunleavy et al., 2009, Joo-Nagata et al., 2017, Papathanasiou-Zuhrt et al., 2017]; context [Azuma, 1997, Barfield et al., 1995, Ganapathy, 2013]; and presence [Hansen, 2012, Milgram et al., 1995, Silva et al., 2016, Slater and Wilbur, 1997].

Existing AR case studies and frameworks are often described using technology-mediated classifications [Avouris and Yiannoutsou, 2012, Azuma, 1997, Diaconu et al., 2018, Endsley et al., 2017, Fedorov et al., 2016, Pryss et al., 2016, Skarbez et al., 2021, Speiginer and MacIntyre, 2018], with reference to hardware and software options and affordances. Indoor and outdoor AR experiences are distinguished because of the impact this has on tracking, and registration of content [Avouris and Yiannoutsou, 2012, Azuma, 1997, Freschi et al., 2015, Hansen, 2012]. Display devices are classified using categories such as handheld, head-mounted display (semi-transparent and camera), projective and multi-modal displays [Azuma et al., 2001, Barfield et al., 1995, Skarbez et al., 2021, Cheng et al., 2019], while interaction devices and metaphors are more diverse [Azuma et al., 2001, Ganapathy, 2013]. Several classes of device (such as backpack systems) and issues (monochrome line graphics) [Barfield et al., 1995, Milgram et al., 1995] have been superseded by hardware advances. The classification schema proposed in this paper purposefully focuses on design choices over technology considerations. While technology is integral to an AR experience, an experience design needs to consider many additional factors and these can be explored before introducing constraints relating to application in practice.

Ideally design of augmented reality applications should include the multiple aspects of the experience [Endsley et al., 2017], incorporating a range of specialist design and development skills [Fenu and Pittarello, 2018], and an understanding of the needs of the participants [Brederode et al., 2005, Lee et al., 2013] and context [Ganapathy, 2013]. Imaginative AR experiences extend participant presence throughout the location, across time and between participants [Carlson et al., 2018, Castaneda et al., 2018, Fernandez-Vara, 2009, Harley et al., 2016, Oleksy and Wnuk, 2017] and operate at levels of abstraction from conceptual knowledge to mechanical skills [de Ribaupierre et al., 2014, Deterding et al., 2011, Harley et al., 2016, Nilsen et al., 2004, Roo and Hachet, 2017].

Relevant design frameworks [Deterding et al., 2011, Lundgren and Bjork, 2003, Milgram et al., 1995] focus on different aspects of the experience, including augmented reality, live-action virtual reality [Silva et al., 2016], ubiquitous computing, games [Walk et al., 2017], exergames [Fernandez-Cervantes et al., 2016, Planinc et al., 2013], location-based games [Weber, 2016], persistent and alternative reality experiences, performance [Fernandez-Vara, 2009], embodiment [Lindgren and Moshell, 2011] and education [Kamarainen et al., 2013].

3 Review Methodology

Google scholar was used to identify the diverse range of existing literature relevant to the design of AR experiences. Google scholar was chosen as the database search tool due to the variety of results produced, representing a multidisciplinary view of augmented and extended reality. As in comparable investigations [Avouris and Yiannoutsou, 2012], this review selects papers from the identified set that inform the classification schema by either presenting relevant design classification schema themselves, or by describing AR relevant case studies suitable for categorization using the design classification schema. Papers are eliminated where the focus is on the workings of a particular technology element or interaction mechanic, focusing instead on relevance to AR experience design. This is a point of distinction relative to previous literature reviews of this nature [Avouris and Yiannoutsou, 2012, Azuma et al., 2001, Diaconu et al., 2018, Endsley et al., 2017, Fedorov et al., 2016, Pryss et al., 2016]. Table 1 summarises review outcomes. The review grouped the literature into common themes (or dimensions [Mann et al., 2018, Speicher et al., 2019]). The outcomes form the basis for the proposed classification schema. This schema derivation aims to maximize coverage across discipline boundaries and diversity in the nature of the applications. These descriptions are also shown in Table 1.

4 Classifying Design choices for AR

The schema consists of seven dimensions based on grouping the criteria described in Table 1, and covering the nature of the reality presented, the way the location that is portrayed, the form of feedback provided to participants, the way in which objects mediate interaction, the nature of the concepts assimilated, the ways in which participants engage with the experience and one another, and how the experience incorporates the user.

Using three axis to define each dimension aligns with Dervin's approach to sense-making [Hajdu Barat, 2010] that defines three types of information: information that is incomplete-objective and includes external reality; information that is subjective and includes internal reality; and information that includes the way in which a person becomes informed.

Each dimension allows elements of an AR experience design to be plotted on the interior of a triangle whose vertex labels are specific to that dimensions and relate to the ways in which that dimension is mediated [Mann et al., 2018]. This produces coordinates quantified relative to 3 axes defined by these labels, similar to those in [Normand et al., 2012]. Each of the original criteria grade an AR experience either on a spectrum between two extrema, or as one category in a fixed set of options [Mann et al., 2018]. Our proposal aims to capture both these aspects by employing a polygon representation with labelled vertices. Any AR application is then categorized by marking a point within the interior of the polygon, with proximity to each vertex representing the degree to which the experience achieves the corresponding label. The schema currently uses triangles to classify using three labels within each of the seven dimensions. Each paper reviewed that overlaps with one or

Existing AR experience classification criteria	Category descriptor used in this paper
Nature of experience/reality (defined as either natural, virtual, mediated, alternating, mental, emotional or imaginative) [Hoang and Cox, 2018, Nilsen et al., 2004, Stapleton et al., 2002, Steuer, 1992, Speicher et al., 2019]. *Form of Augmentation* (participant or environment) [Hansen, 2012, Silva et al., 2016], extent of augmentation (user, world) [Normand et al., 2012], sensory experience [Skarbez et al., 2021], technological environment layer [Speiginer and Maclntyre, 2018]. *Digital twins continuum* (twins, , digital natives, co-existing realities) [**?**], Society 5.0 [**?**]. *Connection* (absorbing content versus immersed in an experience) [Aluri, 2017, de Ribaupierre et al., 2014, Rouse et al., 2015, Stapleton et al., 2002].	Nature of Reality
Dependency on a particular place/location [Rouse et al., 2015, Silva et al., 2016]. *Environment* (with categories of real local, real remote, and synthetic) [Collins et al., 2017, Slater and Wilbur, 1997, Steuer, 1992], spatial environment layer [Speiginer and Maclntyre, 2018]. *Focus* (on impact of experience, location or other people) [Dunleavy et al., 2009, Joo-Nagata et al., 2017, Papathanasiou-Zuhrt et al., 2017]. *Form of Augmentation* (see Nature of Reality)	Location (setting)
Interactivity [Aluri, 2017, Azuma, 1997, Collins et al., 2017, Steuer, 1992, Speicher et al., 2019]. *Modality* (video, audio, haptic, taste, smell) [Barfield et al., 1995, Normand et al., 2012, Speicher et al., 2019]. *Feedback cues* [**?**]. *Lighting* [Collins et al., 2017, Dey et al., 2018]. *Coherence* (internal, external) [Skarbez et al., 2021].	Feedback
Objects [Azuma, 1997, Collins et al., 2017, Fernandez-Vara, 2009], augmentation layer [Speiginer and Maclntyre, 2018]. *Modality* (see Feedback, row 3).	Objects
Experience context (medical, collaboration, manufacturing, training, architecture, visualization, entertainment, commerce, tourism) [Azuma, 1997, Barfield et al., 1995, Ganapathy, 2013]. *Educational experiences* [Avouris and Yiannoutsou, 2012, de Ribaupierre et al., 2014, Joo-Nagata et al., 2017, Radu, 2012].	Concepts Explored
Immersion and presence [Milgram et al., 1995, Slater and Wilbur, 1997, Skarbez et al., 2021, Speicher et al., 2019]. *Collaboration* [Azuma, 1997, Dey et al., 2018, Dunleavy et al., 2009, Nilsen et al., 2004, Slater and Wilbur, 1997, Speicher et al., 2019]. *Target audience* considerations [Fenu and Pittarello, 2018]. Utilisation of *social connections* [Clark and Clark, 2016, Papathanasiou-Zuhrt et al., 2017]. *Focus* (see Location).	Participant Presence
Game play elements [Avouris and Yiannoutsou, 2012, Fernandez-Vara, 2009, Harris, 2018, Lee et al., 2013, Weber, 2016]. Participant *plays a role* as an actor [Carlson et al., 2018, Schneider et al., 2017, Steuer, 1992]. Contains a *story line* [Avouris and Yiannoutsou, 2012, Schneider et al., 2017, Slater and Wilbur, 1997]. *Focus* (see Location).	Interactive Agency and Style

Table 1: Mapping of existing AR classification criteria to the schema presented in this paper.

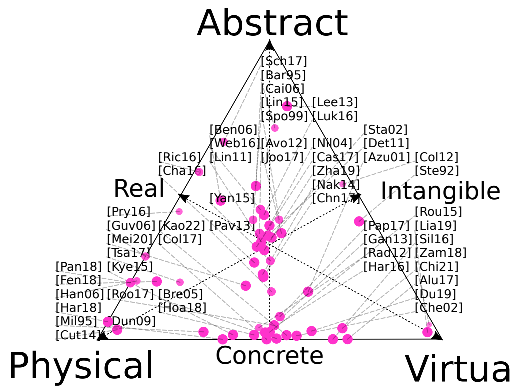

Figure 1: Defining Nature of Reality.

more dimensions is assigned barycentric coordinates for those dimensions, which are 3D coordinates that sum to 1 where the paper describes a design that meets a particular classification, with a lower total score (0.5 or below) where the relationship is less explicit. Coordinates were assigned by the two authors each working independently on half the papers. The scores were then compared and normalized during a joint meeting. The classification outcome for each dimension is described and plotted in the sections that follow, along with a detailed description of each dimension's coordinates in relation to the relevant literature. Minor zero-mean random perturbations in the coordinates plotted are used in these diagrams to support visualization of clusters. Abbreviated citation keys are used to aid readability.

5 Nature of Reality

The nature of reality dimension classifies the complete experience and extends on the Milgram scale [Milgram et al., 1995] with its categories of physical and virtual reality, by including an orthogonal category of abstract reality that extends the computer mediated experience with human mediated elements. Any form of mediated communication can provide an experience that transports the audience [Steuer, 1992], from placing the reader in a story-like novel through to acting upon a narrative in a video game. A consideration when designing an AR experience should be what the desired experience should provide in terms of the representation of reality [Chen et al., 2013]. The literature exploring existing AR experiences shows a mix between virtual and physical realities [Azuma, 1997, Collins et al., 2017, Lindgren and Moshell, 2011, Lukyanenko, 2016, Nilsen et al., 2004, Rouse et al., 2015, **?**]. Providing an AR experience, as with MR, relies on the perceptually successful blending of reality and virtuality, providing a coherent set of stimuli for the participant [Collins et al., 2017], or an interweaving of experience that alternates between the real and virtual environments [Hoang and Cox, 2018].

When defining the nature of reality, we define three vertex labels: *physical* as that which relates to the way in which the real world is experienced through the participant's senses; *virtual* which is provided through a computer mediated experience not detectable through a participant's own unaugmented senses and *abstract* experiences may be a combination of physical and virtual components, but rely on imagination, willing disbelief and human mediation to consider the representation of reality provided [Aluri, 2017, Stapleton et al., 2002]. A blend of the factors: abstract, physical and virtual is required to define the nature of reality presented in any AR application, as shown in Figure 1.

A purely *physical* reality corresponds to traditional reality within the physical world and uses elements consistent with that environment. *Virtual* refers to a computer-generated representation that is physically plausible but represents a world that is not present at that location at that time. *Abstract* refers to concepts that have non-traditional representations that may require human mediated suspension of disbelief or invoke an imaginative process such as when reading a book. Of the minor (edge midpoint) categories, *real* (converse of virtual) refers to physically based elements or concepts available in the world, rather than purely virtual. *Concrete* (converse of abstract) defines the level of imagination required by the participant during the interactive experience. *Intangible* (converse of physical) reality is not physically available, but can be suggested through some form of augmentation. The goals of the experience will direct the concepts included, informing expectations on participant outcomes.

A participant's connection to the nature of the reality relates to their feeling of embodiment [Stapleton et al., 2002] and whether the physical structure of the human body dictates the nature of the experience or needs to adapt to the digital environment by sensing and perceiving abstractions [Hansen, 2012, Radu, 2012]. This mix of physical and virtual can be perceived in different ways by participants, allowing potentially imaginative, abstract and participant rendered representations of reality [Avouris and Yiannoutsou, 2012, Azuma, 1997, Brederode et al., 2005, Ch'ng et al., 2017, Cheok et al., 2002, Collins et al., 2017, Dunleavy et al., 2009, Harley et al., 2016, Hoang and Cox, 2018, Kysela and Storkova, 2015, Nakevska et al., 2014, Roo and Hachet, 2017, Rouse et al., 2015].

Experiences that rely heavily on capturing content from the physical world, such as visiting historical landmarks [Harley et al., 2016, Pavlik and Bridges, 2013], a museum [Fenu and Pittarello, 2018, Papathanasiou-Zuhrt et al., 2017] or playing Pokémon Go [Aluri, 2017], are representing a physical reality. Technology enhanced street theatre, where the audience interacts with both the unaltered environment as well as props and performers as part of the unfolding drama [Benford et al., 2006] provides a physical human mediated connection for this audience within a technology influenced environment. In a pervasive reality city lighting can sense participants and actively guide them in the physical world to achieve their goals [Diaconu et al., 2018]. Often human actors provide a physical augmentation [Papathanasiou-Zuhrt et al., 2017] by playing a role in an unfolding narrative, or providing information relevant to the history of the location [Joo-Nagata et al., 2017], although their roles may represent virtual or abstract content.

Experiences that rely on presenting a computer generated reality, such as showing a landmark as it used to appear [Avouris and Yiannoutsou, 2012], interacting with a virtual guide [Harley et al., 2016], exploring a situated documentary or narrative [Dunleavy et al., 2009, Lin and Chen, 2015, Pavlik and Bridges, 2013], or playing AR Quake [Azuma, 1997], are representing a virtual reality. Digital artworks promote cultural awareness [Papathanasiou-Zuhrt et al., 2017], complementing the existing tourist attractions with virtual content that can be accessed at the participant's discretion. The synthetic component of an augmented-reality presentation does not need to be highly realistic imagery to convey meaning [Barfield et al., 1995], and can even provide a deliberate ambiguity between fictional and real world [Benford et al., 2006].

Augmented reality experiences can increase demand on the participant's attention [Weber, 2016] leading to disengagement from the physical space and a move towards imaginative abstract settings that embrace the magic circle such as a fictional role that represents an alternative image of self [Yan et al., 2015]. Games provide a structure to create fictions separated from real life, such as a tabletop game projected on a horizontal surface [Brederode et al., 2005]. The make-believe abstract reality adjacent to the physical [Brederode et al., 2005, Caillois, 2006, Chatzidimitris et al., 2016] provides opportunity to explore a space that cannot be provided to scale in the real world [Cole et al., 2012, Dunleavy et al., 2009]. Abstract representations remove the participant from "realistic" reality and present concepts including past, future or imaginative fictional settings [Endsley et al., 2017, Stapleton et al., 2002] in ways that are not be directly sensed.

Other dimensions of the schema share the physical-virtual-abstract bounds including: the setting within which the experience takes place, the form of feedback participants receive, the nature of the objects that participants interact with, and the concepts presented.

6 Location (setting) of Experience

The location dimension refers specifically to the representation of place. Location for representing the setting is an important element of location-based augmented reality experiences, being explicit in many definitions for augmented reality [Lin and Chen, 2015, Pavlik and Bridges, 2013]. The term location variously relates to sensitivity to the participant's location [Avouris and Yiannoutsou, 2012, Chen et al., 2013], to integrating the location with the experience [Deterding et al., 2011, Endsley et al., 2017, Richardson, 2016], and to utilizing the context of a specific location [Chatzidimitris et al., 2016, Schneider et al., 2017]. This dimension explicitly focuses on experiences that are "deeply locative" [Rouse et al., 2015] and designed to exploit the context and nature of a specific location(s) as opposed to those intended for use regardless of situation [Lee, 2012, Rouse et al., 2015] which use generic AR location-aware technologies.

Similarly to the nature of reality, a blend of the factors abstract, physical and virtual is required to define

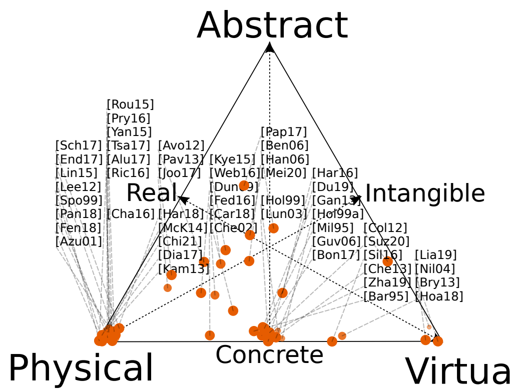

Figure 2: Defining Location

the setting, as shown in Figure 2. *Physical* refers to when an application is set in the real-world location that the participant is visiting and utilizes this physical environment. *Virtual* settings are provided as computer generated synthetic elements that immerse the participant in the place without needing to be physically present. For example, a 360-degree projected space provides a virtual presentation accurately representing key properties of the location despite the intangible format. Opposing a concrete experience are those with an *abstract* link to the location employing imaginative or reinterpreted representations, or those that are not sensed directly. For example, an abstract location could involve inferring a first person perspective from a third person table-top view. A designer may choose to blend these dimensions, but is also able to focus on just one and enrich the experience through design choices related to the other dimensions of a AR experience design.

Typical AR applications maintain a connection to the physical world to register it to the view observed through a camera [Endsley et al., 2017, Weber, 2016] although locations can be incorporated in many other ways. Locations can be distinguished into categories such as indoor and outdoor [Azuma, 1997, Azuma et al., 2001, Hollerer et al., 1999b, Schneider et al., 2017], real or virtual [Avouris and Yiannoutsou, 2012, Chatzidimitris et al., 2016, Milgram et al., 1995], or to note use of public space [Deterding et al., 2011] or geographic locale [Pavlik and Bridges, 2013], often because these affect choice of technologies to both track the participant and to capture the scene [Azuma et al., 2001].

Early interpretations of augmented reality [Barfield et al., 1995] suggest that the location is either experienced directly in its physical form or provided virtually through a head mounted display either computer generated or reconstructed from data captured from a real location [Hollerer et al., 1999a, Du et al., 2019]. The physical location may be the focus of the experience [Richardson, 2016, Schneider et al., 2017], for example where a specific city is the setting of an AR experience played out at defined locations, or workplace training [**?**]. Alternatively, the location can just be a canvas representing context for overlaid content providing information, media, or virtual structures and objects [Guven, 2006, Hollerer et al., 1999a, Spohrer, 1999]. Information annotated onto the entire visible landscape identifies landmarks and mountains [Fedorov et al., 2016]. AR games introduce fictional settings [Benford et al., 2006] distinguishing virtual representations of actual locations from more abstract settings for fictional or unconventional locations, such as regions represented at microscopic scale [Cole et al., 2012]. A role-playing experience at a medieval city [Papathanasiou-Zuhrt et al., 2017] exploits the physical location and enhances it with imaginative elements including a location-linked storytelling device. The concept of place attachment relates to perception of a location as an attractive destination [Oleksy and Wnuk, 2017]. Place attachment results in return visits to sites, or positive goodwill as required in commercial tourism activities [Papathanasiou-Zuhrt et al., 2017, Xu et al., 2016] by using the AR experience to encourage participants to bond with the location.

Experiences that do not depend on specific physical locations [Bonfert et al., 2017, Chatzidimitris et al., 2016], such as Pokémon Go [Aluri, 2017], can incorporate site context when the locations themselves adapt to include references to the AR experience [Aluri, 2017] by incorporating the application into travel guides. Such weakly locative applications are driven by activities linked to a map [Kamarainen et al., 2013, McKenzie et al., 2014, Weber, 2016] which are triggered by visiting those coordinates but otherwise do not rely on that specific location directly. Procedural generation can manufacture virtual settings that conform to the physical location [Cheng et al., 2019]. Activities to encourage exercise can use physical augmentation of the setting such as RFID readers at key locations to register progress [Harris, 2018]. A game of mystery set on city streets [Benford et al., 2006] uses part of the physical setting enhanced with a fictional overlay including actors and clues related to the setting. Technology enhanced theatrical performances [Carlson et al., 2018] takes place in a physical gallery with the setting enhanced with virtual elements.

Physical location plays a key role in AR experiences for museums [Fenu and Pittarello, 2018, Lin and Chen, 2015, Pang et al., 2018, Tsai et al., 2017], where the augmentation is information applied to individual objects in the room. Alternating reality [Hoang and Cox, 2018] switches between the physical location and a virtual location by alternating between viewing directly, and through a head-mounted display. Alternating is used in other tourism and educational applications [Joo-Nagata et al., 2017, Kysela and Storkova, 2015] where a tour of a physical city is enhanced with virtual content (e.g. architectural models) with some fictional, historical or abstract representations using map-based representation or information overlays. Virtual overlays in the setting can make use of modalities such as sound [Chatzidimitris et al., 2016], map-based representations [Chen et al., 2013, Dunleavy et al., 2009, Lundgren and Bjork, 2003] or head-up information overlays [Ganapathy, 2013, Pryss et al., 2016] to present aspects of the setting that may not be directly visible. Participants may share the space across different forms of the location; physically present, as 360° images captured from atypical viewpoints [Zhao and Klippelt, 2019], as maps, or exploiting proximity rather than absolute location [Lundgren and Bjork, 2003]. Pervasive computing applications provide a form of computational augmentation to the physical environment [Diaconu et al., 2018].

The location itself may be completely virtual and experienced through a head mounted display, through a small "window" provided by a mobile screen [Cheok et al., 2002], or through a projection onto a tabletop surface [Brederode et al., 2005, Nilsen et al., 2004]. Locations presented virtually through a head-mounted display may nevertheless incorporate structural and tactile elements of the physical setting [Silva et al., 2016], or recreate familiar environments such as a virtual classroom [**?**]. The virtual location may represent the actual physical location, such as when allowing a performer to monitor their own performance [Yan et al., 2015].

AR also supports locations that could never be visited in person. Locations at different scales (e.g. microscopic [Cole et al., 2012]) can be interpreted virtually or physically in ways that communicate relevant properties of the setting. Historical views are provided by augmenting a contemporary location with representations of the past [Pavlik and Bridges, 2013], or cultural content can be reimagined in game worlds [**?**]. Annotation systems allow the added content to be experienced at the physical location, but also in virtual environments or other representations of the location (e.g. a web page) [Hansen, 2012].

7 Feedback

Interaction in mixed reality sometimes fixates on the mechanisms for managing participant gestures and movements [Collins et al., 2017] although such low-level actions can be progressively abstracted into more complex sets of behaviours [de Ribaupierre et al., 2014] that are both efficient and expressive [Dey et al., 2018]. In AR the interactivity should consider the balance between feedback, objects and concepts to facilitate a space of activity.

Figure 3 defines the relevant categories to define feedback presented in any AR application. Feedback is classified as *physical*, *virtual* and *abstract* based on the form of feedback. Physical feedback involves physical interactions through real-world elements. Virtual feedback is mediated through technology such as a pop-up tour guide in a museum that responds to queries [Lin and Chen, 2015]. Feedback in the physical world is a response to moving around the space of action, and in the virtual world occurs through actions of interface elements or viewing the space of action through AR view. Abstract feedback is participant mediated such as a trigger for imagination or an emotional response [Salen and Zimmerman, 2004]. It is indirect and requires further interpretation such as inferring the behaviour of a ghost based on particular noises or of changes in personal status based on points scored.

The feedback dimension covers the actions of the participant, and the stimuli presented to the participant in response to actions. Feedback provides an engaging participant experience, and a way for participants to evaluate the consequences of their actions [Fernandez-Cervantes et al., 2016, Weber, 2016], particularly in mixed reality settings where traditional cues do not apply. Interaction involves a feedback loop where the participant provides input to the experience, and the output from the experience is reciprocally presented to

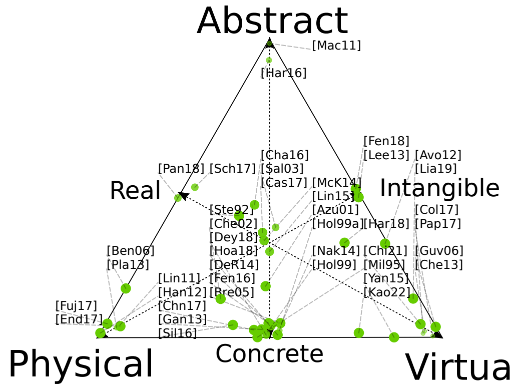

Figure 3: Defining Feedback

the participant [Salen and Zimmerman, 2004, Steuer, 1992]. The part of the feedback loop representing the actions provided by the participant can be achieved by using physical objects directly [Ch'ng et al., 2017], or re-imagined as particular tools [Azuma et al., 2001, Cheok et al., 2002] by manipulating their appearance with a visual overlay. The participant's body can be regarded as the physical source of actions [Hansen, 2012], for example re-imagined as an asteroid participating in a planetary simulation [Lindgren and Moshell, 2011]. Actions achieved without direct physical action include input in the form of speech, as input via a touch screen [Hollerer et al., 1999a, Lin and Chen, 2015], or by clicking on points of interest using a trackball [Guven, 2006]. Mappings [Steuer, 1992] translate the information being exchanged between participant and experience. The input and output directions of information flow can use different mechanisms. For example, the participant may act on physical objects but see the response presented in the virtual overlay [Brederode et al., 2005].

Typical augmented reality applications concentrate on the presentation aspect mixing the actual physical setting with virtual content that may be presented visually or using other modalities (e.g. audio [Ganapathy, 2013], smell [Silva et al., 2016] or haptic [Azuma, 1997, Fujinawa et al., 2017]. The physical and virtual feedback elements can complement one another in the ways they communicate concepts [Hoang and Cox, 2018], mixing the physical spatial concepts with the virtual reimagining [Milgram et al., 1995]. In a role-playing setting physical actors provide feedback through performance, although this may need to be interpreted within the context of the story [Benford et al., 2006]. Robotic museum guides provide the opportunity for physical responses as well as audio feedback [Pang et al., 2018]. The actions of other co-located participants is also a form of direct physical feedback [Cheok et al., 2002] while an avatar representing the participant provides virtual feedback of his/her own physical movement during exercise training [Fernandez-Cervantes et al., 2016, Yan et al., 2015]. Body-based forms of feedback enhance participant embodiment due to the physical connection [Hansen, 2012].

While the physical environment of an augmented reality experience suggests use of tangible and physics-based metaphors [Endsley et al., 2017] to provide feedback, information presented to the participant need not be in a concrete nor a visual form. New forms of feedback and interaction bridge between the physical and virtual world, and allow imaginary elements to become tangible through experience [Ganapathy, 2013]. Ghosts in an augmented Pacman game can be implied using sound effects [Chatzidimitris et al., 2016], rewards provided as status on a leader-board [Macvean, 2011], narrative and clues on an iBook screen [Papathanasiou-Zuhrt et al., 2017] or by an invisible narrator [Castaneda et al., 2018], while the effect of a detonating mine might be presented as a change in score [Cheok et al., 2002].

8 Objects

The objects dimension specifies the nature of the discrete elements that the participant interacts with. Objects in an AR experience include both virtual and physical items, and may represent real objects, parts of an environment or abstract elements in the experience [Avouris and Yiannoutsou, 2012, Azuma et al., 2001, Benford et al., 2006, Ch'ng et al., 2017]. Examples include the virtual elements that appear on surfaces captured from the real world [Roo and Hachet, 2017] whereas physical objects can become tangible interactive

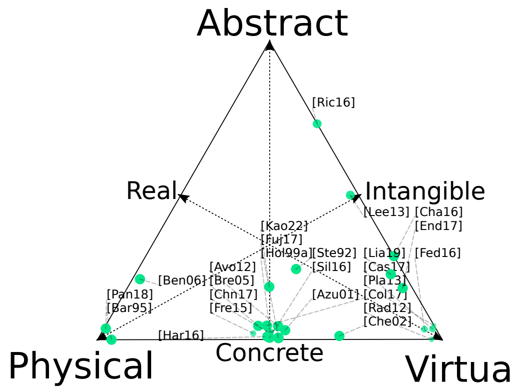

Figure 4: Defining Objects

elements by projecting content onto them [Azuma et al., 2001, Brederode et al., 2005, Van Krevelen and Poelman, 2010].

Figure 4 demonstrates the dimension for objects, again allowing the designer to specify the mix of physical, virtual and abstract elements. Objects in AR may exist in a *physical* sense, as part of the existing environment or placed artificially. *Virtual* objects are representations of objects presented through computer generated means to produce the virtual overlay. Virtual objects appear in 3D locked in position relative to a physical location [Fenu and Pittarello, 2018] although sometimes the overlay is a control for a physical object or information content covering a particular concept [Tsai et al., 2017]. The benefit of working with virtual objects is that the need for a common physical location becomes optional. Objects may also be *abstract*, providing a representation that is not immediately discernible or meaningful for the participant, such as the presentation of an 'aura' [Richardson, 2016]. Abstract objects may be part of the narrative, such as points scored, treasure collected during the experience [McKenzie et al., 2014], or indirect representations of objects using sound cues [Chatzidimitris et al., 2016] to represent ghosts and cookies in an audio augmented game of Pacman. A designer can blend any selection of objects in their application and should consciously decide on which are most appropriate to their requirements.

Objects in an AR experience can be defined in a physical sense, from real world books to furniture. Interplay between physical objects (desk lamp and notebook) and interactivity in a desk simulation shows how these objects transition from real to augmented during the simulation [Collins et al., 2017]. Moveable physical objects in an AR scene can be tangible control elements for manipulating the virtual overlay [Brederode et al., 2005] such as physical puzzle cards that present virtually as logical functions to embody programming abstraction [**?**].

Virtual objects can take physical objects and remap them to the virtual overlay to change their appearance [Silva et al., 2016, Cheng et al., 2019]. This can be used, for example, to substitute physical obstacles with plausible virtual objects that need to be avoided. Such objects exist on the reality-virtuality continuum from real to virtual [Milgram et al., 1995]. The interplay between physical and virtual objects enables participants to better interact with the visual information, providing a tangible interface to support participant interaction with complex information [Azuma et al., 2001]. Virtual AR objects are presented differently than in a non-AR medium: verbal descriptions become visual, static images become animated, 2D representations become 3D objects, and non-interactive content becomes interactive [Radu, 2012]. Virtual objects and elements in an AR experience add customizable complexity but require a degree of persistence [Nilsen et al., 2004] to ensure they represent a form of computer mediated communication that is understandable by the participant. A mixed reality art-science collaboration focused on an artificial life ecosystem [Ch'ng et al., 2017] combines virtual and real objects, with computational agents employed to enable interaction between participants and objects.

Virtual objects (and potentially physical) may not have a direct representation in the participant's known understanding of the real world. AR objects afford the opportunity for novel, imaginative and surprising interaction to occur [Lee, 2012, Radu, 2012, Richardson, 2016]. For example, a serious game in medicine has tasks spanning several levels of abstraction, from kinematic and dynamic aspects to domain knowledge training [de Ribaupierre et al., 2014]. Virtual pets provide a relationship between objects and a player

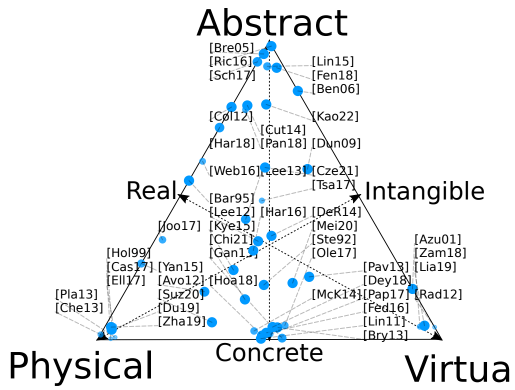

Figure 5: Defining Concepts

actions [Lee et al., 2013].

9 Concepts Explored

The concepts explored dimension describes the nature of the information that the participant is engaging with through the context of the experience. AR experiences cover a wide range of contexts, being used for purposes such as visualization, supporting assembly and maintenance, shopping assistants, games and entertainment, historical recreation, tourism, and training in areas such as surgery [Azuma, 1997, Azuma et al., 2001, Dey et al., 2018, Ganapathy, 2013]. These involve different levels of abstraction ranging from manufacture and repair of existing physical equipment [Azuma, 1997, Barfield et al., 1995], providing a virtual overlay of ultrasound images [Barfield et al., 1995] or forensic evidence [Avouris and Yiannoutsou, 2012], or developing knowledge of concepts such trade and religion [Avouris and Yiannoutsou, 2012].

Figure 5 is used to classify the concepts explored. *Physical* concepts are those that are practical and hands-on, typically with a focus on spatial structure and relationships, for example a site tour or a frog dissection. *Virtual* concepts convey ideas that cannot practically be represented physically, overlaying information about physical objects, such as historical views that no longer exist, showing flow of air around objects or data such as concentrations of chemicals at various points in the location. *Abstract* concepts are those that cannot be presented spatially such as social relationships, emotion or abstract mathematical ideas, and may include elements of deduction or reasoning. Consequently, real concepts are physically verifiable, but not always visible or directly representable.

Physical concepts covered include equipment repair, but also to developing motor skills [Dey et al., 2018, McKenzie et al., 2014], self-assessing dance performance [Yan et al., 2015] and improving physical fitness [Cutter et al., 2014, Harris, 2018] allowing clinical assessment [Ellmers et al., 2017]. Such experiences can adapt to the needs of the participant, both in difficulty but also by considering physical ability and age [Planinc et al., 2013]. Overlays provide ways of presenting content that is not physically present. This ranges from retail spaces where virtual stock can be shown on the shelves [Brynjolfsson et al., 2013] to remote collaborations [Dey et al., 2018].

Higher levels of abstraction are achieved through applications based on puzzles and mysteries which tolerate levels of ambiguity [Benford et al., 2006, Dunleavy et al., 2009]. Games are another way of presenting abstraction, through rules that engage with abstract concepts such as ensuring social interaction between children of differing capabilities [Brederode et al., 2005] or modifying attitudes and behaviour [Cole et al., 2012, Cutter et al., 2014, Harris, 2018, Lee, 2012]. Exploring and problem solving in a AR experience provide opportunities to practice and develop language skills [Richardson, 2016], or learn programming abstractions [**?**]. Simulations work across multiple levels of abstraction and develop problem-solving skills [de Ribaupierre et al., 2014] and convey the complexities of ecosystems [Schneider et al., 2017]. Museum and tourism experiences present media to develop both better awareness of their content but also to develop an emotional attachment to the topic, culture or place [Fenu and Pittarello, 2018, Hoang and Cox, 2018, Joo-Nagata et al., 2017, Kysela and Storkova, 2015, Lin and Chen, 2015, Pang et al., 2018, Papathanasiou-Zuhrt et al., 2017, Tsai

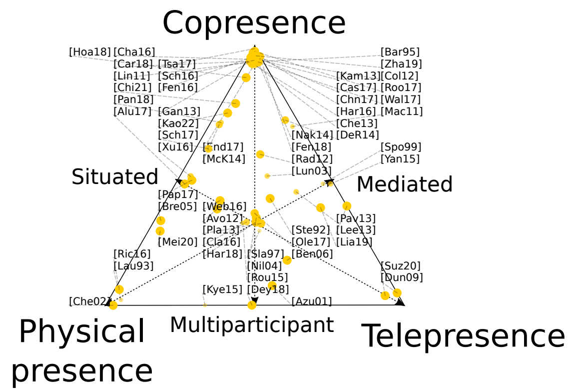

Figure 6: Designing Participant Presence

et al., 2017, Weber, 2016, Zamora-Musa et al., 2018].

Teaching a concept is particularly relevant to education and training. Educational experiences span the range, teaching variously physically oriented concepts such as transportation choice or operating equipment [Radu, 2012] orvirtually overlaid concepts such as greenhouse effect. Teaching abstract concepts is common, involving developing empathy and social norms [Lee et al., 2013], learning to use AR in lesson design [**?**], or learning properties of the physical environment through virtual scenarios while dealing with abstraction in the form of social interactions [**?**]. Concepts can be explored using: problem solving, discovery, experimentation, or through mini-emergent elements [Richardson, 2016, Xu et al., 2016]. AR applications teach through active experiences, support collective learning, adapt to individual needs and allow construction of knowledge [Dunleavy et al., 2009]. Participant created content supports knowledge sharing between participants [Lee, 2012].

10 Participant Presence

When designing the participant experience considerations of experience and presence guide the design of the activity structure for the participant [International Society for Presence Research, 2000]. Participant presence considers how participants are engaged with the experience and with one another. Human perception of an AR experience can be considered in terms of presence, which is a prominent component of our conscious human experience [Carlson et al., 2018]. AR interactive experiences provide varying degrees of physical presence, providing physical proximity for participant interaction, as well as virtual or telepresence which is largely technology mediated.

Figure 6 describes the three elements that define participant presence. *Physical presence* occurs when interaction is between participants in physical proximity, with *telepresence* occurring when it is technology mediated usually because the participants are not co-located. *Copresence* occurs when engagement is primarily with the experience, rather than with other participants who may be at the same location.

Physical connection provides human mediated presence allowing participants to connect either to the environment or to other participants [Aluri, 2017, Cheok et al., 2002, Nilsen et al., 2004, Papathanasiou-Zuhrt et al., 2017, Richardson, 2016, Slater and Wilbur, 1997]. Engaging in the physical world also provides opportunity for meaningful interaction between participants and the environment, and also between participants [Harris, 2018]. The physical interaction between participants in an AR experience is of considerable value as it ensures human connection is mediated and connected to the real world [Cheok et al., 2002]. An AR experience may use direct communication in the physical environment even when access to the virtual overlay is shared among the participants [Schneider et al., 2017].

Participant presence may be provided through virtual or telepresence mechanisms, providing a technology-mediated experience for the participants [Azuma et al., 2001, Brederode et al., 2005, Dey et al., 2018, Dunleavy et al., 2009] such as collaborating through remote control of equipment [**?**]. The telepresence mechanisms can virtually monitor the AR experience, and provide a variety of objects and feedback to guide the participant's experience to provide engagement. Engaging with others is usually indicated visually, but can also be achieved

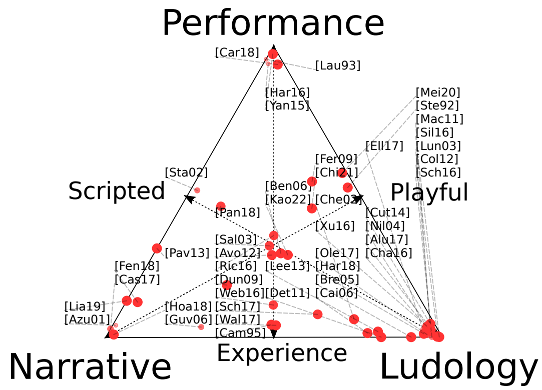

Figure 7: Designing the Interactive Agency and Style

through audio cues [Cheok et al., 2002] which supports awareness of others even when they are outside the field of view. A collaborative experience can involve the interaction between physical and telepresence [Azuma et al., 2001]. Social contact while playing Pokémon Go predicts active place attachment [Oleksy and Wnuk, 2017].

AR also has the potential to allow participants to co-inhabit the same physical space with other participants, providing opportunities for technology mediated collaboration and copresence [Dunleavy et al., 2009, Harris, 2018, Kysela and Storkova, 2015], such as a shared story space [Pavlik and Bridges, 2013]. Participant presence considers what kind of relationships the participant forms during the experience and describes the way the experience connects the participant to and across the physical or telepresence domains [Aluri, 2017]. Recordings of students working through electronic resources can be triggered at appropriate times, providing technology mediated but asynchronous collaboration through the student's virtual avatar representations [Liao et al., 2019]. Copresence in mixed reality experiences can generate face-to-face social interaction through use of common public spaces [Clark and Clark, 2016]. It may see participants engage in a multi-participant experience connected via technology, as teams with only a single device per team, or completed completely solo, such as the cultural heritage experience [Joo-Nagata et al., 2017]. Team cohesion is reportedly improved when working with AR content [Radu, 2012]. Progress can also be monitored virtually in these experiences [Benford et al., 2006], impacting both the social and collaborative experience [Lee, 2012, Macvean, 2011]. Games have the potential to encourage and support social interaction amongst players providing participant presence as they can bring together like-minded individuals visiting a particular location to participate in a common and mediated activity [Brederode et al., 2005, Xu et al., 2016, Papathanasiou-Zuhrt et al., 2017, Aluri, 2017, Nilsen et al., 2004]. Assassination games rely on both physical (co-location) and virtual (game play mechanics) to provide participant presence [Avouris and Yiannoutsou, 2012].

11 Interactive Agency and Style

AR experiences can just present virtual, physical and abstract content but richer engaging experiences result from including additional structure [Azuma et al., 2001]. Such structures include narrative, ludic and role-playing elements [Avouris and Yiannoutsou, 2012, Cheok et al., 2002, Salen and Zimmerman, 2004].

As shown in Figure 7, the corners of the triangle mark the extent to which the application incorporates *performance* aspects [Rouse et al., 2015], *narrative* elements, and *ludic* structure [Schneider et al., 2017]. Performance includes active and interactive elements that provide a sense of agency for the participant (such as role playing) [Fernandez-Vara, 2009, Rouse et al., 2015]. Narrative represents the degree of structured story present in the experience [Walk et al., 2017] which participants can experience but have limited effect on the outcome. Ludic elements impose particular rules defining an explicit relationship between actions and outcomes but allow participants to explore the space of possibilities within this structure [Lundgren and Bjork, 2003, Stapleton et al., 2002, Walk et al., 2017].

Popularity of ludic elements [Aluri, 2017, Avouris and Yiannoutsou, 2012, Brederode et al., 2005, Chatzidimitris et al., 2016, Nilsen et al., 2004, Silva et al., 2016] is attributed variously to the opportunity to engage the participant as an actor through multiple senses [Steuer, 1992], to opportunities to shape behaviour [Cole et al., 2012], provide motivation [Deterding et al., 2011], disguise dull training activities [Schoneveld et al., 2016] and to support task-based collaboration [Cheok et al., 2002]. Gaming experiences market tourism locations even prior to visiting them [Xu et al., 2016]. Location based games facilitate attachment to that place [Oleksy and Wnuk, 2017, Weber, 2016]. The game itself pervades across multiple realities; using physical pieces, in virtual worlds on a computer, or mixtures of these through projections [Lundgren and Bjork, 2003].

Story elements, either embedded or emergent, are fundamental in game design frameworks [Walk et al., 2017]. Game objectives are often expressed in the context of a story [Brederode et al., 2005, Dunleavy et al., 2009] but narrative elements can also be distinct from the game. Stories have a more rigorous schedule and are less frivolous in nature [Cameron, 1995], and are thus supportive of educational goals [Schneider et al., 2017]. Interaction may be limited to visiting each location as the story unfolds [Fenu and Pittarello, 2018, Guven, 2006] under the guidance of a narrator [Castaneda et al., 2018] or can provide opportunities to control and direct the story [Pavlik and Bridges, 2013, Stapleton et al., 2002]. Narrative is driven by participant actions as they collaboratively solve puzzles and unravel the story [Dunleavy et al., 2009, Lee, 2012, Nakevska et al., 2014]. Narrative may be presented in a linear fashion, or as a series of threads [Rouse et al., 2015] integrated with the aspects of the performance. These can leave a mark on the setting through projecting images onto buildings and updating these images to respond to the emerging experience. For example, an overall narrative weaves a common thread through AR activities at multiple monument locations in a gamified tourism experience in the city of Rhodes [Papathanasiou-Zuhrt et al., 2017]. Narrative constructs the bridge between virtual and real in an exhibition highlighting architectural elements of Walter and Marion Griffin's buildings [Hoang and Cox, 2018].

Game playing in a social setting [Cheok et al., 2002] also has performance aspects enhanced through explicit inclusion of actors [Benford et al., 2006]. Observers may be observing indirectly, immersed as part of the scene or can even influence the outcome by their presence. This adds risk through drawing uninitiated bystanders into the virtual setting balanced by the opportunity to challenge expectations about acceptable behaviour. Substantial but invisible "stage" management protects players and ensures progression [Benford et al., 2006]. Dramatic elements may be regarded as frivolous but are also relevant to serious activities [Laurel, 2013]. Games and game engines can be used as an environment for learning through authoring content [**?**], in a process that combines performance with play. Robotic guides employ both storytelling and performance to entertain and educate [Pang et al., 2018]. A physical rehabilitation exergame likewise combines game elements with performance by encouraging participants to act out previously recorded poses [Fernandez-Vara, 2009], and provides feedback with regards to accuracy. Participants may have specialist roles that have access to exclusive information to encourage social interaction [Dunleavy et al., 2009], combining acting out the assigned role with the game play associated with solving a puzzle.

12 Discussion

The goal of this paper is to comprehensively define the design opportunities for AR experiences by developing a classification schema that systematically describes design choices. The application of the classification schema to a broad range of AR applications has been demonstrated in producing Figures 1-7 providing explicit choices for designers that are made across the seven dimensions.

Within the literature reviewed the median number of dimensions per case study is 3 (mean 3.75) suggesting that existing design reporting focuses only on particular features, rather than providing opportunity to consider design from a broader perspective. Ideation can be achieved by sampling coordinates across all triangles and devising design concepts that map to these coordinates. This process is applied to domains such as education, tourism, exhibitions, health and entertainment that benefit from considering the many dimensions of an AR experience, to produce richer and better integrated AR application designs. Once an area has been chosen within each dimension, literature at nearby coordinates can be used as inspiration for specific design decisions. Figures 1 to 7 also yield interesting insights; for example, augmented reality experiences covering abstract concepts (Figure 5) are more common than might be anticipated for "reality" focused applications, while abstract objects (Figure 4) are an opportunity to be explored introducing imaginative or unusual content into an AR experience...

Using the classification scheme is not without its limitations. The schema is not intended to be prescriptive but is an agile tool to support AR experience design. Useful designs result from debating interpretations of schema descriptions and coordinates, which opens opportunities for innovation. The authors make no claims that any particular coordinates are superior designs to any others but do note that the centre of each triangle does offer the greatest mixture of the different classification criteria. Literature selection focused on diversity and thus the density of clusters shown are likely an artefact of this sampling process. The schema focuses on design opportunities and can only help to identify exemplars when guiding implementation decisions around choice of technologies or specific interaction strategies.

13 Conclusion

The goal of this paper is to present a classification schema and design rationale for AR. This uses seven dimensions that designers and researchers should use when making explicit choices about creating an AR experience. The dimensions provided represent the richness and diversity of AR applications and are derived by combining previous taxonomies with other design elements of innovative AR applications identified through the review of literature.

This classification incorporates the descriptive abilities of its base taxonomies but is specifically created to support understanding requirements and developing a design for an AR application. The triangles, enhanced with references to existing applications, enable diverse teams to agree on design intent, to explore other options, and to consider alternate technical and implementation strategies. Most of the AR applications in the reviewed research focus on a subset of the categories identified, suggesting that other dimensions might not be considered during the design process, and that this classification scheme serves to consistently report on all aspects of an AR experience. The breadth-first literature review ensures the resulting classification schema is multi-disciplinary, relevant and representative, despite significant differences in focus across the literature identified.

Further extensions of this work would exploit the extensible nature of the schema to include categories representing design considerations resulting from advances in the field of mixed reality, or by including technology focused elements required to support implementation of these experiences.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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