Cascini, G., O'hare, J., Dekoninck, E., Becattini, N., Boujut, J.F., Guefrache, F.B., Carli, I., Caruso, G., Giunta, L. and Morosi, F., 2020. Exploring the use of AR technology for co-creative product and packaging design. Computers in Industry, 123, p.103308.

Exploring the use of AR technology for co-creative product and packaging design

Abstract

Extended Reality technologies, including Virtual Reality (VR) and Augmented Reality (AR), are being applied in a wide variety of industrial applications, but their use within design practice remains very limited, despite some promising research activities in this area over the last 20 years. At the same time, design practice has been evolving to place greater emphasis on the role of the client or end-user in the design process through 'co-creative design' activities. Whilst offering many benefits, co-creative design activities also present challenges, notably in the communication between designers and non-designers, which can hinder innovation.

In this paper, we investigate the potential of a novel, projection-based AR system for the creation of design representations to support co-creative design sessions. The technology is tested through benchmarking experiments and in-situ trials conducted with two industrial partners. Performance metrics and qualitative feedback are used to evaluate the effectiveness of the new technology in supporting co-creative design sessions. Overall, AR technology allows quick, real-time modifications to the surfaces of a physical prototype to try out new ideas. Consequently, designers perceive the possibility to enhance the collaboration with the end-users participating in the session. Moreover, the quality and novelty of ideas generated whilst using projection-based AR outperform conventional sessions or handheld display AR sessions. Whilst the results of these early trials are not conclusive, the results suggest that projection-based AR design representations provide a promising approach to supporting co-creative design sessions.

1. Introduction

The emerging technologies of Augmented Reality (AR), i.e. technologies that combine real and virtual environments that are interactive in real time and are registered in three dimensions (Azuma, 1997), and Virtual Reality (VR), i.e. technologies that completely immerse a user in a synthethic, three dimensional environment (Azuma, 1997), have long been viewed with interest by the engineering research community. Early work in this field looked at the potential application of these Extended Reality (XR) technologies in applications such as assembly operations (Wang et al., 2016), maintenance (Henderson & Feiner, 2011) and design reviews (Regenbrecht et al., 2005). But the widespread adoption of these technologies in engineering has been hampered by factors such as poor rendering quality, high costs and hardware that was uncomfortable to wear for extended periods. However, in the last five years, a number of XR devices have come to market that offer significant improvements in rendering quality, comfort and affordability, such as the Microsoft HoloLens, the HTC Vive and the Oculus Rift. These devices offer a strong foundation for professional applications in the engineering domain, which is starting to be exploited in a number of prototype systems that are intended to support design activities.

Another major trend that has been influencing design practice in industry in recent years is the increasingly important role of end-users within the design process. At one time, end users were rarely consulted unless it was an 'engineered to order' product, but approaches such as 'usercentered design' and now 'co-creation' have transformed the role of the end-user from the 'subject' of the design process to a 'partner' in the design process (Sanders and Stappers, 2014). Co-creation may offer benefits for manufacturers of mass-produced products, such as increased speed to market and reduced risk of market failure (Business Innovation Observatory, 2014), but in order to realise these benefits, it is necessary to overcome some of the communication barriers that often exist between designers and people not trained in design (whether customers, end-users, marketing staff etc) due to differences in their technical vocabulary and understanding of the design process. This may lead to misunderstandings and frustration when the exchange of ideas is inhibited by communication challenges (Stacey and Eckert, 2003).

The communication challenges of co-creative design activities represent an interesting opportunity for the application of XR technologies. We know that the use of design representations has a significant impact on communication and creativity in co-creation sessions (Bodker, 1998). Also, selecting and preparing design representations for use in co-creative sessions can require significant time, effort and cost (Hallgrimsson, 2012) and may adversely impact creativity if inappropriate types of design representations are used (Atilola et al, 2016). AR technologies might address these challenges as they support the use of real, tangible prototypes augmented with virtual features, which can help to avoid misunderstandings or misinterpretations by non-designers, whilst also providing the possibility to modify concepts on-the-fly based on feedback and new ideas.

1.1. Brief categorization of Extended Reality technologies

Within AR, van Krevelen and Poelman (2010) have provided a categorization of AR technologies, shown in Fig. 1 with minor updates. Three main categories of AR technology are identified as: ‘head-attached’, which includes devices such as Microsoft HoloLens that feature a headset worn by the user with an optical see-through display mounted a few centimeters infront of the users eyes on which the digital content is displayed; ‘handheld’, which requires the user to view the screen of a device such as a smartphone or a tablet PC and displays a camera view of the real world with overlaid digital content; and ‘spatial’, in which the digital content is projected directly on to a target object in the real world.

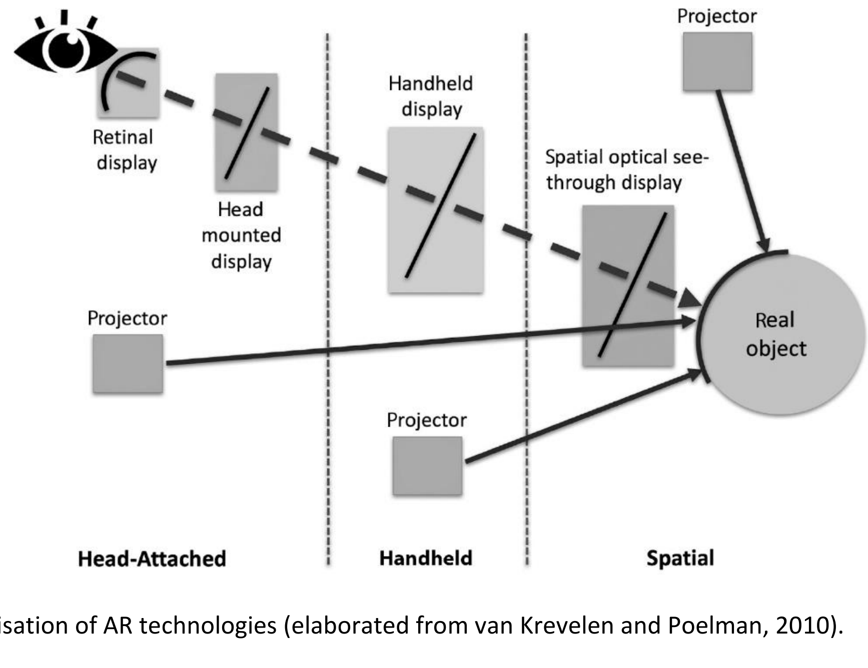

Fig. 1. Categorisation of AR technologies (elaborated from van Krevelen and Poelman, 2010).

1.2. The ANONYMIZED project

The ANONYMIZED project (PROJECT WEB SITE) - a three-year, collaborative project that aimed to develop and test AR technologies in co-creative design sessions, was conceived to eliminate communication barriers between designers and other stakeholders while developing design concepts. The authors, as key developers and testers of the 'ANONYMIZED platform' – decided to focus on projection-based Spatial Augmented Reality (SAR) as this technology avoids the need for users to use a head-mounted or handheld display, either of which might negatively impact the natural flow of information between designers and other involved actors. In this sense, SAR technology has the advantage that the participants can view each other without any obstruction and can view and handle an augmented object in an intuitive manner.

During the development of the ANONYMIZED platform, an initial version was created using handheld display (HHD) technology. This enabled many features of the system to be tested in early trials whilst several novel features of the SAR visualisation technology were still being developed. This HHD version of the ANONYMIZED platform was subsequently used for comparison with the SAR version once it was ready, as this study reports on. The use of head-mounted display (HMD) technology was considered but was eventually ruled out as it was considered that wearing the HMD technology was likely to have significant impacts on inter-personal communication and could become uncomfortable if worn for the 1-2 hour duration of a typical co-creative session. This was confirmed in a survey and analysis involving several design agencies conducted in the early stage of the ANONYMIZED project (AUTHORS 5).

The SAR version of the ANONYMIZED platform is based on the integration of three modules (visualization, tracking and interaction) for the creation of interactive mixed prototypes, i.e. physical objects with white surfaces whose visual appearance is digitally modified thanks to the augmented contents generated by the projector (Fig. 2). The use of physical objects, with real or scaled dimensions, inside a SAR environment requires the objects to have a matte, uniform surface and to be equipped with small infrared (IR) reflective markers. These are arranged in a random constellation on the top faces of the physical object where they can be detected in real time by the array of IR cameras that composes the tracking module. As long as at least two cameras can detect at least three IR markers simultaneously, the tracking module is capable of recognizing any translation and rotation of the physical object in the working space.

The software, knowing the current placement and orientation of the physical object as well as its shape and dimension, is then able to adjust the projector's input images so that the augmented contents are aligned and spatially registered with the same object. The latter operation, performed by the visualization module, can be extended to a multi-projector setup, where two or more projectors are used to increase either the dimension of the augmentable space inside the room or the number of surfaces of the object that can be covered simultaneously by the projected images. This type of configuration for the ANONYMIZED platform enables all the participants in the collaborative session to view the mixed prototype and to manipulate it, i.e. handle it, thus allowing the view of the mixed prototype from any angle simultaneously by all the participants.

Finally, the interaction module enables the real-time modification of the digital content of the mixed prototype, i.e. its surface appearance. The user interface can be presented on a desktop PC, large touch screen, or tablet PC, as shown in Fig. 2. The user interface has been developed to foster an agile manipulation of two-dimensional assets, usually in the form of images or textures, and background colours.

When a collaborative session is performed with the support of the SAR platform, an on-line unit, referred to as the 'information system' is also running in the back-end. This web application works as a repository for the management of the two-dimensional assets necessary to generate the surface design outputs and it automatically records any modification applied onto the mixed prototype. Thanks to this architecture, the ANONYMIZED platform also supplies a reporting tool that can be used by the participants after the session is completed to review every single design change performed during the meeting.

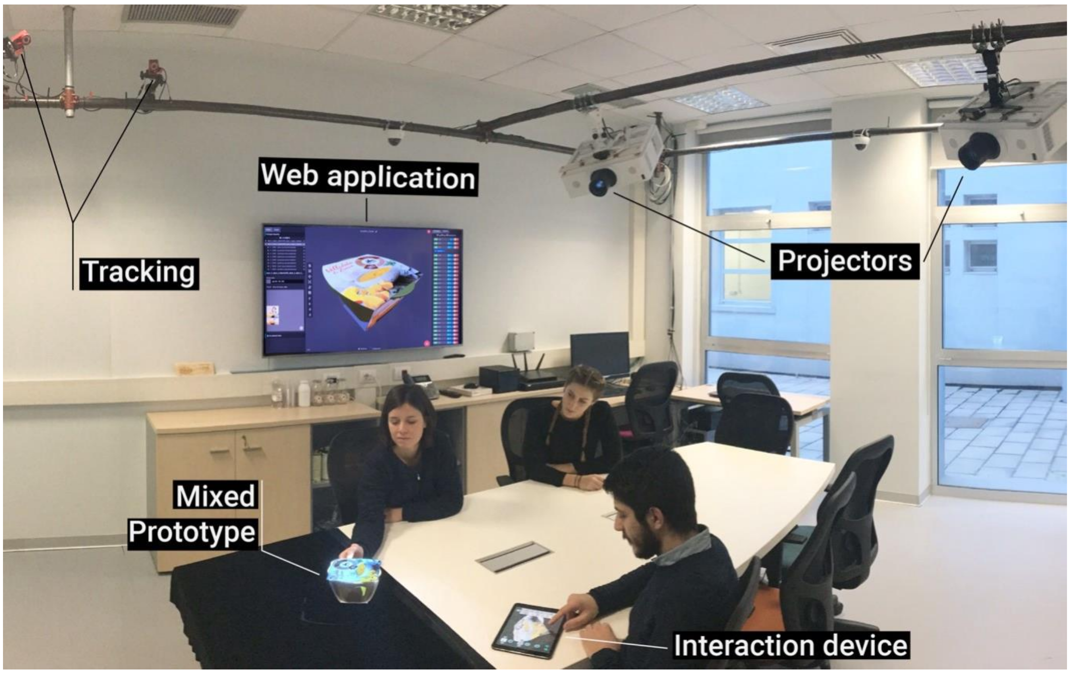

Fig. 2. Main components of the ANONYMIZED platform.

The ultimate goal of the research is to develop a technology suitable to allow the participants in co-creative design activities to get high-fidelity feedback from mixed prototypes. In this paper we investigate the impact of HHD AR and SAR technologies on co-creative design sessions in terms of the quality of the design outcomes and the perceptions of the participants with respect to collaboration, exploration of the design space and degree of satisfaction. This is done through trials and evaluations of the ANONYMIZED platform with two industry partners that are representative of design agencies operating in the packaging design and product design sectors. Packaging design and user interface design activities were selected for investigation, as they both focus on the surface features of the product and the current SAR technology is best suited to rendering of surface features.

We begin by introducing XR technologies and the extant research on their usage within various design contexts. We go on to discuss the common challenges faced by researchers and practitioners when trying to adopt research outputs within industrial practice. The aims, significance and method of the study are described. Responses to the research questions are presented in the results and discussion sections, whilst the conclusions identify opportunities for improvements in the technology to better support the needs of designers.

2. Aims and significance

The overarching aim of the study reported in this paper is to explore the potential impact of augmented reality-based design representations on co-creative design session performance. The specific objective was to test the ANONYMIZED platform in industry to assess the impact of SAR-based design representations on co-creative design performance, particularly for the aesthetic layout of surface graphics in packaging design and for the aesthetic and functional layout of surface graphics and user interface elements in product design sessions. The SAR technology has been tested against an HHD AR system and conventional co-design set-ups. Head-mounted devices were excluded from the study since they would introduce a barrier between the participants in the session, thus hindering their interaction.

The research addresses the following research questions:

RQ1 - "Do co-creative sessions involving SAR-based design representations result in more effective sessions in terms of idea generation, progress on design tasks, and filtering of ideas than those conducted with conventional or HHD AR-based design representations?"

Section 4.2 introduces the benchmarking experiments, while section 4.4 provides a detailed description of the performance metrics adopted to compare the design outcome of co-creative design sessions in different testing conditions with and without the support of the AR/SAR technology. Section 5 reports the results of the experiments.

Besides the assessment of the influence of the HHD AR and SAR technologies through objective metrics, we were also interested in the designers' perception of the impact of the technology on co-creative design sessions. This led to two more research questions. The second research question aims at collecting the designers' impressions of the performance of the technology in terms of: supporting collaboration; enabling the exploration of the design space; and facilitating fulfilment of the design task.

RQ2 - "Do designers perceive SAR-based design representations to be more effective for co-creative design sessions than conventional or HHD AR-based design representations?"

Finally, given that this study forms part of an on-going technology development activity, the third objective was to gather some initial insights into the relative strengths and weaknesses of SAR-based design representations for use in co-creative design sessions through a follow-up survey (detailed in section 4.4.3). This led to the definition of the third research question as follows:

RQ3 - "What are the specific strengths and weaknesses of SAR-based design representations in comparison with conventional or HHD AR-based design representations?"

The significance of this study is that it addresses two important issues for computer application in industry:

- XR-based design representations are an emerging technology and a large number of experimental applications for design practice are currently being explored. There are relatively few studies that have evaluated the impact of these new technologies on design practice with professional design practitioners, particularly within the context of a co-creative design session. These results and insights into the relative strengths and weaknesses of this type of technology will, therefore, be of interest to design practitioners that are considering the adoption of HHD AR or SAR technology within their design practice, as well HHD AR or SAR technology developers.

- Co-creation is an important example of the evolving practices within design. The new challenge associated with co-creation is the demand from industry for new methods, tools and technologies to help improve co-creative design practice. Having a robust set of metrics for the evaluation of co-creative design session performance that can be applied quickly within industry-based experiments will be of great value to both design researchers and technology developers.

3. State of the art review

3.1. Applications of Extended Reality technologies in design

In recent years, XR technologies have been tested in several design applications, covering most of the design process, from design specification through to definitive layout and documentation (AUTHORS 3, 2018). Only a few applications have reached the maturity level needed to be adopted in industry. Typical industrial applications of XR technologies can be found in production or in service areas and concern the guidance of assembly or maintenance operations (e.g. following the pioneering project at Boeing described in Mizell (2001)). In R&D, they mostly support the visualization of the results of simulations. For example, in the ARVIKA project, Friedrich et al. (2002) provided one of the earliest overviews of industrial applications of AR for development, production and service reporting.

However, XR applications to support <u>design</u> activities have a much lower maturity level. Here we provide a brief overview of the types of application that are currently being explored in design research and by technology developers organised in sections representing some of the typical design activities (i.e. conceptual design, user-interface design, detailed design and design review).

<u>Conceptual design</u>

A number of XR tools have been developed that aim to support conceptual design. The focus in this area is on support for 3D sketching in the early stages of conceptual design. Xin et al (2008) have described the development of 'Napkin Sketch', a system that supports 3D sketching through the use of an HHD. The user sketches 2D forms using a tablet PC and can then place their 2D sketched forms onto 3D planes to create complete 3D objects. An initial assessment involving seven participants found that all participants were able to successfully create basic 3D sketches. Most users became 'lost' in the 3D space at some point in the tests, leading the authors to conclude that more extensive use of visual guides would be beneficial.

Israel et al (2009) report on the testing of a different type of 3D sketching technology that used a 5-wall VR CAVE system and a physical pen-like device. 24 furniture designers and interior architects were asked to sketch various items of furniture for use in a university entrance hall using both the 3D VR system and conventional pen and paper. Participants reported a preference for using the 3D sketching system, with many suggesting that it was useful to be able to represent the artefacts at one-to-one scale and that the system facilitated spatial thinking. However, when asked about the challenges of using the 3D sketching system a significant number of participants mentioned the difficulty of finding connection points in the 3D space and drawing at different depths within the 3D space. The authors conclude that, although there was no noticeable improvement in the creativity or quality of the sketches, the positive response of the participants suggests that there is a role for 3D sketching, which will increase as the technology becomes more refined and designers gain more experience of working directly in 3D space.

Arroyave-Tobón et al. (2015) found that modelling in AR environments using the hands as interface allows the designer to conceptualize potential solutions more quickly and efficiently, thus better exploiting inspirational moments. In a test case consisting of the design of a three-level bookcase over an existent desk, they realized that novice designers were able to focus on the product itself and its relation with the environment, using the context as an information input and carrying out the design review during the conceptualization stage. This seems extremely relevant for products whose shape, configuration and dimensions depend mainly on the environment. However, their solution, namely AIR-MODELLING, is based on HMD, thus it better fits individual design activities, while the interaction between designers and other stakeholders would be hindered by the lack of eye contact and gaze awareness, essential factors in design collaboration (Wang et al., 2014).

In the last few years, we have begun to see the first generation of commercially available 3D sketching systems, including Gravity Sketch and Tilt Brush. Academic research continues in this area, with prototype systems such as 'Multiplanes' (Barrera Machuca et al, 2017), which helps users to create more accurate forms by identifying the type of form that the user is trying to create (e.g. straight, line, arc or circle) and then automatically correcting any imperfections due to imprecise movements by the user.

To summarise, no studies were found to report on the application of SAR to support conceptual design activities. Furthermore, as in the examples cited above, no studies report experimental activities involving professional designers, neither measuring how the technology affects designers' perceptions nor the quality of the design outcome. This paper provides an original contribution from these perspectives.

User interface design

Akaoka et al (2010) introduce 'DisplayObjects' as 'a new category of future everyday computational objects with fully interactive skins'. The DisplayObjects workbench uses SAR technology to project graphics and user interface elements onto physical objects. Testers liked the interactive, hands-on approach and the ability to change elements quickly. However, they did find problems with hand occlusions and found it difficult to create good digital models from 3D scans (as the 'cleaning' process is time-consuming).

Barbieri et al (2013) use a mixed reality system, which combines a HMD-equipped AR system with physical objects that include functioning user interaction elements (buttons, dials, slides etc.) which can themselves be augmented to show alternative aesthetic designs. They also propose a usability testing methodology that exploits the benefits of their mixed-reality technology.

As stated above, we discarded HMD AR systems since the beginning of the ANONYMIZED project, since they are considered a major obstacle to natural interactions between the participants in a collaborative design session. In addition, we took into consideration the experience by Akaoka et al (2010) concerning the limitations given by hand occlusions in manipulating the mixed prototypes. This led to the decision to separate the user interface for applying modifications to the augmented contents of the mixed prototype: one or more participants in the design sessions applies modifications through the interaction device (a tablet, as in figure 1, a large touch screen, a desktop PC, etc.), while all the participants can see in real time the changes on the mixed prototype and they can handle the physical object to change its orientation and give preliminary feedback on its ergonomics.

Detailed design

Porter et al (2010) report on the testing of a SAR-based system that incorporates finger tracking for use in the detailed design phase of product development. They compared the time taken to interact with buttons on the prototypes for groups using mixed and standard prototypes. Mean button-press time was significantly increased in the SAR condition and one third reported that not having a physical button affected their interactions. Despite these limitations, many participants felt that SAR provided a good visual representation of the concept and 88% of participants agreed that SAR technology would be useful as a design tool.

The lesson learned for the ANONYMIZED project is that current SAR prototypes have intrinsic limitations that may prevent them from being used to fully support the later stages of product design, while the quality of the visual representation is adequate for earlier design stages.

Design assessment and review

A wide variety of XR technologies have been developed for design assessment and review. The work of Bordegoni et al (2009) provides a useful overview and classification framework for the various combinations of virtual prototypes, real objects and users. A series of usability tests were completed that involved users testing alternative concepts for the design of the user interface panel of a washing machine. Results from the initial trials were used to redesign the control panel. Further tests with the redesigned control panel showed a significant reduction in the number of user errors.

Irlitti & von Itzstein (2013) report on the development of the 'SARventor', which combines SAR with three tangible user interface ‘tools’. The system was presented to three experts from architecture and industrial design. Challenges noted by the reviewers included the lack of a visible toolkit and the inability to manipulate volume (3D geometry). Despite this, the reviewers felt there was ‘…a strong case towards being used as a collaborative tool for use in feedback sessions between designers and stakeholders’.

Verlinden (2014) has proposed the ‘IAP-M’ design methodology, which features the use of a SAR application to generate interactive mixed prototypes for design review purposes. The methodology was validated through tests using a variety of demonstrators that addressed design tasks such as the interior design of a night club and user interface design for a voice recorder. He concluded that the SAR technology and the IAP-M methodology was useful in developing a shared understanding amongst stakeholders of the design and helped with the early identification of errors and flaws in the design.

Despite not explicitly being conceived for supporting collaborative creative sessions, Verlinden’s pioneering work is important prior art for the ANONYMIZED platform. While recognizing Verlinden’s work as pioneering , the ANONYMIZED platform presented here is substantially different from Verlinden’s work for the following reasons:

- The ANONYMIZED platform allows direct and free manipulation of the mixed prototype thanks to the optical tracking (instead of limited to a rotation around a single axis);
- It features multi-projection, thus allowing high-resolution projections also on larger areas and/or the coverage of a broader angle for supporting the participation of several users;
- It allows the manipulation of the digital content of the mixed prototype through a touch interface (tablet or large screen) instead of mouse and keyboard, thus ensuring a more intuitive interaction with the mixed prototype;
- It offers a richer set of functions to edit the digital content projected onto the mixed prototype.

Besides the laboratory experiences, there is some evidence that XR technologies are being applied in industry for design review applications. Södermann (2005) has reported on the use of VR technology for product assessments with potential customers. He concluded that a user's understanding of a design representation depends on both their product knowledge (the prior experience they have of using the product being discussed) and their product representation knowledge (the prior experience they have of the type of design representation being used e.g. 2D sketch, VR, AR etc.). This suggests that the full value of XR technologies will only be realised once users, whether designers, clients or consumers, have gained a reasonable level of familiarity with these technologies.

3.2. The role of design representations in co-creative design sessions

Previous research has shown that design representations have a significant impact on communication and creativity in co-creation sessions (Bodker, 1998). However, design practitioners face several challenges concerning the use of design representations that are important to consider for co-creative design sessions. Examples of these challenges are discussed below.

Reducing the time and cost to make design representations

The creation of design representations can represent a significant cost in the design process, depending on the level of fidelity (i.e. the level of detail represented) and workmanship (i.e. the quality/professionalism of the finish) that is required (Hallgrimsson, 2012). According to Lim et al. (2008), 'the best prototype is one that, in the simplest and most efficient way, makes the possibilities and limitations of a design idea visible and measurable'. Hence, for an internal design review a low fidelity, low workmanship design representation may be sufficient. However, for co-creative design sessions, particularly when a client or end-user is involved, it may be necessary to increase the level of fidelity, the workmanship, or both of these parameters in order to aid communication of the concept and give a more 'professional' representation of the work completed.

Selecting the right type of design representation to support idea generation and review

Many researchers have looked into the impact that the type of design representation has on different aspects of the design process. For idea generation, both Häggman et al (2015) and Robertson and Radcliffe (2009) have suggested that the use of CAD tools early in the design process can sometimes lead to premature limitations on design space exploration, resulting in reduced novelty of ideas.

Another factor that might limit idea generation is the time, effort or cost required to create the design representation. Viswanathan & Linsey (2011) found that designers tend to favour the ideas that they have invested most time and effort on, even when they are less novel or effective than other concepts.

Regarding design review activities, Hannah et al (2012) asked engineering students to review potential solutions against a list of requirements and state if the solution met the requirement and their confidence level in making this assessment. Those teams that were presented with high-fidelity prototypes were most confident and scored the most correct answers. Conversely, those teams using sketches were least confident and had the fewest correct answers.

Concerning the usability of AR as a means to share design representations, Jimeno-Morenilla et al. (2013) explored the applicability of AR for footwear customization; the user is able to choose a model of shoes from a large 3D database and to check, in real-time, the aesthetics of the footwear model through a HHD AR visualization system.

Arbeláez and Osorio-Gómez (2018) tested the potential of AR to collect feedback about product aesthetics from end-users during the product design stages. Despite the positive impressions about the technology recorded by two-thirds of the interviewed subjects, the application showed some limitations in terms of quality of interaction with the AR system in difficult lighting conditions in comparison to real prototypes, and an increased interaction time to complete the evaluation. Nevertheless, overall the product aesthetics evaluation done with the AR system turned out to be fully consistent with the same evaluation done with real prototypes.

All the above findings suggest that quick, cheap, low-fidelity design representations may be most effective in supporting 'divergent', idea generation activities, whilst high-fidelity design representations are required for 'convergent' review and filtering activities.

Avoiding misinterpretations

When designers collaborate with non-designers, the differences in their technical vocabulary and understanding of the design process means that there is a risk of misinterpretation when trying to discuss ideas. For instance, during testing of a mobile phone interface with end-users, Lim et al. (2006) found that building mock-ups of the interface on a PC screen, or out of paper, led to several misinterpretations of how the interface should be used. Another common form of misinterpretation identified by AUTHORS 5 (2018) is the size and scale of objects, particularly when non-designers are required to interpret design representations that lack contextual cues to their size, as is often the case with basic sketches or digital models.

In summary, design practitioners face numerous challenges when preparing and using design representations and many of these issues will be exacerbated within co-creative design sessions due to the variation amongst participants in terms of their knowledge of the design process and ability to interpret and express ideas through design representations. It is proposed that XR technologies, such as the ANONYMIZED platform, could help to address some of these challenges. Specifically, the time and cost of preparing design representations can be reduced when using SAR technology, as a single physical object can be used to present many different design variants (with the same basic geometry). The level of fidelity of a SAR-based design representation can be modified based on the level of detail in the projected augmented content. And finally, the tangibility of the physical object can help to avoid misinterpretation of the intended size and scale of the final product.

Although there has been exploration of XR technologies in individual creative tasks (e.g. user interface design) and group design review tasks (e.g. Verlinden, 2014), there has not been significant exploration of the role of XR in supporting creative group tasks e.g. co-creative design sessions. This is the primary research gap addressed in this paper.

A further observation that can be made about the extant literature on the use of XR technology in design is that very little of the research described involved any kind of validation in a real industry context, with the majority of the testing completed in research laboratories using artificially constructed design tasks. The research presented in this paper takes place in real industry settings.

4. Method

4.1. Overview

The ANONYMIZED platform has been developed through close collaboration with two industry partners that were selected as representatives of two different design domains: packaging design and product design. Representing the packaging design domain was Company 1 (Anonymized), a brand strategy and packaging design consultancy. Representing the product design domain was Company 2 (Anonymized), a product design consultancy.

As part of the verification of the performance of the ANONYMIZED platform, two types of research activity were completed with the industry partners. First, 'benchmarking experiments' were conducted in which co-creative design sessions were held that involved the design teams from Company 1 and Company 2 working on some of their real projects using the ANONYMIZED platform in a laboratory setting. These experiments were designed to allow comparisons between co-creative design sessions using different types of design representation technology, specifically: SAR technology (the ANONYMIZED platform); HHD AR technology with handheld displays; and conventional design representations. The second research activity involved the industry partners testing the ANONYMIZED platform within co-creative design sessions in their own premises, which we shall refer to as 'in-situ trials'. Due to the relatively low maturity and novelty of the technology and the emphasis on exploration and explanation over verification and validation, a 'mixed methods' research methodology (Creswell & Clark, 2017) was adopted.

4.2. Benchmarking experiments

4.2.1. Case studies and participants

The benchmarking experiments featured three sessions that involved designers from product design (Company 2) and three sessions that involved designers from packaging design (Company 1), making six sessions in total – summarised in Table 2. For the packaging design sessions, it was possible to have different teams of designers and end-users working on the same product and the same initial brief for each of the three conditions. For the product design sessions, only two designers were available to participate in the experiments. With this limitation, using the same product and brief for each condition was not desirable as it would have risked the designers (consciously or sub-consciously) carrying over ideas from one session to another or potentially becoming bored of the task due to the repetition. It was therefore necessary to vary the case study product for each of the conditions, although efforts were made to ensure that the case study products and session briefs were as similar as possible in scope, task and design stage.

Table 2. Summary of the products, scope and participants for each condition.

		SAR condition	**HHD AR condition**	**Conventional condition**
Product Design (Company 2)	Product description	EMF detector - Handheld device for assessment of human exposure to electromagnetic fields	Smart fitness device - Device that monitors physiological performance when using gym equipment	Emergency beacon - Handheld device for communicating your location in an emergency
	Session brief	Define the colours, materials and finish of the main housing. Define the location and pattern of LED status lights and speaker. Location of logo.	Define the colours, materials and finish of the main housing. Location of logo.	Define the colours, materials and finish of the main housing for specific environments. Define the location and pattern of LED status lights.
	End users	Female, age 18-30 Male, age 18-30 Male, age 45-60	Female, age 18-30 Male, age 18-30 Male, age 45-60	Female, age 18-30 Male, age 18-30 Female, age 45-60
	Designers	Creative Director, 14 years of experience, male Designer and Business Developer, 15 years of experience, male		

Packaging Design (Company 1)	Product description	Fresh soup - single serving in plastic bowl with film lid and cardboard sleeve		
	Session brief	Further develop three pre-prepared alternative designs for the cardboard sleeve graphics and layout by combining graphical elements (colours, logos, text, images etc) in order to propose a complete packaging design.		
	End users	Female, age 18-30 Male, age 18-30	Male, age 18-30 Male, age 18-30	Female, age 30-45 Female, age 30-45
	Designers	Digital Creative Director, 16 years of experience, female Art Director, 18 years of experience, female	Senior Art Director, 19 years of experience, male Graphic Designer, 10 years of experience, male	Art Director, 10 years of experience, female Junior Art Director, 1 year of experience, female

The teams of designers for each session were selected to ensure reasonable consistency across the conditions in terms of experience and skills. The designers were provided with a video tutorial on the use of the ANONYMIZED platform at least one week before the start of the test sessions and had the chance to practice with its user interface on their own tablet. The end-users were selected to match the target demographic of the case study product for the session they would participate in.

4.2.2. Description of experimental conditions

For the co-creative sessions, three conditions were tested. The 'SAR condition' involved the use of the SAR version of the ANONYMIZED platform described in Section 1, equipped with two projectors, an array of six independent IR cameras and a tablet PC as the interaction device. The projectors were both directed toward the same point but placed in the two corners of the room. The tracking sensors, arranged to increase the detection of multiple orientations of the physical object, were configured on the ceiling of the room to generate an augmentable envelope of about 1 cubic meter. This area was defined on the opposite side of the meeting table with respect to the users' location in order to best show the augmented faces of the mixed prototype and to mitigate the risk of occlusions of the projector beams. The interaction device selected within this setup for running the user interface was a standard tablet PC (Fig. 4) through which a single designer could manipulate the digital content of the mixed prototype, including features like the colour, size and rotation of the graphical elements that compose the design layout (e.g. logos, images and texts), based on the comments and suggestions from the other participants. The second designer and the end-users could see and handle the mixed prototype to adjust their point of view and discuss the design choices.

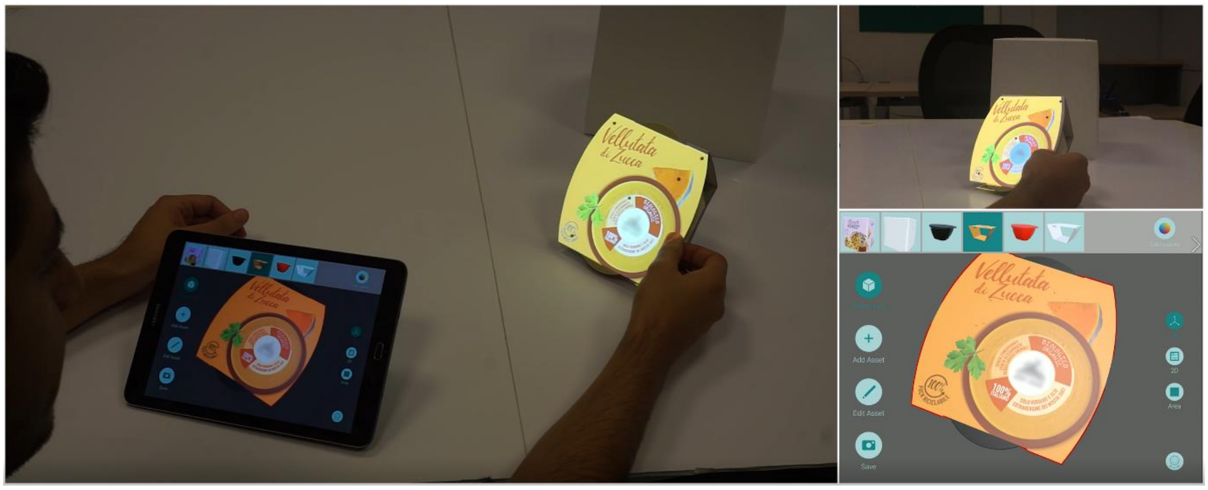

Fig. 4. View of the Spatial Augmented Reality platform from the point of view of: a) the designer manipulating the digital content with the system user interface and interacting with the mixed prototype (left); b) the mixed prototype consisting of cardboard packaging, the projected images and the IR markers (top-right); c) the tablet interface with all the required functionalities and the rendering of the product's digital version (bottom-right).

The second condition was the ‘HHD AR condition’, which involved the use of a physical object and two tablet PCs. Both the tablet PCs could be used as handheld displays to view the physical object with the digital contents defined by the participants in the collaborative design session. In addition, the tablet PC used by the first designer was also enabled to act as the interaction device, enabling them to make the same types of modifcation to the digital content of the mixed prototype as described above for the SAR condition. Any modifications made by the first designer were immediately sent to the second tablet, shared between the second designer and the two end-users, in order to visualize, in real-time and in augmented reality, the current version of the product (Fig. 5c). The use of the tablet’s embedded camera for the detection of the object placement influences the selection of the marker’s type, which are drastically different from the IR-based technology adopted for the SAR condition. The preparation of the session, in fact, requires the creation of a visible and highly recognisable texture that must be applied to the external surface of the physical object (Fig. 5a) so that the software can create the augmented view of the scene by correctly overlaying the digital rendering of the 3D model on the image (Fig. 5b). Also in this setup, the physical object can be freely handled by the participants, but the detection method requires a portion of the object surface to remain visible to the camera to recognize the markers. Table 3 highlights the main differences between the HHD AR and SAR experimental conditions.

Fig. 5. View of the HHD AR mixed prototype through a handheld device: a) without augmentation, showing the marker pattern (left); b) with augmentation - design in progress (middle); c) with augmentation - completed design proposal (right).

Table 3. Comparison of the HHD AR and SAR experimental conditions.

Characteristic	HHD AR	SAR
Primary visualisation of the object	Handheld video see-through display using 10” tablet PC	Projection on to physical object
Means of editing digital content	Interaction device with augmented view of real object and ANONYMIZED user interface	Interaction device with 3D virtual model of object and ANONYMIZED user interface
Object tracking technology	Optical	Infrared

For the third condition, the designers were asked to use conventional materials and tools to prepare the design representations for their co-creative design sessions (henceforth, we refer to this as the 'conventional' condition). For the product design conventional session, the initial designer proposals were displayed on a large television screen using presentation software. After this, physical prototypes featuring neutral colours were presented and Pantone colour swatches were used to discuss alternative colour schemes and logo placement - see Fig. 6 (left).

Fig. 6. (Left) Physical models and Pantone© colour matching system used in the product design 'conventional' session. (Right) Collage system used in the packaging design 'conventional' session.

For the packaging design conventional session, the designers elected to use a collage method, which involved pre-preparing a variety of logos and graphic elements in the form of stickers that could be applied to the cardboard sleeve of the soup packaging, re-positioned as required and further elements added by hand-drawing directly on to the cardboard sleeve – an example of the output using this method is shown in Fig. 6 (right).

4.3. In-situ trials

4.3.1. Case studies and participants

The product design in-situ trials involved two sessions, working on projects from two different clients (Table 4). Both sessions were completed in one day. The packaging design in-situ trials involved three sessions, conducted with one client (Table 5). The three sessions were completed in one day.

Table 4. Summary of the product design trials completed at Company 2.

	Session 1	**Session 2**
Product description	Electrical test device – Test equipment that assesses conformity with Electromagnetic Compatibility Directive 2014/30/EU	Screening device - non-invasive screening device for infant meningitis
Session brief	User interface design optimisation, taking into account technical and aesthetic requirements	Define the aesthetic/graphical layout of the product
Client	EMZER Technological Solutions, SL	New Born Solutions
Client representative	CEO, male Engineer, male	CEO, male Engineer, male
Designers	Creative Director, 14 years of experience, male Designer and Business Developer, 15 years of experience, male	

Table 5. Summary of the packaging design trials completed at Company 1.

	Session 1	**Session 2**	**Session 3**
Product description	Fresh pizza	Parmigiano	Mozzarella
Session brief	Review of first proposals, selection and development of most promising proposal	Review of first proposals, selection and development of most promising proposal	Review of the second iteration of the design proposals, selection and development of most promising proposal
Client	Alce Nero		
Client representatives	Senior marketing executive, female Marketing executive, female		
Designers	Senior Art Director, 19 years of experience, male Art Director, 18 years of experience, female	Senior Art Director, 19 years of experience, male Art Director, 18 years of experience, female	Art Director, 18 years of experience, female Art Director, 10 years of experience, female

4.3.2. Description of trial session conditions

Fig. 7 shows the layout of the rooms where the trial sessions were conducted at Company 1 (left) and Company 2 (right) respectively. Both SAR systems featured dual projectors mounted to a frame at ceiling height as well as an infra-red object tracking system. For the packaging design trials, a 40" multi-touch screen, mounted horizontally at waist height was used to control the graphical user interface of the ANONYMIZED platform. For the product design trials, a PC, with input via a mouse and screen, was used to control the graphical user interface. The hardware to run the user interface (large touchscreen interface, PC with mouse and keyboard, or tablet PC) and the positioning of the projectors was decided based on the preferences of the end-users involved.

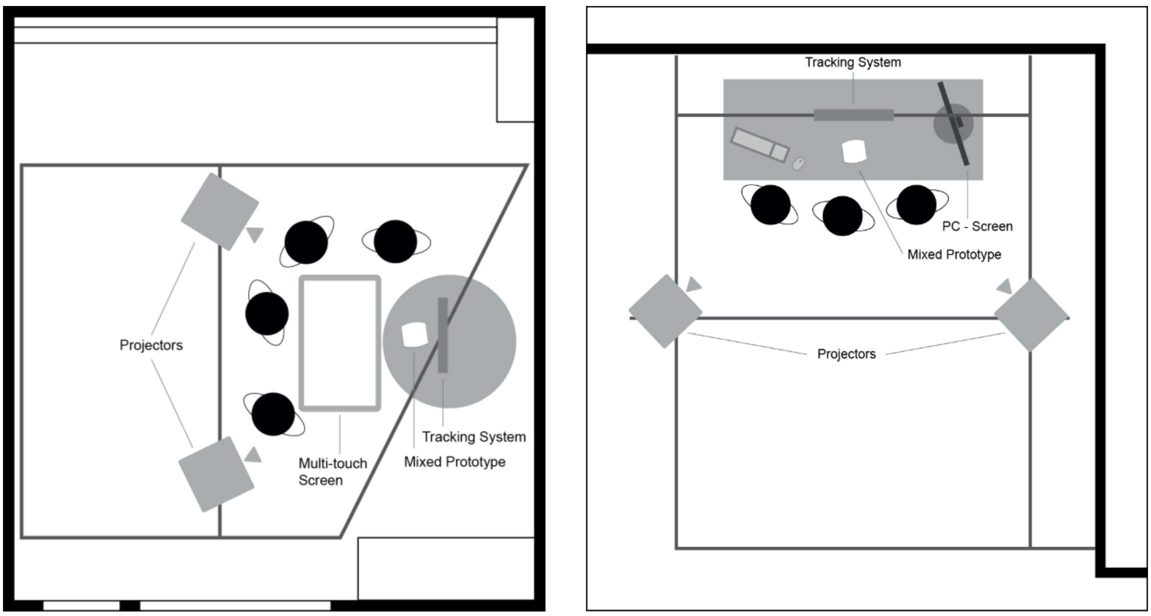

Fig. 7. (Left) Plan view of the layout of the room used for the packaging design trials at Company 1. (Right) Plan view of the layout of the room used for the product design trials at Company 2.

4.4. Data collection and analysis protocol

Three main research methods were employed, linked to the three research questions stated in Section 2. To test if HHD AR and SAR-based design representations result in more effective sessions (RQ1), a suite of quantitative co-creative session performance metrics were applied. To establish if designers perceive SAR-based design representations to be more effective than conventional or HHD AR-based design representations (RQ2), the Creativity Support Index (Cherry and Latulipe, 2014) method was employed. Finally, to understand the specific strengths and weaknesses of HHD AR and SAR-based design representations in comparison with conventional design representations (RQ3), a follow-up survey was conducted with the designers that participated in the benchmarking experiments. The data collection and analysis protocol for each of these methods are presented in the following sub-sections.

4.4.1. Application of the co-creative session performance metrics

The co-creative session performance metrics were iteratively developed during the ANONYMIZED project (AUTHORS 7, 2016; AUTHORS 2, 2018), drawing on the work of Shah et al (2003) on creativity assessment – see Table 6.

Application of the metrics involved a number of data-gathering activities. First, a pre-session interview was conducted with the lead designer, just before the start of the session. The designer was asked about: their objectives for the session; ideas that had previously been generated within the project; any open tasks from previous sessions (for the Task Progress metric); and how many ideas they would like to end up with by the end of the session (which is the 'Desired number of ideas to retain' used in the Filtering Effectiveness metric).

At the start of the co-creative session, all participants were informed that they could ask the designer to save the current configuration of the mixed prototype whenever they felt that they generated 'a new idea'. A researcher sat in the room during each of the sessions to take live notes about the ideas that were being discussed. These notes were captured in the form of a Morphological Chart, where the rows of the chart were used to capture the features or functions that were discussed (e.g. 'position of the logo') and the columns of the chart were used to capture the potential embodiment options that were discussed by the participants (e.g. 'top', 'bottom', 'left side').

After the session, a joint interview with both the designers from the session was completed. In this session, the designers were presented with pictures of the 'ideas' (mixed prototype configurations) that had been captured during the session. They were asked to confirm that all the ideas had been captured and that none of the ideas were duplicates or captured by mistake (for the Quantity metric). The designers were asked to rate each of the ideas on a scale from 1 (low novelty) to 10 (high novelty) (for the Novelty metric) and then asked to decide if each idea would be taken forward in the project for further development (for the Quality and Filtering Effectiveness metrics).

Next, they were then presented with the Morphological Chart that had been captured by the researcher and asked to confirm the accuracy of the chart. They were also asked to identify which of the rows, if any, described new features/functions of the product that had not previously been considered within the project. Such rows were counted as 'new rows' for the Variety metric, whilst all other rows not identified as 'new rows' were counted as 'original rows'. In this way, 'new rows' represent creative activities that expand the boundaries of the 'solution space', whilst 'original rows' represent creative activities that add new solutions within the existing boundaries of the solution space. Finally, the list of open tasks from the pre-session interview was revisited to check which tasks had been completed and what new tasks, if any, had been generated during the session.

Table 6. Definition the co-creative session performance metrics (AUTHORS 2, 2018).

Metric title	Metric definition

Quantity of ideas	Quantity of ideas generated during the session counted as the number of mixed prototype configurations saved at the request of the participants and subsequently verified in the post-session interview.
Variety of ideas	Variety (original) - Number of original feature rows that contain a new idea counted on the morphological chart created by an observer in the session.
	Variety (new) - Number of new feature rows added to the morphological chart created by an observer in the session.
Quality of ideas	Number of new ideas generated that are taken forward at the end of the session for further development. Determined by designers in the post-session interview.
Novelty of ideas	Mean average score for novelty from each participant in the post-session interview for each of the ideas captured as a mixed prototype configuration during the session.
Task Progress	Task Progress = 3pts x (Number of high importance tasks resolved or created) + 2pts x (Number of medium importance tasks resolved or created) + 1pt x (Number of low importance tasks resolved or created). Captured from pre- and post-interview with the session leader.
Filtering Effectiveness	Filtering Effectiveness = Number of rejected ideas[1]/(Quantity of ideas [as per the definition above] - Desired number of ideas to retain)

4.4.2. Application of the Creativity Support Index survey

The Creativity Support Index (CSI) survey was developed by Cherry and Latulipe (2014) to help evaluate the support for creativity provided by ICT tools. The CSI survey was selected because it is based on the well-known NASA Task Load Index survey (Hart and Staveland, 1988), but with more focus on evaluating the support provided by ICT tools for creative activities, and so it is well-aligned with the objectives of the ANONYMIZED platform.

The CSI survey consists of two parts. In the first part, the user rates their level of agreement with 12 statements that cover six aspects of tool performance: collaboration, enjoyment, exploration, expressiveness, immersion, and 'achieving results that are worth the effort they put into using the tool'. In the second part of the survey, the user completes a pairwise comparison of the importance of the six aspects of tool performance listed above. The result of the pairwise comparison is used to generate weighting factors that are applied to the scores from the first part of the survey. Finally, a score is generated ranging from 0 to 100, where 100 indicates that the tool used provided excellent creativity support for the task completed.

The CSI survey was administered immediately after the session, as part of the post-session interview. Only the designer that had manipulated the user interface was required to complete the survey from the HHD AR and SAR conditions, whilst all designers completed the survey separately for the conventional sessions.

4.4.3. Follow-up survey

After the benchmarking experiments, a follow-up survey was sent to the designers via email. It featured four questions that were intended to capture qualitative feedback from the designers about the performance of the session. The four questions were:

- What were all the things that went well during the session?
- How did the [SAR/HHD AR/conventional] tool you were using contribute to the positive aspects of the session you have described above?
- What were all the things that were challenging about the session?

[1] The 'number of rejected ideas' represents the number of ideas that were generated during the session but were eliminated from the design process by the designers during the post-session interview.

- How did the [SAR/HHD AR/conventional] tool you were using contribute to the challenging aspects of the session you have described above?

4.4.4. Summary of data collection activities

Table 7 presents a summary of the data collection activities completed (with number of instances of each activity completed in brackets) and the types of data captured within this study. Note that no tests of statistical significance of the data could be applied due to the small sample size. Nonetheless, the triangulation of data sources - quantitative (session performance metrics and CSI survey) *and* qualitative (follow-up survey with designers) - increases the robustness and validity of the findings.

Table 7. Summary of the data collection activities completed.

	Activities completed	**Data captured**
Benchmarking experiments - comparing the use of HHD AR, SAR and conventional design representations in a lab setting	Pre-session interviews (6 interviews)	Objectives for the session
	Co-creative design sessions (6 sessions)	Ideas generated Tasks completed or initiated
	Post-session interviews (6 interviews)	Validate ideas and tasks captured
	CSI survey (6 responses)	Usability feedback from designers
	Follow-up survey (9 responses)	Qualitative feedback from designers about the advantages and disadvantages of the technology
In-situ trials - evaluating SAR design representations in the designers' normal environment	Pre-session interviews (5 interviews)	Objectives for the session
	Co-creative design sessions 5 sessions)	Ideas generated Tasks completed or initiated
	Post-session interviews (5 sessions)	Validate ideas and tasks captured
	CSI survey (5 responses)	Usability feedback from designers

5. Results

This section reports the results of all the experimental activities, distinguishing between the packaging design tests (section 5.1) and the product design tests (section 5.2). Each subsection describes the outcomes of all the three comparison methods proposed in this study: the quantitative co-creative session performance metrics to objectively measure the differences between the outputs of the diverse testing conditions in laboratory experiments; the Creativity Support Index to analyse the design experience as perceived by the designers both in the laboratory experiments and in the in-situ trials; and the survey which followed the in-situ trials to collect strengths and weaknesses of HHD AR and SAR-based design representations in the testing conditions.

5.1. Results from the packaging design tests with Company 1

Table 8 presents the results of the co-creative session performance metrics for both the benchmarking experiments and the in-situ trials completed on packaging design activities. The first four rows of Table 8 show the characteristics of the session, including: the type of product that was worked on during the session; the primary type of design representation used; the 'session objectives'; and the duration. The session objectives scores came from the pre-session interview with the session facilitator who rated the importance of filtering and generating ideas on a scale of 1 to 10, where 10 is critical importance and 1 is very low importance.

Table 8. Results of the co-creative performance metrics applied to the packaging design activities.

		Packaging design - benchmarking experiments			**Packaging design – in-situ trials**		
Product		*Fresh soup*	*Fresh soup*	*Fresh soup*	*Pizza*	*Mozzarella*	*Parmigiano*
Representations used		*Conventional*	*HHD AR*	*SAR*	*SAR*	*SAR*	*SAR*
Session objectives		*Filtering 8* *Generating 2*	*Filtering 8* *Generating 10*	*Filtering 10* *Generating 8*	*Filtering 9* *Generating 5*	*Filtering 9* *Generating 1*	*Filtering 9* *Generating 3*
Duration		*94 mins*	*28 mins*	*91 mins*	*87 mins*	*36 mins*	*44 mins*
Quantity of ideas		5	4	**11**	4	3	**5**
Variety of ideas	**Original**	**5**	4	2	3	**3**	1
	New	**1**	0	0	0	**1**	1
Quality of ideas		= 5 – 3 rejected = 2	= 4 – 3 rejected = 1	= 11 – 7 rejected = **4**	= 4 – 0 rejected = **4**	= 3 – 1 rejected = 2	= 5 – 3 rejected = 2
Novelty of ideas		= 19 ÷ 5 = **3.8**	= 9 ÷ 4 = 2.3	= 7 ÷ 3 = 2.3	=25 ÷ 4= **6.3**	=12 ÷ 3= 4	=13 ÷ 5= 2.6
Task progress		1xHigh 1xMed 1xLow **Total = 6**	1xHigh Total = 3	2xHigh **Total = 6**	1xHigh =3 4xMed = 8 2xLow = 2 Total= **13**	2xMed = 4 Total = 4	2xHigh = 6 Total = 6
Filtering Effectiveness		= 3 ÷ (5-3) = **1.5**	= 3 ÷ (4-2) = **1.5**	= 8 ÷ (11-1) = 0.8	= 0 ÷ (4-2) = 0	=1 ÷ (3-1) = 0.5	= 3 ÷ (5-2) = **1**
Usability (CSI survey score)		32/100 71/100 Avg 52/100	59/100	**70**/100	**54**/100	23/100 11/100 Avg 17/100	46/100 41/100 Avg 44/100

For the packaging design benchmarking experiments, the SAR condition scored higher against the session performance metrics than the HHD AR or conventional conditions in terms of: the quantity of ideas generated; usability score; and slightly better in terms of the quality of ideas. However, it was the conventional condition that performed best or joint best in terms of the variety, novelty, task progress and filtering effectiveness.

It is somewhat surprising that the conventional condition scored well against several of the idea generation metrics, particularly given that less importance was placed on idea generation in this session than in the HHD AR and SAR sessions. This may be due to the fact that the designers have experience of facilitating this type of session with conventional design representations whereas they have almost no experience of using HHD AR-based design representations. The difference between the CSI survey results from the two designers that participated in the conventional condition (32 vs 71/100) reveals that they had very different views about the usability of the collage system used during the conventional session. The lower score came from the more experienced designer, who was the lead facilitator of the session and was therefore better placed to evaluate the success of the approach. It is not clear from these results alone why the conventional condition performed better overall than the HHD AR and SAR conditions.

For the in-situ trials at Company 1, the Pizza session had the highest scores for the quality of ideas, novelty of ideas, task progress and usability metrics and can therefore be considered the most successful of the three sessions. We might speculate that one of the factors that contributed to the success of the fresh pizza session was the geometry and size of the prototype as it featured a large flat surface that resulted in very good rendering quality by the SAR technology. Also, the high score of the fresh pizza session on the Task Progress metric might be explained by the fact that the pizza session was more than double the duration of the other two sessions and therefore it is to be expected that more progress on project tasks would be achieved.

Considering the results of Table 8 in their entirety, a few observations can be made. First is that the quantity of ideas generated in the in-situ trials is less than in the SAR condition of the benchmarking experiments. This might be explained by the fact that in all three of the in-situ sessions there was greater importance placed on idea filtering (9/10) than was placed on idea generation (1-5/10).

Secondly, the average usability scores are lower for the in-situ trials than for the benchmarking experiments. The Mozzarella session scored particularly poorly, with an average score of 17. This very low CSI score can be explained by a number of factors:

- The concepts being tested featured images of the mozzarella on a white background, which were difficult to see due to the brightness of the SAR rendering.
- The mozzarella packaging was relatively small, which highlighted the limitations of the SAR rendering in terms of text legibility and pixelation of small graphics.
- The project had already advanced further than the other projects and so there was less interest in generating new ideas, which is confirmed by the score given for the importance of idea generation (one out of ten).
- It was the last session of the day and so the motivation of the participants might have begun to decline at this point.

Considering next the results of the follow-up survey (Table 9), which were completed after the benchmark experiments, the main perceived strengths of both the HHD AR and SAR conditions was the enhanced collaboration with the end-users and the ability to make quick, real-time modifications to the mixed prototype to try out new ideas. As one designer stated, the SAR technology "…has made it possible for everyone to see whether the requests made could be a valuable aid to the final product."

Another benefit noted by the designers was the ability to quickly filter out poor suggestions. A notable example of this came in the SAR condition session with Company 1, in which the end-user made a proposal concerning the position of a logo. The designer was confident that this proposal would not enhance the design. In the follow-up survey, she noted that with the SAR technology it was quick and simple to implement the suggestion on the mixed prototype, show it to the end-user and get them to agree that it was not a good proposal before reverting to the original logo position. This type of idea elimination activity can be particularly helpful in co-creative design sessions in which the end-users are staff members from the manufacturer of the product, who might otherwise request further work to be completed on an idea before it is eventually rejected.

In terms of weaknesses for the SAR session, the designers felt that the mixed prototype lacked realism because it was too bright/reflective. This issue is a technical challenge for controlling the projection luminosity: too dim and the augmented content cannot be seen under typical office lighting conditions, too bright and the mixed prototype appears to 'glow' due to the amount of light reflected off the physical object. One solution now being explored is to paint the physical object in grey paint so as to reduce the reflectance without modifying the hue of projected colours. Lessons might also be learned from the work of Park et al. (2015), who used a camera to capture the specteral irradiance from the mixed prototype surface and applied algorithms to adjust the output of the projector in order to reduce colour rendering errors.

For the session using conventional design representations, the designers commented that they liked the simple, intuitive nature of the collage method used but that when the users asked to include elements for which they did not have a prepared graphic, they had to hand draw those elements, which they felt reduced the aesthetic quality of the final outcome.

Table 9. Summary of the feedback from the follow-up survey from Company 1 designers.

	Condition		
Question	**SAR**	**HHD AR**	**Conventional**
What went well?	Helps with detailed refinements. Helps to quickly rule out poor suggestions from end-users.	Improved interaction with end-users.	Good empathy with the end-users, who were willing and able to provide good input.
How did tool contribute to positive aspects?	Quick, real-time modification of a tangible mixed prototype facilitates co-creation.	Real-time modification improved interaction with the end-users.	Intuitive interaction method that enabled the end-users to participate in an uninhibited manner
What was challenging?	Some end-users frustrated by perceived limitations of the system.	Various technical limitations and failures hindered and disrupted the session.	Limited range of elements and hand-drawn elements limits the quality/realism/ fidelity of the final outcome.
How did tool contribute to challenging aspects?	Some limitations on the modelling features. Mixed prototype lacks realism.	Technical problems caused disruption. Limitations of the system discouraged the end-users.	Limited range of pre-prepared elements meant that the final outcome did not entirely represent what was desired/discussed.

5.2. Results from the product design tests with Company 2

Table 10 presents the results of the co-creative session performance metrics for both the benchmarking experiments and the in-situ trials completed with Company 2.

Table 10. Results of the co-creative performance metrics application at Company 2

	Company 2 – benchmarking experiments			**Company 2 – in-situ trials**	
Product	*Emergency beacon*	*Smart fitness device*	*EMF detector*	*Electrical test device*	*Screening device*
Representations used	*Conventional*	*HHD AR*	*SAR*	*SAR*	*SAR*
Session objectives	*Filtering 8 Generating 1*	*Filtering 5 Generating 8*	*Filtering 7 Generating 7*	*Filtering 5 Generating 3*	*Filtering 5 Generating 8*
Duration	*40 mins*	*35 mins*	*57 mins*	*45 mins*	*34 mins*
Quantity of ideas	6	**8**	**8**	**8**	7
Coverage	4	1	**5**	**8**	5

Variety of ideas	**New**	1	1	**1**	**2**	0
Quality of ideas		= 6 – 5 rejected = 1	**=** 8 - 3 rejected = **5**	=8 – 4 rejected = 4	4	**7**
Novelty of ideas		= 23 ÷ 6 = 3.8	= 51 ÷ 8 = **6.4**	= 44 ÷ 8 = 5.5	=39/8=**4.9**	=34/7=**4.9**
Task progress		1xMed Total = 2	2xHigh 1xMed **Total = 8**	1xHigh Total = 3	**0**	**0**
Filtering Effectiveness		= 5/(6-1) = **1**	= 3/(8-5) = **1**	= 4/(8-1) = 0.57	= 4/(8-1) = **0.6**	0
Usability (CSI survey score)		44/100	**90**/100	64/100	**84**/100	72/100

For the Company 2 benchmarking experiments, the SAR session performed better than the conventional design representations session against all the metrics, with the exception of the Filtering Effectiveness. Whilst this is a positive result for the ANONYMIZED SAR technology, it should be noted that the HHD AR condition performed better than the SAR condition against all the metrics apart from the Variety (coverage) metric. Also, the session objectives for the conventional session placed less importance on idea generation, which might explain why this session performed less well against the idea generation-related metrics.

For the in-situ trials, the performance of the electrical test device session was the better of the two, outscoring or equalling the screening device session against all the metrics apart from the Quality metric. This is reflected in the high CSI score provided for the Usability metric (84/100).

That the electrical test device session scored higher against the Quantity metric was somewhat surprising given that in the session objectives there was greater importance placed on idea generation for the screening device session (importance of eight versus three for electrical test device).

Comparing the results of the SAR session from the benchmarking experiments and the in-situ trials, the results appear to be broadly similar. The main discrepancy is the Task Progress metric scores, which were zero for both of the in-situ trials. It is not clear from the current evidence why the in-situ sessions performed poorly on the Task Progress metric.

Table 11 provides a summary of the key points from the designer follow-up survey completed after the benchmarking experiments. The points were summarised by the authors from the original responses provided by the designers.

Table 11. Summary of designer feedback from the follow-up survey after the benchmarking at Company 2.

	Condition		
Question	**SAR**	**HHD AR**	**Conventional**
What went well?	Freedom to try many different ideas.	Good interaction/ communication with end-users.	End users were positive and focused.
How did tool contribute to positive aspects?	Able to generate and test some new ideas for colours and logo position.	Intuitive sharing of ideas between end-users and designer allowed quick iteration of concept	It was a basic way to support the engagement between the end-users and the designer.

What was challenging?	Technical problems had an impact. Limited interaction with the physical object. Major differences between the designer's view (tablet) and end-users' view (SAR).	More chaotic, less focused session with more random/trial and error - requires more pro-active facilitation.	LED position options difficult to represent.
How did tool contribute to challenging aspects?	3D effect and on-the-fly changes within SAR is useful but needs more user interaction features.	Tablet creates a barrier to direct interaction with the physical object.	Designers had to build a fourth concept (mixing elements of the three pre-prepared concepts).

From Company 2's perspective, the main benefit of the SAR condition was the ability to try many different ideas quickly and easily. The Company 2 designers also noted that the end-users proposed some ideas for the position of the logo and some background colour combinations that they had not previously considered. For the HHD AR condition, the designers stated that there was a very free exchange of ideas with the end-users, who were able to propose many ideas. For the conventional condition, the Company 2 designers commented that the end-users appeared to be very focused, as they were commenting on small details of the design such as the background colour of the logo.

In terms of challenges, Company 2 noted that there were notable differences in colour hue and shade that were observed when viewing the design representation on the designer's user interface compared to the view seen by the other participants when looking at the mixed prototype of either the SAR or the HHD AR conditions. Given that selecting colours, materials and finishes was a key objective of the Company 2 sessions, this was a major problem. More comprehensive colour calibration of the projector might have reduced the errors in colour rendering for the SAR session but such procedures are currently complex and time-consuming and need to be done for each mixed prototype to achieve maximum accuracy and so were not completed due to resource constraints. In the HHD AR technology, the problem is a function of the rendering engine (Vuforia®), which was attempting to correct the colours for the lighting conditions but appeared to overcompensate, resulting in less realistic colour rendering.

During the SAR session, technical problems were encountered on three occasions (mixed prototype rendering was not updating to reflect changes made by the designer). This led to pauses in the session, each lasting several minutes, whilst the system was rebooted. This caused some 'uncomfortable moments' in the session according to the designers but such technical problems are common with early-stage prototype technologies.

Another challenge noted by the designers was that the HHD AR technology made it so quick and simple to try new ideas that the session became a little chaotic. As one designer put it, "…the meeting became a 'gaming session', with no boundaries for end-users to participate and share ideas." To counteract these effects, the designer suggested that they would need to be more proactive in the facilitation of the session in future, particularly in rejecting ideas that stray too far from the brief proposed by the client/manufacturer.

The Company 2 designers proposed a number of enhancements that they would like to see in the SAR technology. Beyond the basic necessity of better reliability – being an early protype, the software of the ANONYMIZED platform happened to crash in some tests – the main interest was having more features to represent user interaction. For example, they suggested that it would be useful to be able to represent LED lights switching on and off, or blinking, to show the status of the device. Also, for several of the devices tested by Company 2 sound plays a vital role in the user interaction experience. The designers suggested that being able to work with sounds in the system would support better user interaction design.

6. Analysis/Discussion

This section consists of three subsections. The first analyses the results of the experimental activities and the CSI survey to discuss the impact of HHD AR and SAR technologies on collaborative design sessions involving designers and end-users. The second subsection elaborates the responses to the survey on the strengths and weaknesses of the HHD AR and SAR technologies relative to conventional design representations. The final section reflects on the lessons learned from this study concerning the methodological approach we followed.

6.1. Discussion on the impact of AR/SAR technology on co-creation

The first research question asked: "Do co-creative sessions involving SAR-based design representations result in more effective sessions in terms of idea generation, progress on design tasks, and filtering of ideas than those conducted with HHD AR-based or conventional design representations?". The results of the co-creative performance metrics from the benchmarking experiments have highlighted certain aspects of session performance where the SAR condition scored higher against the performance metrics than both the HHD AR and conventional design representations condition. In the packaging design sessions, this included the results for the quantity of ideas, quality of ideas and the usability performance. In the product design sessions, the SAR condition outperformed the conventional condition in all metrics apart from the Filtering Effectiveness metrics. However, the HHD AR condition scored higher than the SAR condition against all the metrics apart from the Variety (coverage) metric. Hence, whilst the comparison between the HHD AR and SAR conditions offers no clear 'winner', the results do suggest that both the HHD AR and SAR condtions were more effective than the conventional condition (noting that the evidence from this study is insufficient by itself to reach a definitive conclusion on this matter).

Technical faults during the product design SAR session and during the packaging design HHD AR session appear to have affected the performance of those sessions, as confirmed by the designers who explicitly mentioned these technical faults in the follow-up survey. Given the impact of these technical faults, further technological development of the ANONYMIZED platform to increase its robustness and refine its functionality are required, as well as continued collaboration with industry to gather additional feedback, in order to be able to provide a definitive response to this research question.

The second research question asked: "Do designers perceive SAR-based design representations to be more effective for co-creative design sessions than conventional or HHD AR-based design representations?". The CSI survey results portray a complicated situation. In the packaging design benchmarking experiments, the SAR condition scored highest on the CSI survey. However, the CSI survey scores decreased during the in-situ trials, particularly for the Mozzarella session. A possible explanation for this could be that the benchmarking experiments were conducted in a laboratory setting rather than in their normal working environment, and involved 'end-users' (volunteers who represented potential consumers) rather than representatives from the client organisation (i.e. the manufacturer of the food products). Hence, although the benchmarking experiments involved real designers working on their own real projects, it is possible that they still viewed the benchmarking experiments as an academic activity and were not overly concerned about the outcomes of the session. In contrast, the in-situ trials were completed in their own offices with representatives from the client organisation. The presence of the client representatives might have placed greater pressure on the designers to ensure that the outcomes from the session were useful and of high quality and so they may have been less willing to overlook any shortcomings in the SAR technology.

Some possible reasons for the particularly poor performance of the Mozzarella session were presented previously, including the suggestion that the small surface area of the Mozzarella resulted in poor rendering quality of the mixed prototype. The Fresh Pizza session performed much better overall, and it was again suggested that this was related to the size and shape of the physical object, which featured a large flat surface, making it ideal for SAR rendering. The difference in size and shape of the Mozzarella and Fresh Pizza physical objects can be seen in Fig. 8, which are screengrabs from the video recordings of the sessions.

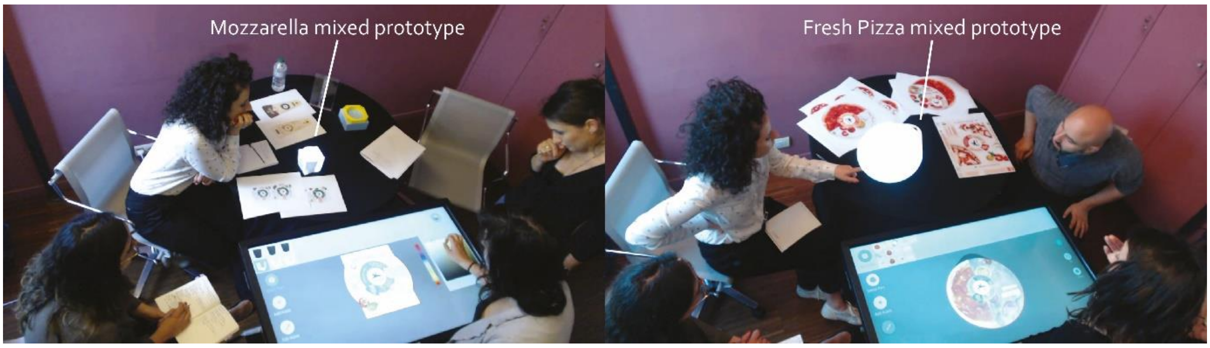

Fig. 8. Screengrabs from the session video recordings showing the size and shape of the Mozzarella (left) and Fresh Pizza (right) mixed prototypes.

The results of the CSI survey from the product design sessions showed a different trend. In the benchmarking experiments, the SAR condition (64/100) performed better than the conventional condition (44/100), but it was the HHD AR condition (90/100) that was the highest rated. The CSI survey scores for the in-situ trials were both very good (84 and 72/100), resulting in a higher average (78/100) in comparison to the average from the benchmarking experiments (66/100). The most likely explanation is that the technical difficulties experienced during the SAR condition of the benchmarking experiments were the main cause for the lower CSI survey score. No such difficulties were encountered during the in-situ trials and so the Company 2 designers were more satisfied with their experience of using the ANONYMIZED platform.

Hence the tentative conclusion from the product design session results is that designers do perceive SAR-based design representations to be more effective than conventional design representations, but not clearly better than HHD AR-based design representations. From the packaging design session results, the large variance in the results makes it impossible to draw conclusions. In both cases, firmer conclusions will be possible after the designers have had more experiences of using the SAR technology within such real projects.

6.2. Discussion of improvements for the ANONYMIZED platform

While the answers to the first two research questions provide a balanced view of the objective and perceived impact of the HHD AR and SAR technologies on collaborative sessions involving designers and end-users participating in the session, this study also helped to collect suggestions to direct the development activity of the ANONYMIZED platform, which is still on-going given the encouraging results of the tests in industry.

For this reason, the third research question asked: "What are the specific strengths and weaknesses of HHD AR and SAR-based design representations in comparison with conventional design representations?". The designers were invited to respond to this question with specific reference to their experience with the ANONYMIZED platform, rather than on intuitive thoughts about the potential achievements of the technology.

The main perceived strengths of both the HHD AR and SAR conditions were: the enhanced collaboration with the end-users; the ability to make quick, real-time modifications to the mixed prototype to try out new ideas; and ability to quickly filter out poor suggestions. In all of the sessions observed that made use of HHD AR and SAR-based design representations, the session participants were able to: provide feedback on design proposals; make suggestions for modifications; and implement multiple modifications to create new concepts collaboratively.

In terms of weaknesses, the reliability/robustness of the HHD AR and SAR systems was a problem for both companies as it disrupted the natural flow of the session and caused frustration for all participants. There were instances where they had to restart the software application because of a sudden crash due to some bugs still present in the prototype software. Other technical limitations previously discussed include the limited realism of the SAR-based mixed prototype due to the brightness of the reflected light and the discrepancy in the colour rendering between the representation displayed on the tablet PC and the SAR or HHD AR representations.

From a session facilitation perspective, it was noted earlier that the speed and ease with which new ideas could be displayed on the mixed prototypes resulted in a 'gaming' approach, in which many different ideas were proposed through trial-and-error experimentation. This led to the suggestion that more proactive facilitation is required to manage the session when using HHD AR or SAR technologies.

Whilst several weaknesses and challenges were identified by the packaging and product design teams, they were also keen to discuss how the system could be improved to address these weaknesses and support new types of functionality.

From these suggestions, we can conclude that enhancements to the functionality of the ANONYMIZED platform are required, particularly in terms of: use of the platform for interaction design of products (e.g. the inclusion of standard interaction assets such as buttons, lights, screens, text, or sound); colour rendering accuracy; robustness and reliability of the platform; and the quality and realism of the rendering - particularly when used with small physical objects. Such shortcomings are normal for a prototype technology and these findings will provide useful guidance for the future development of the ANONYMIZED platform, and other technology developers working on XR technologies for use in design.

6.3. Reflections on the methodological approach

Two important methodological insights have emerged from this study. First, is the difficulty in evaluating new technologies for use in design and their impact on design activities. Within the benchmarking experiments, we adopted the widely-used research approach of comparing the results of an activity (a co-creative session) conducted with a new technology with the results of the same activity conducted using the designers' conventional technology/approach. This makes for a difficult, and perhaps unfair, comparison because: firstly the new technology is still in the early stages of development, is not entirely stable and the designer is not yet fully aware of the full range of possibilities and limitations of the technology; and secondly the existing technology/approach is mature, stable, and the designer knows how to use it to best effect. The lack of SAR 'design representation knowledge' (Södermann, 2005) of both the designers and the end users may have exacerbated this problem. Hence, when making this type of comparison, we should avoid dismissing a new technology if it does not perform considerably better than the existing technology during early-stage experiments. In this study, we were unable to conclusively confirm (or deny) that co-creative sessions involving SAR-based design representations result in more effective sessions (RQ1), but a number of positive results were obtained and the designers were able to identify new, more effective ways of interacting with their clients. As the SAR technology matures and the designers' knowledge of the technology grows, further testing will be able to provide comparisons that more accurately reflect the true potential of the technology. From a methodological perspective, it is suggested that future tests should conduct an initial assessment of the participants' familiarity with the types of design representation to be used in the co-creative design session so that this can be factored into the analysis of the results. A method for testing 'design representation knowledge' (Södermann, 2005) would be useful for this purpose but no such test has been identified from a brief review of the extant literature.

The second methodological insight has confirmed the importance of collaborating closely with industry throughout the tool development process, which is in keeping with the recommendation from Blessing and Seering (2016). In the case of the ANONYMIZED platform, the close working relationship with the two industry partners and their regular feedback have provided good input for the technology development activities.

7. Conclusions

The paper aims to contribute to research on the application of XR technologies in support design activities. The paper describes a novel projection-based Augmented Reality platform developed within the European project ANONYMIZED that has been tested with two industry partners both in the laboratory and in real operational environments throughout the project.

The scientific objectives of this study were: to begin gathering data comparing the effectiveness of co-creative design sessions conducted with SAR-based design representations versus HHD AR-based and conventional design representations; and to identify specific strengths and weaknesses of SAR-based design representations in comparison with HHD AR-based and conventional design representations. These objectives led to the formulation of three research questions, which were addressed through controlled benchmarking experiments with professional designers working on real projects with end-users and in-situ trials.

It was not possible from this study to provide a definite response to the first research question concerning the effectiveness of using SAR-based design representations within co-creative design sessions. Nonetheless, some session performance metrics, such as the quality and novelty of ideas, were found to score higher when using the SAR-based design representations compared to the conventional or HHD AR-based design representations condition. Furthermore, the results appear to suggest that the technology-enabled sessions (SAR and HHD AR conditions) were more effective than the sessions using conventional design representations. Of course, care must be taken to avoid bias in the interpretation of the results, as both the researchers and the designers from the industry partners have invested considerable time and effort in the project based on the assumption that HHD AR and SAR-based design representations will result in more effective co-creative design sessions.

The second research question focused on the designers' perception of the effectiveness of HHD AR and SAR-based design representations for co-creative design sessions. The evidence from the CSI assessment suggested that designers do perceive HHD AR and SAR-based design representations to be more effective than conventional design representations, but this will need further experimental sessions to be confirmed.

The third research question was intended to help understand the relative strengths and weaknesses of HHD AR and SAR-based design representations in comparison to conventional design representations. The main perceived strengths of both the HHD AR and SAR conditions was the enhanced collaboration with the end-users and the ability to make quick, real-time modifications to the mixed prototype to try out new ideas. Important weaknesses identified included: the overall software system reliability issues; the current ANONYMIZED system prototype's insufficient projection quality; and problems in both the HHD AR and SAR conditions with differences in colour rendering.

In addition, HHD AR and SAR systems may provide a promising technology for remote design collaboration, as it enables "workspace awareness" (Wang et al., 2014), which is considered an essential factor for the development of the design activities. AR has been also applied to support remote collaboration between experts and workers, allowing more accurate and consistent annotations for sharing ideas and suggesting instructions with respect to a standard CAD system (Choi et al., 2018). In this context, the ANONYMIZED platform shows the potential to be further developed for running distant co-creative design sessions by connecting multiple rooms equipped with the proposed projection-based SAR system.

The contributions of this study are: data and insights into the value of SAR technology within co-creative design activities; several requirements for the future development of such systems; and a demonstration of how metrics of co-creative design session performance can be applied within industry-based experiments to yield these insights. These results will be relevant to XR technology developers with an interest in design-related applications and academic researchers studying co-creative design.

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