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Exploring Tablet Interfaces for Product Appearance Authoring in Spatial Augmented Reality

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Abstract

Users' acceptance of innovative product appearance authoring tools based on Spatial Augmented Reality (SAR) is still limited due to their perception of a high technology complexity and a low performance/functionality of the current interaction systems. The integration of SAR technologies in professional design activities is still marginal, though many studies in this field have already proved their potential as supporting tools. To overcome this barrier, efficient means for interacting with the digital images projected onto the surfaces of real objects are essential. The aim of the current study is to respond to this demand by proposing and validating three UI configurations displayed by a unique and portable device embedded with a touch screen. These interface layouts, designed to cooperate with the output of the SAR system and to not affect the well-known benefits of its augmented environment, provide different types of visual feedback to the user by duplicating, extending or hiding the information already displayed by the projected mock-up. The experimental study reported here, performed with a panel of 41 subjects, revealed that accuracy, efficiency and perceived usability of the proposed solutions are comparable with each other and in comparison to standard desktop setups commonly used for design activities. According to these findings, the research simultaneously demonstrates (i) the high performances achieved by the touch device when coupled with a SAR system during the execution of authoring tasks, (ii) the capability of the projected mock-up to behave as an actual three-dimensional display for the real time rendering of the product appearance and (iii) the possibility to freely select - according to the user's preference, the design task or the type of product - one of the three UI configurations without affecting the quality of the result.

Keywords: Spatial Augmented Reality, Human-Computer interface, Touch interaction, Authoring tool, Usability evaluation, Interface validation

1. Introduction

Spatial Augmented Reality (SAR) is a relatively new approach to merge computer-generated contents into a real environment (Raskar & Low, 2001) by means of a more straightforward visualisation technique in comparison to other Augmented Reality (AR) paradigms (Raskar et al., 1998). SAR systems integrate projection-based spatial displays (Bimber & Raskar, 2005) to generate beams of coloured light that change the aesthetic appearance of any registered two- or three-dimensional object without placing any visualisation medium in front of the user's eyes. Its output is in the form of a mixed environment where the coexistence of physical items and digital contents improves the understanding of any augmented information by means of spatial and tangible attributes. By converting the same working environment into an output display for

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10 the visualisation of relevant information and an input interface for the manipulation of the data, the impact of such systems on human activities is reduced in comparison with other AR setups (Raskar, 2002).

Hardware displays and users are physically separated in a SAR system and this efficient use of the installation space allows computer-generated information to be shared in an obstacle-free environment. This capability, in addition to the availability of hands-free interactions and the absence of wearable devices (Lantz, 1996), becomes highly relevant when dealing with the design domain. In this field realistic prototypes are manufactured throughout the design process to gather supportive information that cannot be gained with a purely digital model displayed by a flat screen (Broek et al., 2000). Consequently, a Projected Mock-up (PM), a neutral physical object whose surface appearance is visually enhanced by projected digital contents, allows users to access information in a less abstract form. The benefits related to the employment of SAR-based tools in design have already been investigated in the literature. These studies have measured: a decrease in the number and duration of the iterations required during development activities (Marner et al., 2011); a better exchange of ideas while testing and/or validating different design solutions (Porter et al., 2010); a reduction in the language barriers between participants from different backgrounds (Verlinden, 2012); a simplification in the procedures for preparing physical mock-ups (Thomas et al., 2011); a larger exploration of the design space and a more efficient design process (Cascini et al., 2020). Nevertheless, the majority of current SAR applications still limits the use of the technology to the evaluation or presentation of design solutions, including: visualisation of predefined alternatives (Park et al., 2015); quick collection of annotations (Calixte & Leclercq, 2017); collaborative review (Ben Rajeb & Leclercq, 2014); initial exploration of scenarios (Yu Sheng et al., 2011); functional/ergonomic testing (Port et al., 2010).

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30 In previous studies, the adoption of SAR is limited to a visualisation tool only. This can be explained by the inadequate knowledge of the features required by an interaction system suitable to enable the real-time modification of the SAR output within design activities (i.e. when an individual or a team are exploring different design solutions). According to the experience gained by the authors in the development of AR systems aimed at supporting design activities (O'Hare et al., 2018a), the correct development of a User Interface (UI) for SAR should firstly take into account the presence of the PM. Its capability to render graphical modifications projected onto the external surface, realistically and in real-time, means that the PM is actually a three-dimensional display that changes its visual appearance according to the needs. Consequently, the UI generally needs to provide the means to deal with these modifications in such a way that the space and view for user interactions are not negatively affected. Moreover, the requirement to support professional design activities, for which rapid prototyping methods and software have existed for years, implies the adoption of a UI that simultaneously guarantees an effective and accurate manipulation of the graphical assets (i.e. graphical resources like images, textures, texts). The involvement of experts, from different design domains, leads to the definition of specific requirements for the interactive functionalities and visualisations, which are common in graphic editing activities.

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60 In terms of aspects related to intuitiveness and effectiveness, as well as the outcomes presented by other researchers in the field (Section 2), this research proposes a tablet device with a multi-touch input system as part of the UI for SAR-based design applications. This type of input-output configuration and standard gesture control have been shown to be more effective than other input devices (e.g. mouse, pen and trackpad) by providing the users with natural (Sears & Shneiderman, 1991) and direct interactions (Forlines et al., 2007) for the displayed contents. However, there are still doubts about its limited accuracy and speed of modelling, in comparison to more widespread input systems, while performing navigation tasks (Zabramski, 2011) and manipulating data in a 3D environment (Besançon et al., 2017). To understand the real impact of the proposed solution for design outputs, this study explores the integration of three different touch-based interaction modalities with an existing SAR platform named SPARK. These interface layouts are designed to provide different types of visual feedbacks to the user by duplicating, extending or hiding the information already displayed by the PM. A total of 41 university students, with more than three years experience in CAD modelling, were involved in testing activities where the objective was to replicate the graphical layout of a real product design with and without the support of the projection. The tests were organised to measure and compare the accuracy, efficiency and perceived usability of the three interaction modalities - physically separated from the PM. The ultimate aim was to identify the most useful UI features for the SPARK system as a design supporting tool and to validate the touch paradigm in professional activities.

2. Background

The research community has been studying projection-based SAR technology with increasing interest for more than twenty years. Most of the studies in this field deal with the development of technological features able to improve the quality of the generated mixed environment: robust and high-speed methods for tracking physical objects (Sueishi et al., 2015); multi-projection treatment algorithm for the dynamic optimization of augmented images (Siegl et al., 2015); fast and automatic calibration procedures for the definition of the hardware configuration (Griesser & Van Gool, 2006); or simplified and portable setups for improving the technology adoption (Willis et al., 2013). Other research activities are specifically focused on the exploration of usage scenarios that benefit the most from the application of the SAR paradigm: education (Laviolo et al., 2018); gaming (Jones et al., 2010); exhibition (Schmidt & Steinicke, 2017); cultural heritage (Yoshida et al., 2003); maintenance (Schwerdtfeger et al., 2008); industrial assembly (Doshi et al., 2017); medical contexts (Ni et al., 2011); rehabilitation (Thevin et al., 2019); programming (Zaeh & Vogl, 2006); remote collaboration (Ben Rajeb & Leclercq, 2013); architecture (Tonn et al., 2008); and simulations (Yu Sheng et al., 2011) - are just some examples included in a wider usage panorama. A common trait of these publications is the adoption of dynamic projection systems for the visualization of digital information directly onto the environment surrounding the users in order to support, facilitate and improve aspects of human activities. Despite its potential, SAR is mainly explored as an innovative means of visualization, capable of providing some of the users' required information more intuitively. By acting as an output display with the awareness of the real space, these systems simplify the manipulation, navigation and creation of digital data due to their tangible interactions with physical and three-dimensional objects.

Only few systems have tried to fully exploit the SAR's potential by developing tools that go beyond a solely visualization support. These are mainly applied in the design domain, including engineering, creative and architectural fields, and take advantage of the Interactive Augmented Prototyping (IAP) concept introduced by Verlinden et al. (2003) where projected images dynamically change the external appearance of products. A supporting tool based on projected mock-ups to render an infinite range of real-like products can be easily integrated within the design process for exploring all the desired alternatives starting from a single physical model (Verlinden & Horváth, 2009). This real-time rendering is fundamental in the whole development process even if the greatest impact is during the early phases, where rapid and various changes are applied on the product appearance (Becattini et al., 2018). Thanks to the adoption of projector devices, whose light beams are directed onto the external surface of white physical prototypes, there are no external means of visualization that can interfere with the user's view, such as head mounted displays or handheld devices. This creates a shared space in the real environment where the collaboration between each participant of the design session is fostered by the possibility to look at the same augmented contents from their own perspective (Hartmann et al., 2010). The digital part of PM brings another relevant advantage to the design activity related to the simulation of the behaviour of hardware components (e.g. LEDs, displays, buttons, connectors, etc.) or the aspect of materials without being physically included in the prototype (Nam & Lee, 2003). Thanks to this, the cost for iterative prototyping is reduced in those intermediate steps where the design alternatives are just explored and not refined (Bordegoni et al., 2009). Moreover, the physical properties of the PM allow all the designers to perform direct, natural and tangible interaction with the design concept (Becattini et al., 2017b). This feature, when joined with a multi-projection setup, enhances the realism of the SAR outputs thanks to a wider augmentable volume and an increased coverage of the prototype's external surface with the projected images. The selected hardware affects both the quality and the dimensions of the shared space in which PMs of various types and sizes can be used. Thus, it is possible to run the design session on scaled or real-sized models according to the scope of the activity (Marner et al., 2011) and to perform functional and ergonomic analysis from the early development stages (Akaoka et al., 2010).

However, there is still an open question which has prevented the adoption of IAP applications as design tools. The complex and immersive augmented space typical of SAR systems, in fact, allows the exploration of innovative and engaging interaction modalities for manipulating the external appearance of the PMs without considering their efficacy in professional contexts. For this reason, existing interaction solutions are collected and classified into the following 4 groups to justify the selection and testing of touch interactions

over the other common approaches.

Desktop screen with mouse and keyboard

115 The use of a standard computer screen and mouse as an input device to control SAR projection exploits the mature capabilities of the desktop setup, already widely adopted in the design domain. The system developed by Gervais et al. (2016) uses such a setup; a tracked object is placed in front of a computer screen to obtain seamless navigation between the two means with the mouse pointer. A similar approach is proposed by Von Itzstein et al. (2011) with a prototyping application aimed at reviewing the aesthetic features of consumer goods. According to the system workflow, each asset of a product is firstly designed using commercial software running on a computer and then loaded into the SAR system to enable the static projection. Another attempt to integrate a mouse-based interface with SAR is explored in the work of Verlinden et al. (2003) where the GUI is projected onto physical planes placed around the physical object. Choices related to their development enable an editing environment which is easily sharable between multiple users, but the quantity and the quality of the available functionalities for altering the product design are limited. A similar limitation can be seen in the research by Menk et al. (2011) and Park et al. (2015) where the user can choose only between predefined materials and colours to achieve a high-quality visualisation of the projected aesthetic features of the product.

Hand and body gestures

130 Interaction techniques based on hand gestures can be implemented using direct or indirect detection of human body motions. Direct methods have been explored in the work by Felip Miralles et al. (2015) where a single user skeleton that is moving in the free space is tracked inside a Cave Automatic Virtual Environment (CAVE). The high intuitiveness achieved with the adoption of body or hand gestures which change the design of interior spaces is countered by the limited amount of interaction system functionalities and their poor precision. With the capability to track the gestures of multiple users, Port et al. (2010) presented a SAR application for the design of dashboards. Thanks to markers attached to the finger, the user interacts directly with the digital contents representing physical input elements (buttons) to change their state. In this context the greatest limitation is linked to the occlusion caused by the hands on the projector light beam. This drawback is also apparent in those systems where the projected contents are indirectly modified by handling physical objects. An example is the application developed by Yu Sheng et al. (2011) to study the impact of different daylight illuminations on architectural projects. Designers can re-arrange the floor plan of a building by moving tangible elements representing the walls and then visualise the results projected onto the new scene configuration. This flawless and intuitive manipulation is also available in the system described by Mitasova et al. (2006) where a 3D laser scanner detects any changes applied to the shape of a landscape scene.

Tracked tangible tools

Interactions based on tangible tools are adopted to simulate some of the manual operations that designers undertake with the instruments commonly used in prototyping activities (e.g. paint brush, chisel, etc.). Multiple configurations of this interaction modality can be found in the literature with the main differences relating to the type and quantity of tangible tools, the functionality and the setup of the GUI, as well as the dimensions and the manipulation of the physical object. There are applications where a unique tool owns all the available editing functionalities of the SAR system, since a complementary GUI allows for switching between each editing option (Bandyopadhyay et al., 2001), and others that embed numerous instruments with different meanings and shapes that can be manipulated simultaneously by a single user (Marner et al., 2009) or by multiple participants (Irlitti & Itzstein, 2013) to apply the desired modifications to the projected contents. With the latter configuration, the GUI becomes extremely relevant in order to enrich the capability of the SAR system and it can be projected onto static surfaces surrounding the physical object, as in Jacucci et al. (2005), or directly onto tangible objects handled by the user (Chan & Lau, 2010). Despite all the advances in recent years, this type of interaction modality still suffers certain limitations related to the presence of people that can cause occlusion problems for the projection and the detection of tracked objects. In order to overcome these drawbacks, Kitajima et al. (2017) developed a tangible pen

integrated with a photosensor which can estimate its position in relation to the light beam, while Cortes et al. (2018) mounted a projector and a tracking system on a wearable helmet to enable free movements and interactions with the tangible objects or tools. With a similar aim, Darbar et al. (2019) adopted a panel mounted on a drone to provide the user with additional surfaces where, by means of the same projection system adopted for the augmentation of the physical object, displaying the GUI. Their solution integrates a controller to point directly towards the interactive elements visible onto the flying panels.

Touch and multi-touch surfaces

The use of a touch screen to interact indirectly with the projection enables the user to exploit different touch gestures (e.g. pinching, rotating, swiping, single and double tapping) to accomplish different tasks, while taking advantage of the information displayed on the screen. Calixte & Leclercq (2017) developed a setup in which a hand-held tablet device allows interaction with the projected contents of a static prototype representing an architectural building. It can be used by one person at a time, during the design review session, and includes a capacitive stylus so that real-time handmade drawings and annotations can be added. A similar approach is also used in the PARIMC application (Mendes et al., 2019) where Artificial Intelligence (AI) algorithms are combined with the SAR to augment an aerial view of a city area. Each user can interact with the projected contents of the static model by means of a smartphone or a tablet to simulate itineraries or to reconstruct historical places. To fulfil the requirements of simplicity, mobility, flexibility and multi-projector support, Schmidt et al. (2015) proposed a touch-based interface running on a portable device to interact with different type of projected contents. Their study, which is somehow coherent with the one proposed in this paper, validated the interaction metaphor against desktop environments based on the user's personal evaluations only without considering any performance indexes.

The above overview highlights that interactions with digital contents generated by a SAR system applied in design can take place in the context of a PM itself as an interface or by using independent devices. A gestural-based interface, for instance, belongs to the first group since it provides innovative, engaging and user-friendly modalities by which to modify the projection by means of the natural movement of the human body or hands. Nevertheless, the need to track the user and the risk of occluding the projected images reduce the interface performance of such a system in terms of precision and reliability, especially when dealing with a small prototype. For this reason, applications based on free body movements often integrate a space which is separate from the SAR and complementary that, by displaying a traditional GUI, extends the interactive functionalities of the system (Laviolle & Hachet, 2012). This promising strategy of separating the system into two environments demonstrates an attempt to avoid selection errors that can occur if the work and the menu spaces are blended. A similar option is obtained by providing users with tracked and tangible tools, which make the interaction more physical and similar to real manual operations. The instruments, which are directly usable in the mixed environment or on external interfaces, extend the number of available functionalities by using different tools and shapes and improve simultaneous participation in collaborative scenarios. Gesture and tool-based interfaces are necessary to simplify the understanding of the effects of the interaction for those users who are not experts in the target field, but they limit the range of possible modifications, such as swapping between different pre-loaded design alternatives, visualising the results of simulations or guiding the human work. This means that the potential applications of the SAR system are constrained to specific phases of the design activities when minor changes in output layouts are required. Moreover, since these interfaces require large body or arm movements and/or the handling of physical objects for prolonged periods of time, the risk of fatigue for the user is very high.

To overcome these disadvantages, computers or touch devices are efficiently adopted to provide a consolidated interaction modality which comes at the expense of having a less engaging experience. The well-established desktop setup, for instance, can be easily integrated with commercial software to offer a wider spectrum of possible editing options. However, since the target users of these applications are mainly professionals and the input device allows only one person to apply modifications, it is expected to make a lower active contribution of those participants with less design experience. The usage of a touch-screen device in the SAR scenario drastically mitigates the previously listed restrictions by merging the interaction of

natural finger gestures with a high-resolution screen in a complementary space. The screen, in fact, can display traditional GUI layouts, can be scaled to a wider dimension, or duplicated on multiple devices, and can even be used with tangible tools like a stylus in order to make the simultaneous participation/collaboration of all the users more agile.

3. Research objectives

From the review of previous studies that investigated the adoption of SAR technologies in design domains, it emerges the capability of touch interactions and mobile devices to be easily integrated with the PM for the manipulation of its external appearance. The touch paradigm provides designers with a standard interaction modality, due to the diffusion of smartphones and tablets in our everyday lives. The dual state of the interaction and the intuitiveness of the gestures help reducing the user's cognitive load as well as the learning time required for efficient use of the interface (Rogers et al., 2005). Moreover, the fingers movements simulate those natural gestures required for the manipulation of real two-dimensional objects on a surface and, thanks to the direct touch on the displayed digital elements, it replicates physical actions in the real world. Another strength of mobile devices is their compactness, which ensures high manageability of the interface. This aspect is strongly relevant because of the SAR context in which the UI is used, as it reduces the physical distance between the interface and the PM. Despite these well-known considerations, there are still gaps in the knowledge of the features that the interface layout should own to be effectively used during 3D authoring activities, as well as on the performances ensured to the user by the touch paradigm. A SAR system, in fact, introduces several changes in the standard professional environment of designers and a preliminary investigation is essential to facilitate the technology acceptance. With the current research, an experimental activity is conceived to fill this gap by answering to the following Research Questions (RQs):

- RQ 1 Is the PM alone sufficient for the user to dynamically render the external appearance of an object during the execution of digital authoring activities using touch interactions (the tablet device acts only as an input system)?
- RQ 2 Is the user better supported during the execution of authoring activities when provided with an interface displaying redundant visualizations of the PM (a 3D copy of the PM) or complementary ones (a 2D layout of the PM)?
- RQ 3 Considering accuracy and efficiency of the authoring task, what are the differences (if any) when adopting touch interactions on a tablet device coupled with a PM in comparison with a well-established software with standard input devices?

The first two research questions consider the relationship between the interface layout and the PM to identify the most suitable type of editing environment. Since the PM displays all the modifications applied to its layout in real time, it is important to understand whether its visual output is enough to perform authoring activities or additional information on the tablet screen is necessary. In this second case, the experimental activity aims at offering relevant insights for an optimal visualisation modality between a 3D view of the prototype or its two-dimensional representation. While the first layout does not add any additional visual information, and for this reason it is defined as redundant, the second shows the product appearance in a different and complementary form in comparison to the PM, which is coherent with the two-dimensional space where digital contents are manipulated. The third research question, instead, defines a comparative evaluation of the proposed interface layouts with respect to standard authoring software and common input systems, namely mouse and keyboard. The impact of the PM on the human ability to replicate a reference layout for a product given as a physical mock-up is considered and quantified with performance indexes.

4. Interface implementation

The tablet device used to run the interface application manages the interactions with the digital contents and, at the same time, sends modifications to the PM. An early analysis of the target users' requirements

has been performed to identify those functionalities of the interaction module that are necessary to perform digital authoring tasks (Becattini et al., 2017a). These are selected to replicate those functionalities offered by 2D authoring tool, since the SAR application is not meant to create/edit 3D geometries but just to change the appearance of their external surfaces. The selected configuration gathers all the main functions together according to their meaning and distributes them on the sides of the screen to generate a wide interaction area where the user can easily visualise and manipulate the external appearance of the product (Figure 1). The left side of the screen is reserved for four icons which are always visible and allow the user to switch rapidly between different functionalities of the interface. The first one named “Select part”, manages the selection of the mesh or the 3D model where the external appearance needs to be edited and integrates a palette to modify the background colour (Figure 1 top-left). The large previews displayed by the contextual top panel simplify the identification of the different portions into which the 3D model is divided and all the available versions of the same prototype. Only when a part is selected (red outline on the 3D view), it is possible to modify its appearance by interacting with the assets pre-loaded in the application. The term asset includes various types of two-dimensional resources that can be wrapped on the surface of the 3D model, like images, textures, animated images and texts. The second icon, called “Add asset”, allows adding further assets on the selected part by means of the asset library (Figure 1 top-right). The user can filter the previews by using a tag-based search and, by selecting one of them, he/she can instantiate a new asset with a single tap of the finger on the screen. Even if this environment allows the position, orientation and scale of the assets to be modified by means of multi-touch gestures, only the third icon (“Edit asset”) enables other functionalities, which are typical of graphic editor software. In this case, after the selection of one or multiple assets by means of the central view or the top menu (Figure 1 bottom-left), the application uses the contextual panel to display additional editing functions, which depend on the type of selection (Figure 1 bottom-right). For instance, an image can be moved to a different layer level, replaced with another one,

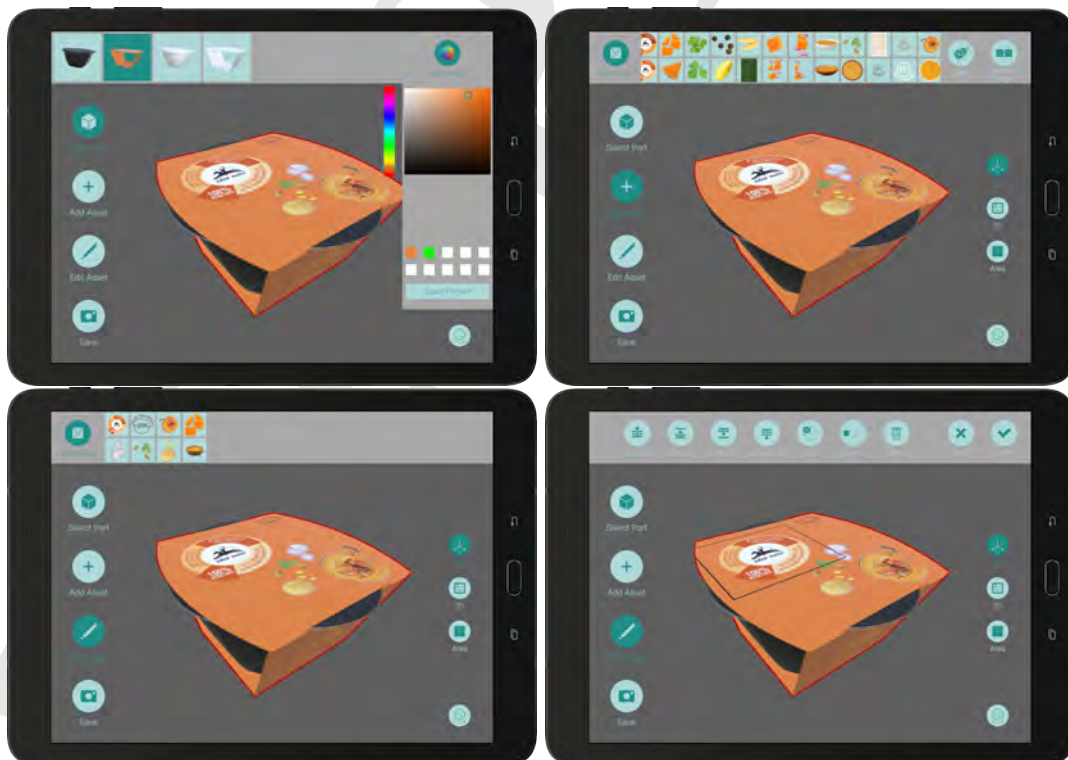


Figure 1: Representation of the three different environments designed for the interface: select part (top-left), add asset (top-right) and edit asset (bottom-left for asset selection and bottom-right for asset modification).

duplicated in a pattern or removed. Finally, with the last icon, a user can save the current layout so that it can be identified and restored easily after the session.

The right side of the screen is used to change and adjust the layout of the central digital visualisation. Three different visualization modalities have been designed and implemented for the manipulation of digital contents. The first shows the 3D model associated with the PM (Figure 1), the second shows the UV map of the 3D model (Figure 2 left) and the third is a graphical simulation of a trackpad (Figure 2 right). The proposed visualizations, called respectively *3D view*, *UV map view* and *touch area view*, act as redundant, complementary or blind representations of the current status of the PM.



Figure 2: Representation of the two additional GUI layouts: UV map view (left), touch area view (right).

The *3D view* allows the manipulation of the digital assets directly onto their digital representations, as applied to the PM. This means that, when the user's finger moves on the displayed model, the application identifies the contact points on the mesh of the 3D model and transforms them into the corresponding coordinates of the PM, which has the identical geometry. The same principle is also applied for asset selection since it is sufficient to tap where the image should be placed on the mesh. This is the standard visualisation of commercial 3D design software, where a realistic representation of the 3D model is needed for the comprehension of its physical features (e.g. dimensions, shape, surface render, etc.). However, in an environment where the physical properties are already available with the PM, the importance of this GUI layout is reduced to an additional 3D visualiser.

The *UV map view* mimics the graphical editor software commonly used by professional designers where graphical elements are arranged onto a 2D artboards delimited with die-cut drawings. The same approach is also used in the texture mapping process where the relationship between the coordinates of the UV and the mesh allows 2D images to be projected onto the 3D model surface. Since the 3D rendering is provided by the PM, this interface layout supplies a complementary visualisation. As a result of this layout, the interaction with the digital contents becomes more natural and intuitive when dealing with the complex shapes of the virtual model. The user, in fact, interacts with the same modality as for the previous GUI layout but, in this case, the movements of the finger and the image occur in the same plane.

The *touch area view* is what makes the role of the PM crucial as a visualisation medium. In this configuration the PM is the only available visual output for rendering the product external appearance, while the tablet provides only the functionalities to interact with the digital contents. The interface works when integrated with the SAR platform because its behaviour changes according to the manipulation of the physical prototype. To instantiate a new image, for instance, the system detects the placement position in accordance with the orientation of the PM, so that it is always visible to the user. All the modifications on the assets are applied with the same multi-touch gestures as for the previous GUI layouts but in a sort of "blind mode". This means that, after selection on the scrollable menu, the direction of the image displacement and rotation are defined according to the prototype orientation in relation to the user. With the touch area view, there is no direct relationship between the tablet screen and the PM; for this reason, the sensitivity of the asset manipulation can be adjusted as needed.

It is worth noticing the different interaction schemes characterising a standard desktop setup and the three touch-based interface layouts when coupled with the PM. Being these interfaces developed to answer to the research questions of Section 3, it is necessary to explain for each variant what are the information flows from the user to the system and vice versa (highlighted in Figure 3 with a reference to the test conditions detailed in Section 5.2). With a desktop setup, the visual feedback (state in condition A-B4) of the current product layout is displayed only by the monitor screen while the manipulation of the digital contents (action in condition A-B4) is performed by means of mouse and keyboard acting as input systems. The touch-based conditions introduce the PM as visual feedback (state in condition B1-B2-B3) for the authoring activity, but it also allows the user to handle the physical object (action in condition B1-B2-B3) inside the projection space for changing its position and/or orientation. Their differences are based on the types of information that are rendered by the tablet screen in addition to the GUI necessary to apply the modifications to the projected contents. In the 3D view and the UV map view, the tablet device is used as input system and output visualiser while, in the touch area view, the tablet device does not display any information complementary to that already provided by the PM and it only acts as an input system. The link of the research objectives with the current implementation can be thus expressed as follow: RQ1 is the comparison between the performance achieved with the touch area view and those achieved with both the 3D and the UV map views; RQ2 is the comparison between the performance achieved with the 3D view and the one achieved with the UV map view; RQ3 is the comparison between the performance achieved with any of the touch-based conditions, which are coupled with the PM, and the one achieved with the desktop setup.

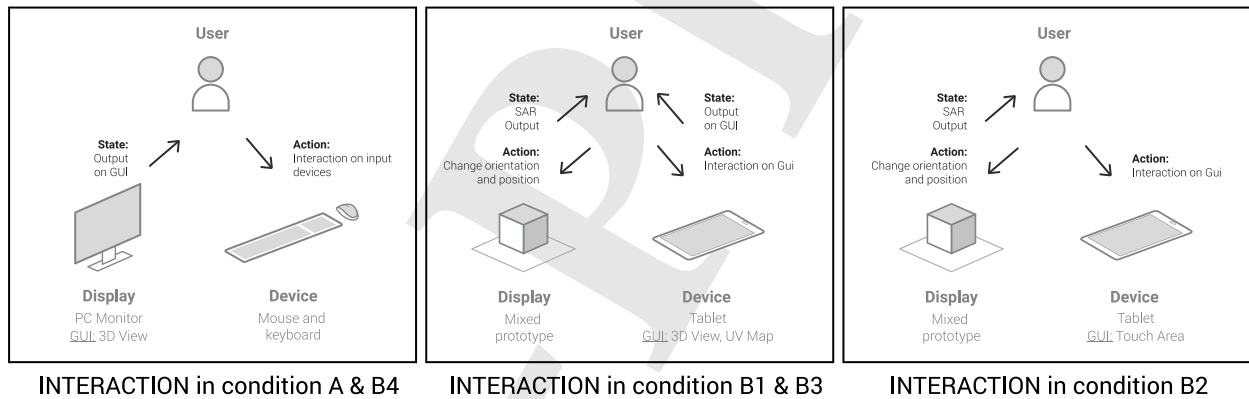


Figure 3: Interaction elements for each test condition: User, Display and Device. The information flows occurring between these elements including States (visual feedback from the system) and Actions (activities performed by the user).

5. Experimental set-up

With the aim of answering the proposed research questions empirically, an experimental activity has been conceived to study how much the UI architecture and the visual feedback of the proposed interfaces affect the human ability to correctly replicate the appearance of a real product (accuracy), the time and the number of actions required for the accomplishment of the task (efficiency) and the perceived usability. The type of task, the setup and the organisation of the experiments have been studied to limit the impact of the variables related to the user's creativity. These factors can drastically affect the reliability of the data and they are strongly influenced by the user's personal skills. For this reason, the outcome of each individual session is evaluated only in terms of its similarity with a reference object and not for the originality or the appeal of the solution. The task objective is thus restricted to duplicate, within a limited time, the appearance of a real product as precisely as possible.

5.1. Participants

The participants in the testing activity were recruited from a panel of students enrolled in their last year of a bachelor's degree, a master's degree or attending a doctoral programme at Politecnico di Milano. The background of the involved 41 subjects was either engineering or product design with at least three years of experience in using 3D modelling software, defined as the time which had elapsed since they started using those tools. Participants were asked to estimate the total amount of ECTS (European Credit Transfer System) points they had earned by attending classes in which it was somehow necessary to use 3D modelling software, to better characterise their technical skills. Table 1 summarises the data collected on demographics and experience for the subjects.

PARAMETER	TOTAL	TREATMENT GROUP			
		1	2	3	4
Number of subjects	41	11	10	10	10
Number of females	7	3	1	1	2
Average age (years)	25 (± 2.16)	25.1 (± 2.12)	24.7 (± 2.38)	25.2 (± 1.90)	26.2 (± 2.19)
Average experience (years)	4.67 (± 1.52)	4.24 (± 1.62)	5.10 (± 1.43)	4.34 (± 1.20)	4.67 (± 1.74)
Average experience (ECTS)	18.1 (± 4.47)	17.6 (± 4.09)	17.9 (± 5.94)	17.8 (± 4.54)	18.1 (± 3.71)

Table 1: Demographic and experience data for the participants involved in the experimental activity.

5.2. Test protocol

The activity consisted in replicating the external graphical layout of a cardboard packaging starting from its white 3D model. This type of authoring task was taken as a test case, since it allowed performing all the basic functionalities of the SPARK system (e.g. the definition of background colour, introduction, positioning, orientation and scaling of superficial assets, etc.). Four equivalent layouts of the packaging, in which only the external appearance was changed, were built to avoid any learning mechanisms due to the repetition of the task. Figure 4 shows the four aesthetic layouts of the product used as references for

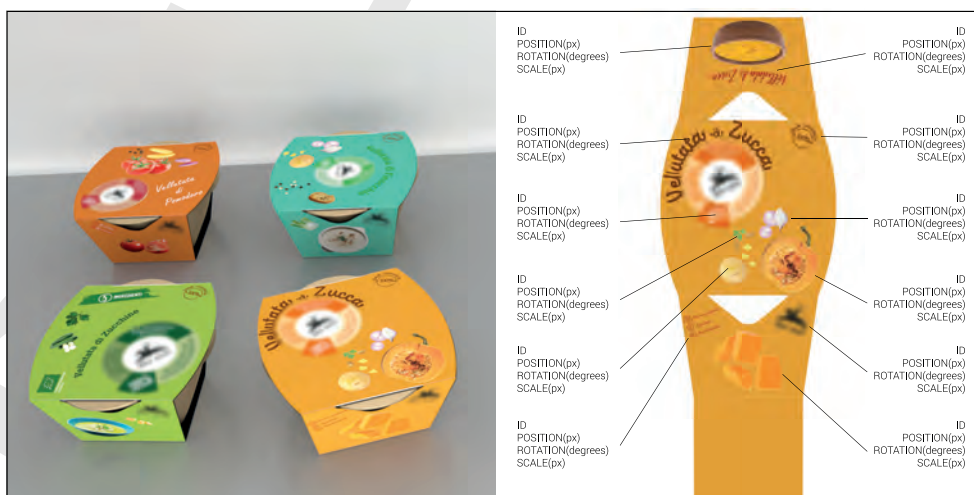


Figure 4: The four aesthetic layouts of the product used as a reference for the test tasks (left), 2D development (canvas space) of the cardboard sleeve displaying all the assets and their individual attributes.

the test (left) and the two-dimensional version of one sleeve only (right) to highlight the attributes of its graphical elements. Each layout contained 12 assets (images), equally distributed across the 3 planar faces of the packaging, which were not overlapping to be clearly distinguishable from each another. These images had different shapes, dimensions and contents in order to have an experimental task that closely resembles the one performed during packaging design activities. The simplified and flat shape of the product had been selected to limit the presence of factors associated to the user's three-dimensional perception of the output that could influence the execution of the task. Despite this, the inclination of the lateral surfaces still required an appropriate manipulation of the 3D visualization onto both the digital model displayed on the screen and the PM generated by the SPARK system.

Each subject had to complete the task twice with two conditions, identified as "A" and "B". In Condition A, the user worked on a computer with a mouse and keyboard as the interaction inputs and a monitor as display. This condition used the same GUI layout as the 3D view and, since it includes interaction devices commonly adopted for authoring activities, it has been used as a reference for the test. In addition, the desktop setup has the benefit of being widely diffused among users since it is suitable for prolonged use, it ensures high precision during its manipulation and it provides multiple visual feedback. Condition B, involving one of the three user interfaces developed for the tablet and the same setup used for the first round, subdivided the whole panel of participants into four treatment groups:

- Condition B in treatment group 1 (B1) - tablet screen displaying the UV map view.
- Condition B in treatment group 2 (B2) - tablet screen displaying the touch area view.
- Condition B in treatment group 3 (B3) - tablet screen displaying the 3D view.
- Condition B in treatment group 4 (B4) - same setup of Condition A.

With the given architecture for the testing activity (type of subjects, task and conditions), the participants were treated with the following protocol subdivided into nine different phases:

1. Briefing - introduction at the SAR technology and description of the task.
2. Training A - description of the desktop interface functionalities by means of a step-by-step video-presentation.
3. Practice A - free play with the desktop-based interface to learn how to use the GUI functionalities.
4. Condition A - one of the sleeves was assigned to the user and he/she was asked to replicate its graphical layout as accurately as possible starting from the scratch in 10 minutes. If the user required more time to complete the task, he/she could continue until the completion of the task after being told that the 10 minutes had expired.
5. Questionnaire A - the user filled in a SUS questionnaire to assess the perceived usability of the system.
6. Training B - using the same modality of the first training phase, another step-by-step video-presentation was used to illustrate the assigned interaction modality of condition B (each subject was involved in just one of the 4 B conditions). The focus here was on explaining how to apply the multi-touch gesture, according to the selected GUI layout, and how to correctly manipulate the PM in order to avoid tracking instability and projection occlusion.
7. Practice B - free play with the selected touch-based interface to better learn how to interact with the digital contents and the PM.
8. Condition B - a sleeve, different from the one used in Condition A, was assigned to the user and he/she was asked to replicate its graphical layout as accurately as possible using the assigned interface. The time to complete the test and the type of task were kept consistent with the Condition A.
9. Questionnaire B - the user filled in a SUS questionnaire to assess the perceived usability of the system.

It is worth noticing that group 4 (control group) skipped phases 6 and 7 because of the adoption of the same setup of Condition A and thus there was no need to let them practice again with the interface. Moreover, the test protocol previously defined is based on the assumption that touch and multi-touch gestures are familiar interaction modalities for the population studied (students aged 20-30) thanks to the diffusion of handheld devices like smartphones and tablets. For this reason, these interactions do not require intensive initial training to be correctly performed.

5.3. Materials

The experimental protocol previously described was carried out in a controlled environment with only one user at a time to avoid any type of distraction while performing the activity. The two different setups detailed below were defined to comfortably perform in the same laboratory the desktop (A and B4) and the SAR conditions (B1, B2 and B3) expected by the experimental protocol.

The hardware for the desktop conditions was a Dell Inspiron 7559 computer¹ with Intel core I7, 16GB of RAM, 4GB of graphic card dedicated memory and a standard 1600 DPI optical mouse. Its high resolution 15.7" screen (3840x2160 pixels) was used to display the same interface described in Section 4 with the 3D view GUI layout (Figure 5 right). While the interaction with the GUI elements was achieved with single mouse clicks, the manipulation of the graphical elements placed onto the 3D model occurred by means of different actions on both the input devices: a single click with the left mouse button above an asset for selection, a single click with the left mouse button above the selected asset and drag for translation, scroll with the mouse scroll wheel above the selected asset for scaling, single click with the left mouse button above the selected asset and drag while pressing the keyboard Alt key for rotation.

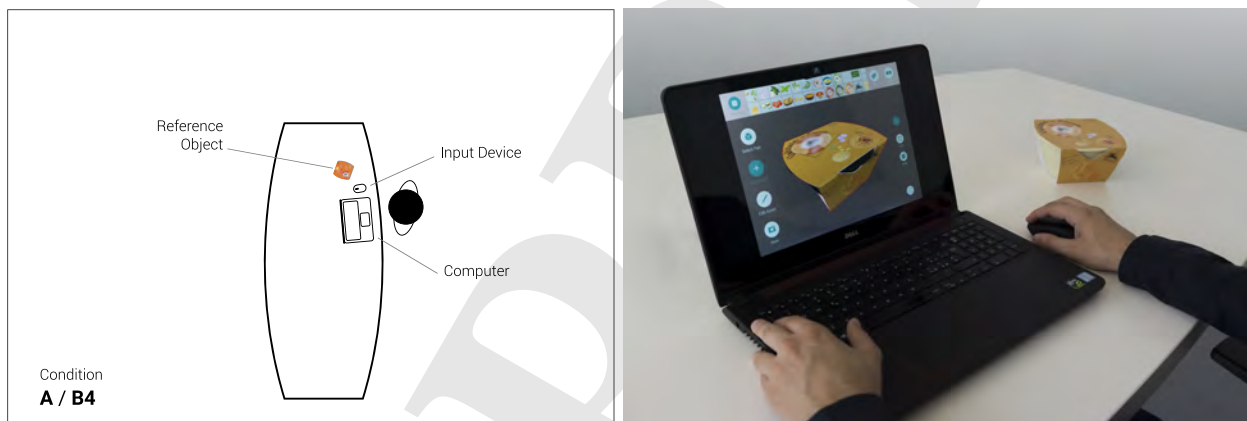


Figure 5: Schematic definition of the hardware arrangement for the execution of the desktop conditions (A and B4) and detail on the selected devices (a computer with a mouse and keyboard).

The SAR conditions, instead, required the integration of the touch-based interfaces with SPARK² (Spatial Augmented Reality as a Key for co-creativity), a SAR platform that aims at supporting design activities thanks to realistic visualisations and a real-time means of interaction (O'Hare et al., 2018b; Cascini et al., 2020; Morosi et al., 2017, 2018). The overall architecture of the platform is illustrated in Figure 6 (left) where the front-end components are the PM and the tablet device while the back-end technologies are a computer, two projectors and six IR cameras. This hardware has been integrated to enable the functionalities required by an authoring tool for the generation of a PM and to achieve optimal performance during an individual use. For this reason, the array of six OptiTrack Flex3 InfraRed (IR) cameras and emitters³ is fixed on the ceiling of the room to detect the hemispherical reflective markers that are attached to the top surface of the physical object. By applying the triangulation technique to the images streamed by the IR cameras, Motive software⁴ can track the PM within a volume of about one cubic metre. The optical tracking solution has been selected for its capability of detecting any object with a matte uniform surface and for its high reliability despite the occlusion problems caused by the projected object, the user's presence and direct PM manipulation. The physical object can be translated and rotated in the three-dimensional space if a minimum of two cameras are able to detect at least three IR markers simultaneously. The augmented

¹ www.dell.com/support/home/en-uk/product-support/product/inspiron-15-7559-laptop (accessed October 5, 2021)

² www.spark-project.net (accessed October 5, 2021)

³ www.optitrack.com/products/flex-3 (accessed October 5, 2021)

⁴ www.optitrack.com/products/motive (accessed October 5, 2021)

contents, instead, are generated by two Maxell CP-WU8600 projectors⁵ with medium throw ratio lenses (2.8-4.9:1) that are placed in two corners of the ceiling and pointing to the same area at the opposite end of the table. This multi-projection configuration allows to have a high quality of the images composing the digital rendering of the PM and simultaneously a high percentage of coverage for the object's external surfaces. Once the session is running, the input and the output data flow (i.e. the 3D tracking values and the rendered images respectively) are managed by the SPARK software, developed with the Unity3D game engine⁶ and running on a workstation with this configuration: Intel Core I7-6800K 3.4G CPU, 2 x HyperX 32GB RAM and NVIDIA GTX1080 8GDDR5 graphic card. As soon as the IR sensors register a variation in the position or orientation of the marker set, the SPARK software adjusts the projection so that the projected contents are correctly aligned/deformed according to the shape, size and actual orientation of the real object as well as blended in correspondence of those regions where the light beams are overlapped. The device used for the manipulation of the projected contents composing the layout of the PM is the Samsung Galaxy Tab S3 tablet⁷. Its 9.7" sAMOLED capacitive display (2048x1536 pixels) provides a high-quality image rendering and a precise touch detection to run the interface application designed with Unity 3D (Figure 6 right). The graphical elements of the PM can be manipulated thanks to multi-touch gestures: single finger tap above an asset for selection, single finger drag above the selected asset for translation, two fingers pinch for scaling and two fingers opposite swipe for rotation.

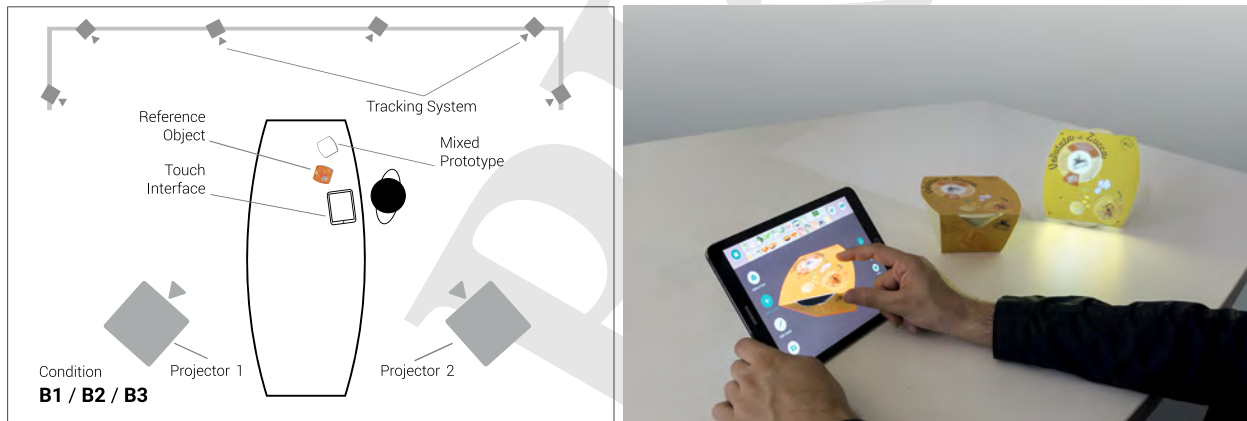


Figure 6: Schematic definition of the hardware arrangement for the execution of the SAR conditions (B1, B2 and B3) and detail on the selected devices (a tablet with a touch interface supported by the PM).

5.4. Metrics

Objective and subjective data were processed for the analysis and the evaluation of three main aspects related to the interaction: (i) accuracy, (ii) efficiency and (iii) perceived usability. These indexes are composed of several metrics which are listed and defined in Table 2.

The evaluation of the accuracy of the touch interaction, and therefore its appropriateness for the execution of professional authoring activities, was achieved by comparing the layout of the assets obtained on the digital model at the end of the task with the one of the reference products. This comparison is an estimation of the errors, by considering placement, rotation and scale values for all the 12 assets composing the packaging. These data are exported from the SPARK software inside a XML file. The evaluation of the overall interaction efficiency was carried out by measuring the amount of time spent completing the test condition and through analysis of participants' time partitioning (i.e. how the duration of each entire session was subdivided according to the different types of modification and interaction). The analysis of

⁵ www.maxelldisplay.com/products/projectors/installation-8000-series/mc-wu8601w-1 (accessed October 5, 2021)

⁶ www.unity.com (accessed October 5, 2021)

⁷ www.samsung.com/uk/tablets/galaxy-tab-s3-9-7-t825 (accessed October 5, 2021)

METRICS	DESCRIPTION	
Placement accuracy Rotation accuracy Scale accuracy	Distance error in canvas coordinates of each placed asset with respect to the target Rotation error of each placed asset around its pivot point with respect to the target Dimension error in canvas unit of each placed asset with respect to the target	
Time efficiency	Asset move	Total time used for changing the position of each asset placed on the mesh (single touch interaction)
	Asset rotate/scale	Total time used for changing the rotation and the dimension of each asset placed on the mesh (double touch interaction)
	View adjustment	Total time used for adjusting the visualization of the 3D model or the canvas displayed on the interaction device
	Colour adjustment	Total time used for the choice of the background colour of the mesh from the palette
	Prototype manipulation	Total time used for the physical manipulation of the mixed prototype and changing its position and/or orientation
	Remaining actions	The remaining time of the entire session used for interacting with the interface, looking to the mixed prototype and make comparison with the reference prototype
Action efficiency	Asset move	Amount of separated interactions for changing the position of each asset placed on the mesh (single touch interaction)
	Asset rotate/scale	Amount of separated interactions for changing the rotation and the dimension of each asset placed on the mesh (double touch interaction)
	Asset place	Amount of times a new asset is placed on the mesh
	Asset selection	Amount of times an asset already placed is selected
	View adjustment	Amount of times the visualization of the 3D model or the canvas is changed
	Colour adjustment	Amount of time the palette is opened for changing the mesh background colour
	Prototype manipulation	Amount of separated interactions with the mixed prototype for changing its position and/or orientation
	Environment change	Amount of times the working environment is changed between “Select part”, “Add asset” and “Edit asset”
Usability	Evaluation of the interface used during the test calculated by applying the metrics of the System Usability Score (SUS)	

Table 2: Metrics adopted for the assessment of the interfaces with details on the related data.

efficiency also includes the estimation of the quantity and types of action required by each condition for the completion of the task. These two aspects of the metrics were evaluated by elaborating 2 log files generated by the SPARK software. The first file contains the chronological list of all the events which occurred on the interface when the participants were working on the task. The data is organised in a text file and involved the recording of the following actions: continuous manipulations of the assets (position, rotation and scale); single interactions with the GUI elements related to the asset library (scrolling, selecting and filtering by tag) and to the assets already instantiated (selection, order of layer, swap and deletion); adjustments of the visualization (model orbit/zoom, canvas pan/zoom); manipulations of the background colour of the mesh. The second file is a CSV that contains the position and rotation values of the PM, streamed with a fixed time stamp by the tracking system, to identify the moments when the user interacts with the physical prototype.

Since the testing activity involved human factors, the users’ judgment is another fundamental parameter by which to evaluate the different interfaces. The perception of the usability of the system was assessed with the System Usability Scale (SUS) survey developed by Brooke (1986), which is widely used to quickly measure the “appropriateness to a purpose” of products, software and websites (Tullis & Albert, 2013). The survey is composed of 10 statements, five positives (e.g. “I think that I would use this system frequently”) and five negatives (e.g. “I found the system unnecessarily complex”), that are evaluated by means of a five-point Likert scale to produce a maximum score of 100. This overall usability value, together with the informal feedback gathered after the session, allows to delineate strengths and weaknesses of each interaction modality according to the feeling of the participants.

In this experiment, touch and multi-touch gestures were hypothesized to provide less precise interaction in comparison to more “indirect” user interfaces due to the so-called “fat finger” and “occlusion” problems (Albinsson & Zhai, 2003). For this reason, it is expected that the accuracy of the asset placement, rotation and scale would be lower in Conditions B1, B2 and B3 in comparison with Condition B4, which used a

495 mouse and keyboard for the interaction. Similarly, the necessity to be more focused on the interface and the presence of an additional mean that renders the packaging layout (i.e. the PM) can increase the time required to accomplish the task in the tablet conditions in comparison to the desktop one. On the other hand, a touch-screen interface should increase the engagement of the users so that the previous limitations do not excessively affect the perceived usability of the system.

6. Test results

500 This section analyses all the data collected during the testing activities and then post-processed according to the proposed metrics: accuracy, efficiency and usability. The statistical analysis follows a between-groups methodology with the eight groups obtained by dividing the sample according to the condition number and the treatment. Subdividing the first condition according to the treatment group also allows any influence of the subjects' capability in using the proposed authoring tool to be considered. Any trend on the accuracy, efficiency and usability data for the four groups performing in the first round of the test is useful to weight the results for the second. This means that, condition A, split into 4 subsets of subjects coherently with the distribution of B, can be used as baseline for the comparisons of the interfaces on which the current study is focused on.

6.1. Accuracy

510 Three different types of error are evaluated: position, rotation and scale. These errors relate to the definition of the final layout, which consists of two-dimensional images contained in the library. These errors are calculated individually for each asset as Euclidean, angular and dimensional differences between the result achieved at the end of the task and the reference values. Given the 41 participants, the two conditions performed and the 12 assets necessary to replicate the reference product, a total of 984 measures ($41 \times 2 \times 12$) were obtained for each error. Figure 7 presents the box-and-whiskers plots of the datasets, to visualise the

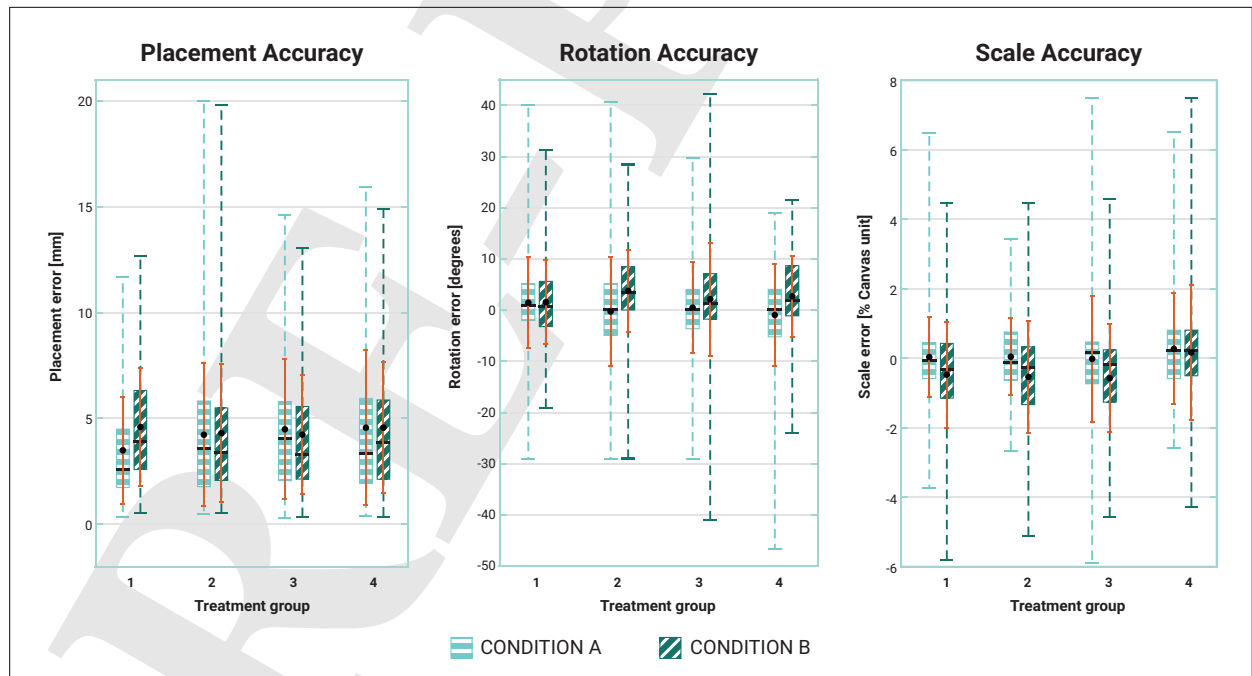


Figure 7: Boxplots representing the placement (left), rotation (middle) and scale (right) errors made by the users during the execution of the tests. These data are subdivided according to the two conditions (A and B) and the four different treatment groups (UV map, touch area, 3D view and desktop setup).

distribution by means of the quartiles (green line), as well as their mean values (black dot) and standard deviations (red line). From the graphs, it can be observed that the users, while performing touch conditions, had a higher tendency to rotate some degrees counter-clockwise and to undersize some percentage points for the assets with respect to the desktop-based interactions where the means were closer to the 0 and the quartiles were more symmetrical around the null value. This suggests the presence of systematic rotational and dimensional errors in B1, B2 and B3 where the designed output is rendered using PM. With a similar investigation on the placement errors, no significant trends can be observed by comparing the boxplots of groups belonging to different conditions and the same treatment or vice versa.

All the measured accuracy-related data have been grouped according to the conditions, A or B, and the treatment groups (1, 2, 3 or 4). Each of the eight groups were analysed to assess the normal distribution of error rates, with the 68-95-99.7% empirical rule, and to identify the presence of any outliers, with a confidence interval of $\mu \pm 2.9 \sigma$. Outliers were excluded from the sample due to their notable differences from the other data points. The new reduced samples were made positive to consider only the magnitude of the errors and then used to compute means, standard deviations and one-way analysis of variance (ANOVA), listed in Table 3.

	ERRORS TYPE					
	Position [mm]		Rotation [deg]		Scale [%]	
	M	STD	M	STD	M	STD
A1	3.12	(± 1.97)	4.71	(± 4.28)	0.61	(± 0.44)
B1	4.56	(± 2.77)	5.55	(± 4.97)	0.96	(± 0.86)
A2	3.93	(± 2.65)	6.85	(± 6.47)	0.89	(± 0.65)
B2	3.93	(± 2.58)	6.14	(± 5.05)	1.14	(± 1.09)
A3	4.20	(± 2.88)	4.93	(± 4.82)	0.75	(± 0.58)
B3	4.11	(± 2.69)	6.10	(± 5.45)	1.01	(± 1.02)
A4	4.31	(± 3.30)	6.11	(± 5.27)	0.82	(± 0.68)
B4	4.21	(± 2.57)	6.20	(± 5.53)	0.76	(± 0.64)
ANOVA	$F(7, 957) = 3.20$ $p = 0.00234$		$F(7, 940) = 2.01$ $p = 0.0519$		$F(7, 946) = 5.36$ $p \ll 0.001$	

Table 3: Statistical results (mean values and standard deviations) for the placement, rotation and scale accuracy measurements. The ANOVA p-values are highlighted to show when there is a statistically significant difference (horizontal green) or not (vertical red) between the groups.

By observing the mean values in Table 3, participants in the A1 group seem to have performed better in terms of position accuracy, whereas the A1 and A3 groups achieved higher accuracy in terms of defining the assets' scale. The remaining error means are equally distributed around 4 mm, 6 deg and 0.9 % for position, rotation and scale respectively, without significant variation between the groups. These statements are also confirmed by the ANOVA testing, which strongly suggests that one or more pairs of treatments are significantly different for the position and scale errors ($p_{position} < \alpha$ and $p_{scale} \ll \alpha$ where α is the cut-off value for significance assumed as 0.05) while the rotation values are only close to being statistically significant ($p_{rotation} > \alpha$). For this reason, a post-hoc Tukeys Honest Significant Difference (THSD) test with the Gleason (1999) algorithm has to be applied for each of the 28 pairs of the first two types of error to pinpoint which of them shows meaningful variation in terms of the mean. In detail, a statistically significant difference ($p < 0.05$) is obtained between the position error pairs A1-A3, A1-A4, A1-B1 and scale error pairs A1-B1, A1-B2, A1-B3, A3-B2, A4-B2.

6.2. Efficiency

The analysis of the efficiency metrics considers the time required by each user to perform the assigned task as well as its partition into the different types of action necessary to complete the activity. The total duration was estimated as the time which elapsed between the beginning, when the user received the reference product, and the end, when he/she pressed the save button, of the activity; the data were registered inside the application logs. The same files were also analysed to reconstruct the operations history

with a focus on: the definition of the background colour, the asset placement, orientation and dimension, the adjustment of the digital visualisation of the product layout (depending on the selected condition) and the manipulation of the PM. The method of combining the definition of the action, as available in the log, with an effective modification of the output layout allows those moments when the user is clicking/touching the interface, without causing any variation in the product appearance, to be designated. These events are distinguished from others since the focus of the participants at these times was not on the interface itself but on the layout of the reference product or the result rendered by the PM. All these events, together with the actions, which cannot be recorded because of their impulsive nature (e.g. single selections on the GUI elements), were collected under the caption “Remaining time” which is the total task duration subtracted from the previously allocated seconds.

With the two different testing conditions completed by all 41 subjects and about 4000 lines for each log file, a total of 106000 performed actions were analysed for the generation of the bar graphs in Figure 8 and Figure 9. Unlike the previous metric, none of the observations was removed from the analysis in order to ensure the minimum of 10 data items for each group required by statistical tests. Therefore, some of the results listed in Table 4 or Table 5 present relatively high standard deviations despite having similar means.

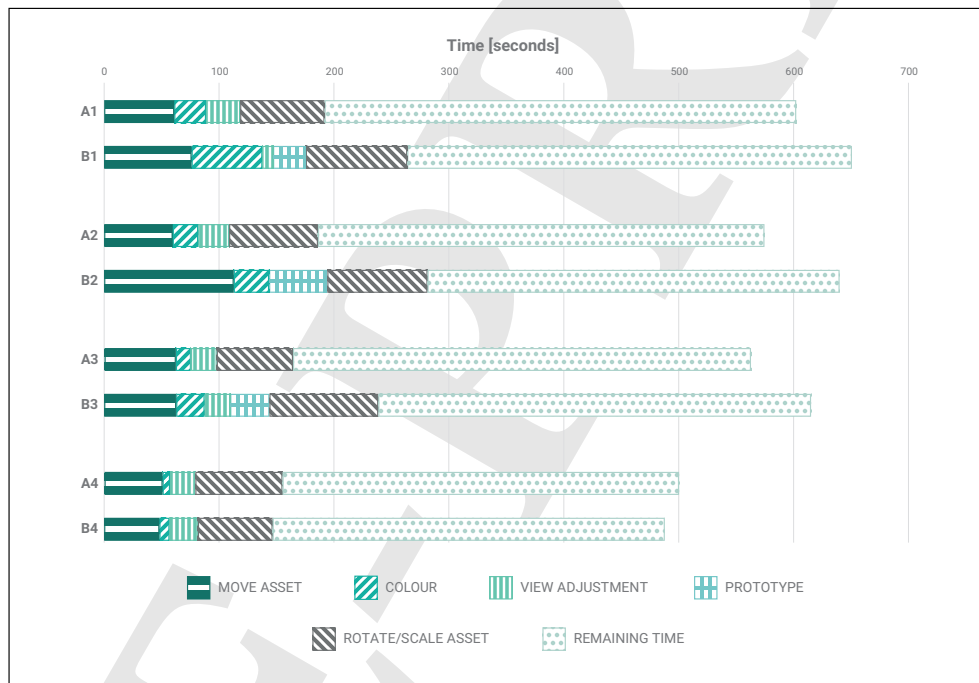


Figure 8: Bar chart representing the mean values for the total time required by each condition and sample group to complete the task. The length of each bar is subdivided with the mean values for time spent to perform all the recordable actions listed in the legend.

By considering the full length of the bars in Figure 8, it can be noticed that the same group of participants took an average of 50 seconds more to complete the assigned task when switching from the first condition to those based on touch interactions. This consideration is also proven by the correspondent ANOVA result, which suggests a low statistically significant variation ($p < 0.05$) even though the post-hoc THSD test does not reveal any difference in the means between the 28 pairs. A similar approach based on the post-hoc THSD test was also used to analyse the other portions of the graph that, with an ANOVA p-value lower than 0.01, suggested relevant differences between the groups in terms of the duration of the performed actions. Starting with the time required for assets positioning, there is a statistically significant decrease in the number of seconds when moving from the mean for B2 to the means for all the other groups based on both mouse and touch inputs (B2-A1, B2-A2, B2-A3, B2-A4, B2-B1, B2-B3 and B2-

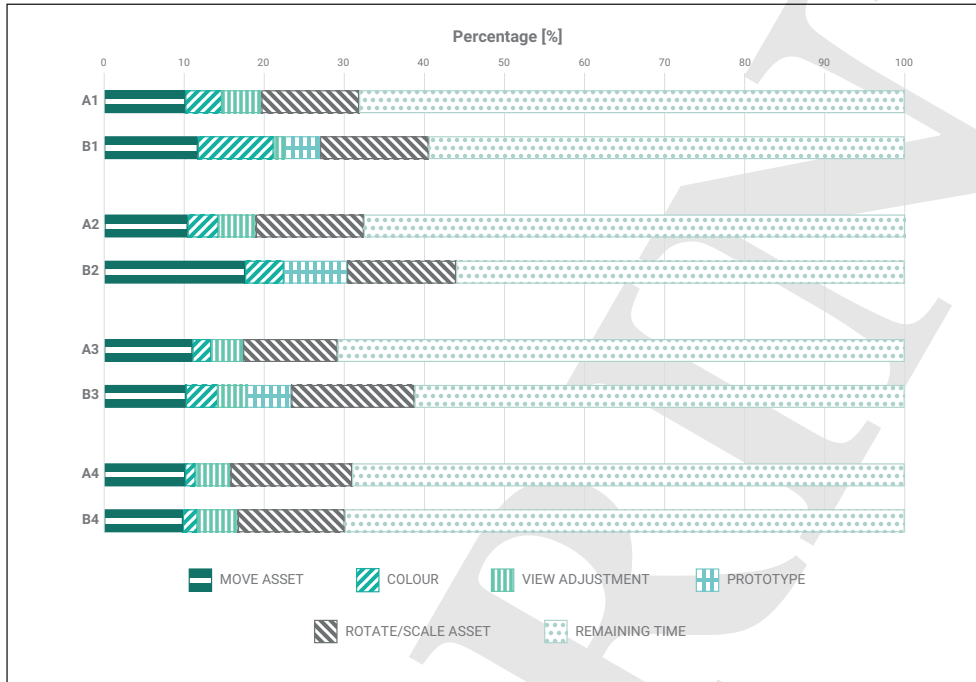


Figure 9: Bar chart representing the means for the percentages for the total task duration for the different recordable actions required during the execution of the activity (listed in the legend).

B4). The B1 group had, simultaneously, a lower and higher efficiency in comparison to the majority of the mouse-based interactions for the identification of the background colour (B1-A2, B1-A3, B1-A4, B1-B4) and the adjustment of the screen visualisation (B1-A1, B1-A2, B1-A3, B1-B4) respectively. Finally, no statistically significant differences are detected for the definition of the asset's rotation and scale, the tangible manipulation of the PM or the remaining time.

The absence of statistical differences in the total execution time between any of the pairs enables the analysis of the efficiency data from another perspective, which gives additional insights into the trends for the current metrics (Figure 9). In this case, the different portions of the bars, which correspond equally to the five measurable actions plus the residuals, are expressed as percentages of the task duration and are calculated as means of each single test according to the condition and treatment. By observing the values of Table 5, the percentages among the eight groups for the asset move, asset rotate/scale, screen view adjustment, background colour and the manipulation of the PM have similar trends with even more significant statistical differences of Table 4. This result increases the accuracy and the meaningfulness of the presented data by leading the research activity to stronger conclusions on the efficiency metrics. Many more different insights between the eight groups are discernible from the analysis, in terms of the quantity of the total task time taken by the remaining actions. The post-hoc test revealed a strong statistical difference in 12 pairs (all mouse vs. touch interaction) out of 28: A1-B1, A1-B2, A1-B3, A2-B1, A2-B2, A3-B1, A3-B3, A3-B3, A4-B1, A4-B2, B4-B1 and B4-B2. This means that a smaller percentage of the time available for the test was used when the interaction was based on touch gestures rather than when using the mouse.

A better understanding of the reasons why the different input interfaces and GUI layouts introduced efficiency variations is given by the analysis of the action-based data illustrated in Figure 10. The plot, based on bars corresponding to the results for each type of measurement, represents the first conditions as a single group (independent from the treatment) while the second conditions, with more relevant differences in terms of the quantity of actions performed, are kept separate. These mean values are obtained thanks to the elaboration of the log files, where a new action is supposed to end only when the next line refers to a different type of modification or interaction with the interface. A one-way ANOVA, along with the post-hoc

ACTIONS TYPE - DURATION [s]													
Asset move		Asset rotate/scale		Screen view adjusted		Background colour		Mixed prototype		Remaining time		Task execution	
M	STD	M	STD	M	STD	M	STD	M	STD	M	STD	M	STD
A1	61 (± 20)	73 (± 17)	30 (± 12)	28 (± 28)	—	410 (± 75)	602 (± 119)						
B1	76 (± 29)	88 (± 26)	9 (± 9)	62 (± 48)	29 (± 19)	387 (± 80)	651 (± 138)						
A2	60 (± 18)	77 (± 14)	27 (± 12)	22 (± 29)	—	389 (± 59)	575 (± 95)						
B2	113 (± 39)	87 (± 32)	—	31 (± 23)	51 (± 28)	359 (± 84)	640 (± 161)						
A3	62 (± 25)	66 (± 12)	22 (± 13)	13 (± 9)	—	399 (± 79)	563 (± 113)						
B3	63 (± 11)	95 (± 21)	22 (± 6)	25 (± 27)	34 (± 31)	377 (± 66)	615 (± 78)						
A4	51 (± 27)	76 (± 11)	22 (± 8)	6 (± 5)	—	345 (± 78)	500 (± 103)						
B4	48 (± 25)	65 (± 8)	25 (± 13)	9 (± 10)	—	319 (± 92)	488 (± 113)						
ANOVA	$F(7, 74) = 5.97$ $p \ll 0.001$	$F(7, 74) = 2.41$ $p = 0.029$	$F(6, 64) = 4.95$ $p = 0.0004$	$F(7, 74) = 3.69$ $p = 0.0020$	$F(2, 30) = 2.08$ $p = 0.144$	$F(7, 74) = 1.22$ $p = 0.303$	$F(7, 74) = 2.59$ $p = 0.0191$						

Table 4: Statistical results (mean values and standard deviations) for the time-related efficiency measurements expressed in term of action duration. The ANOVA p-values are highlighted to show when there is a high (horizontal green), low (oblique yellow) or null (vertical red) statistically significant difference between the groups.

ACTIONS TYPE - PARTITION [%]													
Asset move		Asset rotate/scale		Screen view adjusted		Background colour		Mixed prototype		Remaining time			
M	STD	M	STD	M	STD	M	STD	M	STD	M	STD		
A1	10.3 (± 3.1)	12.3 (± 2.1)	4.9 (± 1.7)	4.1 (± 3.8)	—	68.4 (± 3.7)							
B1	11.6 (± 3.3)	13.6 (± 3.4)	1.4 (± 1.3)	9.1 (± 6.5)	4.5 (± 2.6)	59.8 (± 5.9)							
A2	10.2 (± 1.9)	13.6 (± 2.0)	4.7 (± 2.3)	3.6 (± 4.1)	—	67.9 (± 4.0)							
B2	17.5 (± 2.6)	13.6 (± 3.3)	—	4.6 (± 2.7)	7.8 (± 3.2)	56.5 (± 7.0)							
A3	10.9 (± 3.8)	11.9 (± 1.4)	3.8 (± 1.8)	2.4 (± 1.5)	—	71.0 (± 3.4)							
B3	10.4 (± 2.4)	15.5 (± 3.7)	3.7 (± 1.1)	3.8 (± 3.7)	5.6 (± 5.1)	61.0 (± 5.6)							
A4	9.9 (± 4.0)	15.4 (± 2.0)	4.5 (± 1.5)	1.2 (± 0.8)	—	69.0 (± 4.6)							
B4	10.3 (± 4.1)	14.7 (± 3.6)	5.2 (± 1.9)	1.6 (± 1.6)	—	68.2 (± 5.0)							
ANOVA	$F(7, 74) = 6.26$ $p \ll 0.001$	$F(7, 74) = 1.93$ $p = 0.078$	$F(6, 64) = 6.19$ $p \ll 0.001$	$F(7, 74) = 3.93$ $p = 0.0012$	$F(2, 30) = 2.31$ $p = 0.118$	$F(7, 74) = 10.51$ $p \ll 0.001$							

Table 5: Statistical results (mean values and standard deviations) for the time-related efficiency measurements expressed in terms of percentage for each action of total task duration. The ANOVA p-values are highlighted to show when there is a high (horizontal green) or null (vertical red) statistically significant difference between the groups.

600 THSD test, was performed to gain further insights. Some of the means are almost equivalent between the groups and, thanks to their small standard deviations, these are excluded from the discussion. These actions, without dependency on the interface or the type of interaction, are related to the number of times (i) a new image is added or confirmed on the mesh, (ii) the background colour of the mesh is modified, (iii) the working environment is changed between the add and edit asset, (iv) the PM is physically manipulated and (v) the visualisation of the virtual object is orbited. The most noticeable difference is in relation to the number of operations necessary to manipulate the assets (move/rotate/scale); these are more than doubled in Condition B2 in comparison to the others. This is also confirmed by the high statistical significance of the ANOVA ($F(7, 74) = 39.0$ for move and $F(7, 74) = 33.8$ for rotate/scale with $p \ll 0.01$ in both) and by the paired group highlighted in the post-hoc test (A1-B2, A2-B2, A3-B2, A4-B2, B1-B2, B3-B2 and B4-B2). 605 The greater number of repeated interactions is a consequence of the physical distance between the position of the finger on the screen and the selected asset on the PM as well as the fact that it was impossible to select a specific point on the mesh on which to instantiate the assets. With the touch area, there is not a 1:1 scale that links the input touch with the output visualisation and the user always has to move each new asset from the position established by the orientation of the PM to the desired one. Even for the variation in the actions related to the selection/deselection of the images, there is a significant difference for B1 and B2 in comparison to the other groups ($F(7, 74) = 8.74$, $p \ll 0.01$). This is a consequence of a higher risk of accidentally pointing to an area of the 3D model or canvas where another asset is already placed and selecting it with the touch-based interfaces. Nevertheless, in the touch area group, this drawback is drastically reduced since an asset to be modified has to be chosen from a scrolling list. 615

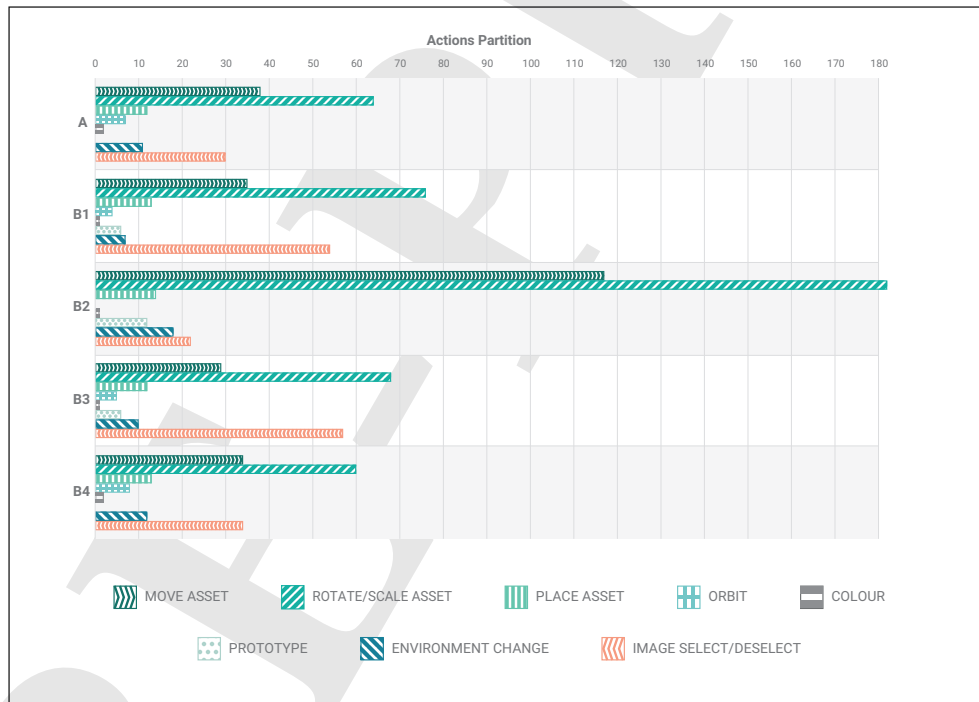


Figure 10: Bar chart representing the mean values for the number of different actions performed by the users to complete the task. These operations, listed in the legend below, are subdivided according to the relative test condition (Condition A is grouped due to a small variation between each treatment group).

620 6.3. Usability

As described in Section 5.4, the SUS survey was used to assess the users' perception of the usability of the interfaces. Since the same questionnaire was filled in by all the subjects twice, one for each session,

a total of 82 completed questionnaires were collected. The answers were scored and then compiled into a single value in order to obtain a meaningful measure for overall usability. The results of this post-process are presented in Figure 11 along with an adjective grade (i.e. "Best imaginable" if above 90.9, "Excellent" if between 90.9 and 85.5, "Good" if between 85.5 and 71.9, "OK" if between 71.9 and 50.9, "Poor" if below 50.9) based on the recommendations of Bangor et al. (2009). As for the previous metrics, the usability results are grouped according to the condition and treatment to calculate the mean values and the standard deviations described in Table 6. Due to the high dispersion of some groups, the same table also presents the distribution of the scores along with the four qualitative ranges, as previously defined. This allows any difference between them to be better highlighted and the necessary conclusions to be derived.

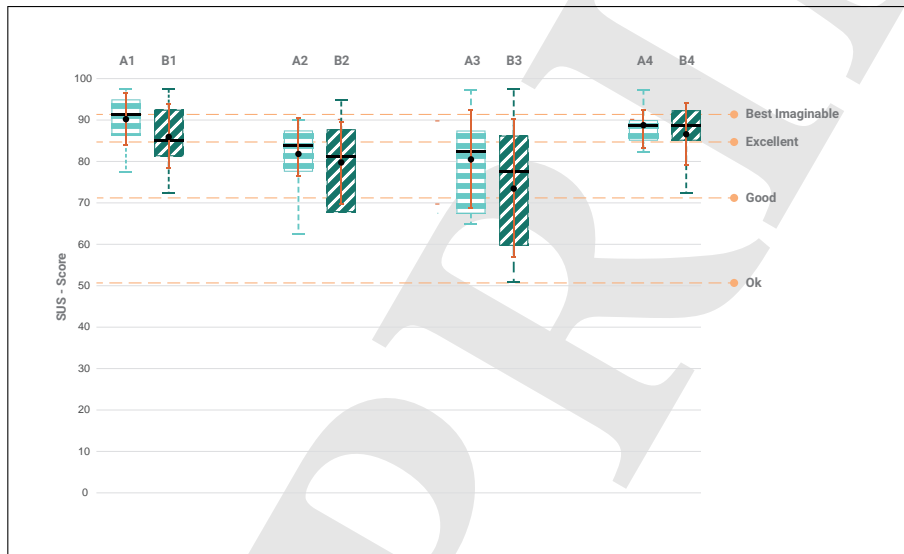


Figure 11: Boxplots representing the usability scores. These data are obtained by applying the metrics of the SUS survey completed by all the users at the end of each condition.

The data, analysed by means of the one-way ANOVA followed by the post-hoc THSD test, indicate a statistically significant difference only with the pair A1-B3, which is the one with the highest and lowest mean respectively. This variation between two groups with different participants does not allow for any relevant insights to be ascertained about the perceived usability of the SPARK system in comparison to the desktop setup or the three multi-touch interface layouts. For this reason, it is necessary to examine the distribution of the scores among the different ranges defined by the adjective categories. Considering only the touch-based conditions, it is possible to note that: (i) Condition B1 has more than half of its scores allocated to the "Good" range while the remainder scored "Excellent" and "Best imaginable"; (ii) Condition B2 has 70% of its scores equally distributed in the "Good" and "OK" ranges; (iii) Condition B3 has almost half of its perceived usability scores in the "OK" range while only 20% are equal to or above "Excellent". This translation towards the lower levels of the SUS registered in the different treatment groups for the second condition is partially justified by a similar trend in the first one. Moving from A1 to A3 passing through A2, in fact, there is a reduction in scores in the top two grades (75% in A1, 40% in A2 and 30% in A3) and a consequent growth in the last two levels of the scale with a positive attribution (25% in A1, 60% in A2 and 70% in A3). Moreover, the slight reduction in the means in the touch conditions compared to the corresponding desktop-based setups is due to the significantly lower scores obtained for question numbers 1, 8 and 9. Users, in fact, required more information to understand how to interact with the PM, which is a novelty in comparison to the other interface. On the other hand, only the questions number 4 and 10, which relate to the learnability as suggested by Lewis & Sauro (2009), revealed a slight improvement over the mouse-based input system.

	SUS FINAL SCORE		ADJECTIVE GRADE DISTRIBUTION			
	M	STD	Best imaginable	Excellent	Good	OK
A1	90.2	(± 6.17)	50 %	25 %	25 %	0 %
B1	86.0	(± 7.87)	25 %	20 %	55 %	0 %
A2	81.8	(± 8.42)	0 %	40 %	50 %	10 %
B2	79.8	(± 10.03)	10 %	20 %	40 %	30 %
A3	80.6	(± 12.04)	20 %	10 %	35 %	35 %
B3	73.3	(± 16.95)	10 %	10 %	35 %	45 %
A4	88.8	(± 5.18)	15 %	50 %	35 %	0 %
B4	86.7	(± 7.52)	35 %	35 %	30 %	0 %
ANOVA	$F(7, 74) = 2.92$ $p = 0.01002$					

Table 6: Statistical results (mean values and standard deviations) for the SUS scores and their distribution according to four different adjective grades. The ANOVA p-value is highlighted in horizontal green to indicate that there is a statistically significant difference between the groups.

7. Discussion

The current study aims to validate a UI running on a touchscreen for SAR-based authoring applications. An experimental activity was carried out involving a sample of 41 subjects and the adoption of three different GUI and interaction modalities: 3D rendering of the prototype model, 2D unwrap of the prototype mesh according to the UV map and an empty touch area. These represent interaction modalities where the visualization of the PM is increasingly important (from its exact digital copy to its complete absence). The results achieved by the users while using the three GUI configurations were analysed according to the accuracy, efficiency and usability metrics. Moreover, a condition involving a desktop setup was included to define the reference values for each measurement and to estimate the impact of a learning effect on task repetitiveness.

The overall analysis of the data from the accuracy metrics reveals that none of the three proposed touch-based interaction modalities outperformed the others. This proves that all the interfaces can be used to achieve a similar precision in terms of asset manipulation. Apart from the position and scale errors in the first treatment group, none of the pairs from the same sample of participants shows a significant reduction in accuracy when switching from a mouse to the touch-based setup. The two exceptions in this case were primarily due to the high accuracy of the first condition rather than the low quality of the second, as demonstrated by the statistical difference between pairs using the same setup.

The data from the efficiency metrics was analysed to establish, for each treatment group, the duration of the task and the actions performed. In general, there is not a statistically significant effect on the total activity duration between the three touch interfaces, but they differ in terms of the manipulation of assets, virtual model and PM, as was predictable given the type of visualisation they provide. The UV map (B1) simplifies the interaction with the digital contents (apart from for the selection of background colour) and reduces the need to adjust the visualisation. The touch area (B2) makes the interaction with the PM and the correct definition of the asset location more challenging but it avoids any manipulation of a virtual model. Finally, the 3D model (B3) requires more time to be spent on the camera orbit to place the faces of the virtual object in a way which is suitable for the interaction.

The analysis of the usability data shows strong similarities between the groups in terms of the users' personal evaluations. The presence of the PM during the execution of the task is twofold: it improved the user's engagement and the learnability of the touch interfaces but failed to simplify the users' understanding of the interaction modalities. Being a new means to present the product appearance, the PM was wrongly perceived as a fragile or unstable object in terms of natural interaction and for this reason, many of the users limited their frequency of physical manipulation.

Finally, the almost identical results achieved by the two conditions in the fourth treatment group (A4 and B4) strongly validate the correctness of all the measurements by revealing the absence of learning effects

due to the execution of the task for a second time.

7.1. Exploration of the main findings

The experimental activity described in this paper reveals that different types of interface and visualisation layouts can be beneficially used, together with the PM generated by a SAR platform, to perform tasks where the objective is the manipulation of the external appearance of an object. Each of the three proposed interfaces based on touch interactions have some intrinsic advantages and drawbacks, but they ensure similar efficiency, accuracy and usability results in comparison to desktop setups. In the sections which follow, all the relevant outcomes of the tests are presented to answer the three research questions introduced in Section 3. The discussion of the main findings of the research is further enriched by feedback gathered from informal interviews with the participants at the end of each experiment.

Research Question 1

The PM can be considered a valuable means to represent the outputs generated during the execution of authoring tasks. Users were able to accurately replicate the graphical layout even with the touch area view, which does not include any additional visualizer. The absence of any other visual feedback makes the quality of the projected images crucial since they have to augment the physical object perfectly. Any error introduced by the calibration procedure of the hardware integrated in the SPARK system can cause small misalignments in the digital contents in relation to the target surfaces and thus cause users to wrongly interpret the modifications they make to the product layout. On the other hand, the trackpad simulation version (B2) makes the users' workflow less fluent while defining the asset placement, orientation and dimensions resulting in a larger amount of time spent and number of actions performed in comparison to the UV map (B1) and the 3D view (B3). Moreover, the need to switch between two editing modalities (add/edit asset) for the already instantiated images has a considerable effect on the total task duration. However, it mitigates accidental modifications of other images that are always visible.

Research Question 2

If the development of the SPARK system, or a peculiar type of task, requires users to be provided with some visual information on the tablet screen, the performed testing activity reveals that complementary visualisations of the PM are more effective than the redundant ones. The effectiveness and ease of the interaction of SPARK are preferred in comparison to the high-quality rendering of the prototype proposed in the GUI (B3). The high realism of the PM while displaying the current layout, allows the adoption of visualisations that are generally more appropriate for professionals with a high level of experience thanks to the schematisation of the 3D model as a two-dimensional canvas. This is confirmed by the comparison of the efficiency and usability results for the touch-based tasks performed with the interface set on the UV map view (B1) and the 3D model view (B3). The first has the highest mean value for the perceived usability of the three conditions, due to the simultaneous visualisation of all the faces of the mesh, the reference of the 3D model outline for asset manipulation and the direct relationship between the planar motion of the fingers on the screen and the assets on the canvas. These three features find some correspondence with the shorter time and number of actions needed for the adjustment of the visualisation. The 3D view, in fact, is perceived as the least usable interface among those proposed due to the greater difficulty encountered by the users in rotating the 3D virtual model on the touch display so that the desired side of the mesh is correctly oriented. This aspect becomes even more crucial if the authoring activity is performed on objects with complex shapes and/or small faces that require a continuous orbit of the render camera.

Research Question 3

The PM, and the whole architecture of the SPARK system, had a significant impact on users' performances when coupled with a tablet device. In terms of accuracy, the results of the test demonstrate that the touch-based interaction is no less precise than the mouse as stated by the majority of previous studies focused on benchmarking the two input systems. Since the PM is the variable that differs from those studies, it can be assumed that its presence increases the user's perception when defining the position, orientation

and scale of an image onto the three-dimensional surface of a model. This statement has even more relevance when looking at the distribution of the accuracy results for B1, B2 and B3 which are not as close to the null value as the first condition but are affected by systematic errors. These inaccuracies, even if almost negligible, are caused by the non-perfect alignment of the physical and digital counterparts which make up the PM. In terms of efficiency, there is an average increase in the test execution time, above the reference limit of 10 minutes, in the touch-based conditions. The presence of the PM, together with the reference object and the tablet screen forced the participants to observe three distinct elements when performing the task. In terms of usability, the PM was perceived as a novel factor that improved engagement with the activity but also an element requiring additional training.

7.2. Generalisation of the outcomes

The outcomes of the testing activity might be helpful for researchers interested in developing interactive SAR systems where the focus is to work effectively on the external appearance of a physical object augmented by projections. All the recommendations derived from the quantification of the variations occurring in the metrics rely on the important presence of the PM itself. The latter, behaving as the actual display of the current layout state, enables the two complementary elements of the communication to be split between the human and the computer: the input and the output. For this reason, it is possible to completely re-define what is displayed on the interface screen, in contrast to the common software layouts, to improve specific features or functionalities. Touch and multi-touch gestures achieved the accuracy and efficiency of more diffused and solid input devices (like a mouse and keyboard) without affecting the visualization of the real output of the SAR technology. Moreover, the results in Section 6 demonstrate that it is not necessary to duplicate what is already rendered by the PM, and the touch screen can display the information according to the specific design activity, the role and quantity of participants, the dimension and shape of the product and so on.

8. Conclusions

The experiment described in this paper investigates the performance and perceived usability of three different user interfaces, based on a multi-touch tablet device, to visualise and manipulate digital contents with SPARK, a SAR-based design application. Three novel UIs (B1-B2-B3) were compared in a controlled environment against a standard desktop setup (A-B4) without the use of the PM, to highlight any differences in terms of accuracy, efficiency and perceived usability. The results discussed in Section 7, demonstrate high similarities with a standard desktop system in terms of accuracy and efficiency but do show how the new UIs took advantage of the real-time visualisation provided by the PM. The usability metric was lowest for the 3D view condition due to the extensive work required to adjust the visualisation and the redundant information included which was not appropriate for the execution of the task. Conversely, the UV map view condition was better received for its usability since it can render the entire layout of the packaging in one view, as well as simplifying the link between input movement and output modification.

The standard desktop system was expected to exceed the multi-touch interface device in terms of perceived usability and this result was confirmed by the SUS score results. However, the multi-touch interface, together with the use of the PM, performed as well as the desktop system in terms of accuracy and efficiency, and may offer further advantages when combined with future SAR systems that, for technical or contextual reasons, cannot be integrated with a standard desktop system. For example, a multi-touch device offers the use of common finger gestures and it can be easily scaled for collaborative contexts where multiple tablet devices or a single wider touch screen could be operated simultaneously by a group of users to make modifications to the PM. Such set-ups would allow future investigations on the dynamics of collaboration between users and their interaction with a SAR system.

8.1. Future research directions

Due to the unique investigation of the relationship between the interaction system and SAR technology, the current paper opens the way for research in multiple directions on both the development of advanced

780 editing features and validation in different scenarios. An example would be understanding the extent to which
performance results are affected by scaling up the dimensions of the display surface, a function necessary to
enable the platform in collaborative scenarios, or when more than one person is performing an authoring
task using the same device. In both those cases, there may be subsequent effects on the PM since it could
be placed far from the observers and the interactive area, or it could be occluded by the presence of users.
785 Another possibility for future research would be defining new interaction paradigms for different types of
digital contents, by looking at the design workflow in a SAR environment such as this one. A hybrid input
system - where the touch paradigm is coupled with gestures or tangible tools - could be designed with the
aim of fostering simultaneous collaborations or engaging the participation of non-experts. Such a system
could then be evaluated using suitable testing activities such as those used in this research. Of course,
790 any of these advancements must also be evaluated by real experts working on realistic design projects to
understand if the confirmed advantages of these technologies are strong enough to overcome the obvious
resistance to changing their traditional design workflow. Finally, another branch of development relates to
the assessment of SPARK for remote collaboration. This does not simply imply analysis of the interface
functionalities or management of the roles between two remote setups, but also how the communication
795 channels between the actors vary from those in a co-located scenario.

CRediT authorship contribution statement

Federico Morosi: Conceptualization; Data curation; Formal analysis; Investigation; Methodology;
Software; Validation; Visualization; Writing - original draft; Writing - review & editing; **Iacopo Carli:** Data
curation; Investigation; Visualization; Writing - original draft; **Giandomenico Caruso:** Conceptualization;
800 Supervision; Writing - review & editing; **Gaetano Cascini:** Conceptualization; Funding acquisition; Project
administration; Resources; Supervision; Writing - review & editing; **Elies Dekoninck:** Conceptualization;
Supervision; Writing - review & editing; **Jean-François Boujut:** Conceptualization; Supervision; Writing
- review & editing;

Declaration of Competing Interest

805 The authors declare that they have no known competing financial interests or personal relationships that
could have appeared to influence the work reported in this paper.

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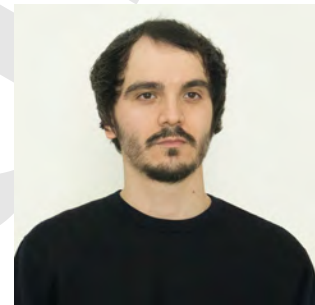
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