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Challenges and opportunities in combining physicalization with augmented reality: an exploratory case.

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Abstract: Data is the new "natural resource" of the 21st century. Recent years have witnessed its rapid expansion, increasing the production and availability of data. In this context, there are still significant challenges to fully realizing its potential, especially to make it accessible and more useful to the larger public. Considering design as an activity of cultural mediation and since "data has no naturally corresponding form", we detail the process and challenges involved in combining different artifacts to support data visualization and exploration. "GRAC" combines a physicalization (physical object embedded with data) with an augmented reality application, enabling users to explore two datasets related to design education and design companies in Portugal. The artifact was tested with 21 people at the DesignOBS exhibition of the Faculty of Fine Arts of Lisbon and Porto. Based on participants' feedback, we draw design implications for artifact integration; and propose future research directions.

Keywords: information visualization, augmented reality, physicalization, research through design

1. Introduction

The rapidly changing context of artificial intelligence (i.e. big data, open data, augmented reality), has put the production and use of data at the forefront of innovation (Morelli et al., 2017; Buchanan 2019; Verganti et al., 2021). Since "data has no naturally corresponding form" (Dulake & Gwilt, 2017) it represents a potential opportunity for the exploration/affirmation of the role of design as a "cultural mediator" in these emerging contexts - where the exploration of interface (between people, functionality, needs and desires), symbolic construction, aesthetics and experience is of vital importance (Branco & Providência, 2018).

In design research, studies exploring the role of design in data, through digital medium, and/or physical objects, already exist. For instance, the work of Ishii & Ullmer glass bottles (Ishii & Ullmer 1997); Pierre Dragicevic and Yvonne Jansen 250 collection of data driven objects (dataphys.org/list/);

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or Whitelaw (2010) 3D printed drinking beaker based on 150 year of temperature data from Sydney, are some of the most common examples that use design to non-verbally communicate about data through physical objects (i.e. physicalizations, according to Jansen et al., 2015). In the field of information design, visual metaphors, forms/shapes, colors, numerical information were integrated through multiple practices (illustration, graphic design, cartoonist, information design) to provide a semantic layer that facilitates data interpretation, making certain ideas about specific datasets more accessible for non-expert publics (Costa et al., 2022). More recently, other digital techniques such as Augmented Reality (AR) have multiplied the possibilities for data visualization, going from conceptual to more exploratory narratives (Marques et al., 2023).

These cases constitute an important backbone of data visualization and interpretation; demonstrating the rich design-enabled ways of materializing data, through different forms, colors, textures; and even metaphors. Despite this, most design studies focus on designing and developing one certain type of data-driven artifact (physical/digital). While there is extensive literature on the design process to develop "physicalizations" (physical artifacts whose geometry or material properties encode data, Jansen et al., 2015) or infographic materials, the challenges of designing at the intersection of different media is still quite unrecorded.

With these challenges in mind, we use datasets from the DesignOBS project (www.designobs.pt) to produce two artifacts: a physicalization about design education and a digital object about design companies, developed through augmented reality. The paper details the design process followed, the challenges experienced of designing for combined objects; and points to future research directions in this area.

2. Literature review

2.1 Embedding data in physical artifacts

Physical representations of data help people think about, explore and share data (Jansen et al., 2015). The idea of turning data into physical artifacts is not new. Physicalizations, for instance, are defined as "physical artifacts whose geometry and/or material properties encode data" (Jansen et al., 2015). They have been used for thousands of years to collect and store quantitative data (e.g. dataphys.org/list/), leveraging perceptual exploration skills; making data more accessible, with the potential to benefit cognition and learning; as well as engaging people and larger audiences (Jansen et al., 2015). They also offer perceptual, cognitive, communicative value that neither paper nor computer displays may be able to offer.

Technological advances in digital fabrication, tangible user interfaces, programmable matter; and user interfaces, however, have radically changed the way with which data can be made physical. Designers have used this new material to create data sculptures, using scale, colors and/or different materials to convey information – expanding perception, and enabling a more integrated experience of data (Gwilt, O'Dubhghaill, & Sano, 2013). Other physicalizations have been used to emphasize certain messages, increase persuading power during presentations (e.g. tinyurl.com/roslingBox); or to manually update information about production lines in factory floors (e.g. lego-based board from General Motors). However, these physicalizations are mostly static; and can be difficult to read by users since data points are embedded within the object (Jansen et al., 2015). Certain physicalizations include "dynamic display" of information which for instance can be made through the reconfigurability of modular pieces (e.g. switch datasets to physicalize dynamic data; or to get different perspectives on the same dataset), but this can be restrictive. Other studies have already explored how the use of digital fabrication technologies (e.g.3D printing) can be more accessible to

develop these objects within shorter timeframes, developing objects closer to 2D configurations and graphs (Swaminathan et al., 2014). Although useful, these studies still do not take full advantage of the most recent data visualization technologies such as Augmented Reality; nor explore/detail how the integration of physicalization and these new digital interfaces should be undertaken.

2.2 Augmented Reality for data visualization

Augmented reality (AR) is a technology that provides an immersive experience for data exploration and analysis (Chandler et al., 2015). Individualized AR in particular uses head mounted displays or mobile devices to overlay virtual content in objects, places or persons present in the physical world, offering an augmented perspective of an object to a single individual (Satriadi et al., 2022).

Attaching a virtual experience to a physical location (reference point) recovers the importance of the physical presence of the visited object/artifact, which has been lost with the era of "technical reproducibility" (Benjamin, 2012). For Benjamin, the importance of the location of the artwork is related to its aura, which is a unique and irreproducible quality that results from its original context. The loss of aura, in turn, is a consequence of technical reproducibility, which turns the artwork into a commodity that is decontextualized (whose copy can exist outside its original context). In this kind of combination between the physical and the virtual world, the full experience only happens in the presence of the physical referent.

One of the most popular applications of this type of technology embeds information into historical places, as exemplified by the 5G Roman Baths AR app (BBC Research & Development, 2019) which simulates the reconstruction of the Roman Baths ruins (England) or the Heritage Within project (Heritage Within, 2020) that virtually extends and reconstructs the Archaeological Museum of Carmo (Portugal).

By contrast, little research has been conducted on using individualized AR visualization onto physical objects developed for data visualization as existing literature about physicalizations with AR is quite recent (Satriadi et al., 2022). In a recent survey undertaken by Djavaherpour et al. (2021), only 3/141 projects with these characteristics were identified. Although useful, these references do not deal with data visualization specifically, but on scientific visualization which deals with physically based data (Gillet et al., 2004; 2005; Nittala et al., 2015). Experiments rehearsing the combination of physicalization with the use of AR to represent information are still scarce and this presents a set of opportunities for design whose action entails imagining the new, and creating meaning through the cultural mediation of technology (Branco & Providência, 2018). Moreover, the use, exploration and appropriation of this technology is still being developed by designers, thus empirical studies are still much needed.

Studies mentioned by Djavaherpour et al. (2021) constitute the first steps of artifact integration (physical with digital), which have so far addressed scientific visualization. It is necessary to investigate other domains of visualization, namely data visualization which covers the representation of quantitative data.

2.3 The case of DesignOBS

Following the research challenges above mentioned, this study focuses on exploring two datasets about key vectors of the Portuguese nacional design ecosystem, namely, design education and design companies, using a research through design approach. While Costa et al. (2021; 2022) explored these datasets using information visualization techniques and a participatory approach with design students and design professionals to represent data in 2D infographic posters, this study goes one step ahead, combining physical and digital artifacts to support data exploration and interpretation.

The datasets were created within the DesignOBS project (www.designobs.pt) which aims to collect, map and represent data about design in the Portuguese territory, following existing observation models used in Europe (Whicher et al., 2018). Both datasets contain multiple variables that characterize the "design education" and "design companies". In particular, "design education" contains information about design schools, degree level (i.e. bachelor, master, PhD); design area (e.g. industrial design, communication design); number of graduates between the years 2002 to 2020, and geographical location. Additionally, the "design companies" dataset contains information about the number of companies with code 74.10 (design activity), turnover, employees and staff costs, by geographical location.

3. Methodology

The development and combination of the artifacts to support data interpretation followed two major iterative stages, combining the guidelines proposed by Fallman (2008) and Forlizzi et al. (2008) to design, develop and test artifacts:

i) building new artifact(s): The first activity aimed to identify opportunities for the creation of knowledge that is important for the construction of design theory and that is relevant for design practice. This research focused on exploring how the combination of physical and digital artifacts can better support data exploration and interpretation. While physicalizations have already been combined with 2D and 3D applications (Swaminathan et al., 2014), there are still few empirical studies that provide guidelines for designers to combine and take more advantage of these different types of medium. Building on top of existing knowledge on information visualization, physicalization, as well as augmented reality, the researchers created GRAC (name which combines "graduates" and "companies"): a physical wooden-based object with an augmented reality application. It follows the stages of the design process, going iteratively through (1) data exploration and analysis; (2) information and material selection; (3) design and development; (4) test and reflection. These stages are detailed in the next section.

ii) reflection about the artifact(s): To reflect about the artifact in a real-world application, GRAC was integrated in the exhibition "Towards a Design Observatory in Portugal - situation", at the Gallery of the Faculty of Fine Arts of the University of Lisbon between the 3rd and 10th of December 2021, where it was tested by 21 visitors. User feedback was collected through the "thinking aloud" method (Nielsen, 2012), a user experience test in which participants are asked to interact with systems while verbalizing their thoughts aloud, in a continuous monologue. Moreover, tests were preceded by a brief presentation of the study being conducted; request to sign an informed consent to record audio and sociodemographic characterization form; and a contextualization about DesignOBS project.

The research involved the collection of two types of data: audio recording and participant observation with field notes. Observations focused on exploring how people engage in data exploration with the artifact(s). Besides time and error metrics that could help enhance GRAC technicalities and design (e.g. changing colours, increasing the size of buttons), other insights were captured during these experiments, to understand to what extent these artifacts promoted other types of interactive and aesthetic experiences.

The audio records were transcribed and analysed in Atlas.ti software, following the guidelines proposed by Charmaz (2014) a process which involved qualitative data analysis through thematic coding. On average, each experience lasted for 15 minutes. Initial codes emerged from the data, and then shared and discussed amongst the coauthors during joint sessions, and online, via the collaborative Atlas.ti web platform, built to enable more efficient iterations of the emerging codes and thematic descriptions.

4. The birth of GRAC

The development of the physical object followed four major stages of the design process, going iteratively through (1) data exploration and analysis; (2) information and material selection; (3) design and development; (4) test and reflection (Fig1). These stages have already been depicted in another exercise with design students, to support the design of infographic posters (Costa et al., 2021), but have not been applied for the design and development of a physicalization with an augmented reality application.

First, data exploration and analysis, included the application of multiple software/tools e.g. excel, tableau and/or rawgraph (online visualization tools) and data thinkering (Costa et al., 2021) to understand and discuss about the available data. A first portray of each dataset was undertaken to select and understand which information to select from the two datasets about design graduates and companies (e.g. how/where are design graduates located through time). This analysis and iterative reflection was undertaken between the co-authors in regular meetings and captured in an internal report.

Second, because the artifacts are the combination of two datasets with different types of information, the authors decided to select similar types of variables, to enable overlap and comparison. Thus, two specific equal variables were identified: geographical location; and time (year). Hence, the artifacts combined would provide a representation of the evolution of the number of graduates and companies through time, and per geographical location.

Third, the preliminary sketches about the shape to represent the evolution design graduates through time were undertaken iteratively by hand/drawing and 3D modeling techniques. Several shapes were tested: from cones, to pines, columns and lines – while also considering the overlap between two layers of information (number of graduates versus design companies), which would be undertaken with different media (physical versus digital). Since the proportion of certain NUT regions were quite abrupt (Portugal has 7 NUTs regions), providing little to no exploratory potential, the research team decided to maintain a more detailed view of the data, including 20 districts in the artifact.

Early physical prototypes were developed, first, with paper; then with styrofoam, to try different sizes, analyse proportions while considering the lowest cost for testing and development; and have sufficient elements to start the digital development of the augmented reality application (next section). In parallel to these design decisions, other contextual variables had to be considered, namely, the space in which the artifact would be displayed. The exhibition “Towards a design observatory in Portugal – situation” was going to be undertaken in, at least, two different places with different light, and architectural conditions (Faculty of Fine Arts of Lisbon University; and of Porto University) which would affect the perception of both the physical and digital artifacts (e.g. shadows of the physical object; or the correct functioning of the digital application). Additionally, the GRAC artifact was embedded within the exhibition with other infographic materials, thus the storyline and location of the object would have to be considered.

This brought additional challenges and restrictions to the physical object in terms of size. If too small, the physical object could become “lost” in the exhibition; while, if too big, it could become impossible to display in both places. In parallel to size and proportion, the choice of material was also subject of discussion. The size of the object was defined to be a 1x1m object to ease transportation, installation and to still enable an effective interaction with the AR application. The material was changed from styrofoam to pinewood (a lighter material, pleasant to see, and touch); and the shape also was iterated several times, to explore different visualization potential (e.g. from curved lines to removable blocks, to enable the reconfiguration of the physical form) (see Fig.1) in a recycled

plywood material base. The years as well as the first piece of wood (year 2015) was laser engraved with the name of the district.

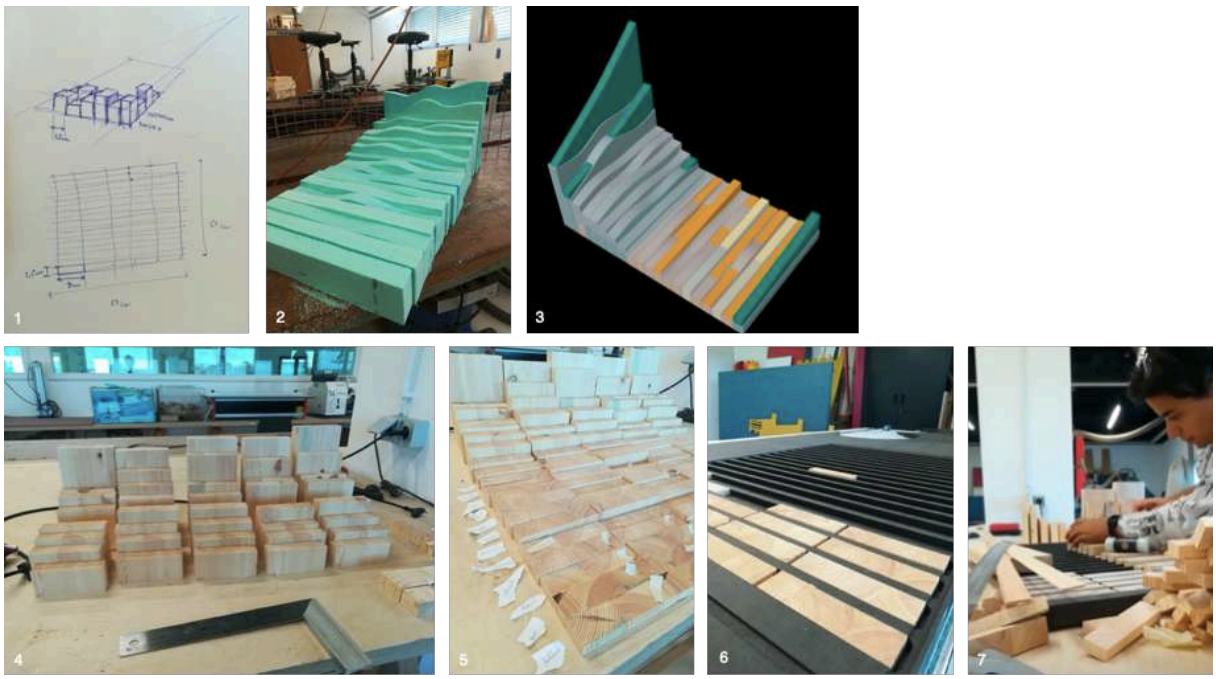


Fig1. [1] early sketches, [2] preliminary prototype made of styrofoam, [3] simulation intersecting both databases (number of design graduates versus number of design companies per year and district), [4-5] organization of the removable blocks, [6] laser cutting of the base to fit the blocks; [7] assembly of the final physical object

The physical object presented in the exhibition represented the number of design graduates in Portugal (including bachelor, master and PhD) by year (2015 to 2019) and by district (20 in total). The years are represented in the width of the piece, the districts are represented in the length and the number of graduates in the height. Therefore, each piece of wood represents the total number of design graduates in a given year and district. The arrangement of districts follows a descending order of the number of graduates relative to the most recent year (2019) (Fig.5).

4.1 Combining a physicalization with augmented reality

The development of the AR application was initiated after the emergence of the first physical prototype; and aimed to focus on the evolution of the number of design companies over time. The development of the application for android mobile devices was done using the Unity game engine combined with the Vuforia SDK, used to create a model target. A Model target enables apps to recognize and track particular objects in the real world based on the shape of the object and launch the virtual content.

It was intended that the physical object could be perceived independently of the virtual component (although the opposite is neither possible nor desirable) and that the virtual layer would add layers of information to the physical part. Hence, visitors of the exhibition could understand the information encoded in the physical piece independently of the virtual dimension. This relationship in which the virtual is subordinate to the real guided the development of the app, that is, the virtual prototype accompanied the successive stages of development of the physical object and not vice versa. In fact, the only impositions of the virtual object over physical one had to do with the size of the physical piece and the light exposure: the object could not be too small so as not to compromise

tracking and registration, and it was also necessary to avoid natural light exposure, which, being constantly changing, could compromise the AR experience.

The main challenge in app development was to find a sufficiently suitable way to overlay virtual information on companies with the physical piece on graduates, complementing it without replacing it. With this goal in mind, different hypotheses of virtual content were tested, which accompanied the configuration of the various iterations of the physical object. We tested, for example, the representation of the number of companies using pins placed in the corresponding location of the physical piece (with the number of pins equivalent to the number of companies); we tested the use of circles with different radius placed in the corresponding location of the physical piece, with the area of the circle corresponding to the number of companies (Fig.2). Finally, the information on companies was represented using the same logic as the physical object, where the height of each polygon corresponds to a number, in this case, the number of companies (Fig.3). The virtual model was superimposed on the physical model of the graduates. The aim of this solution was to obtain a coherent visual language for the same type of information (number of graduates and number of companies).

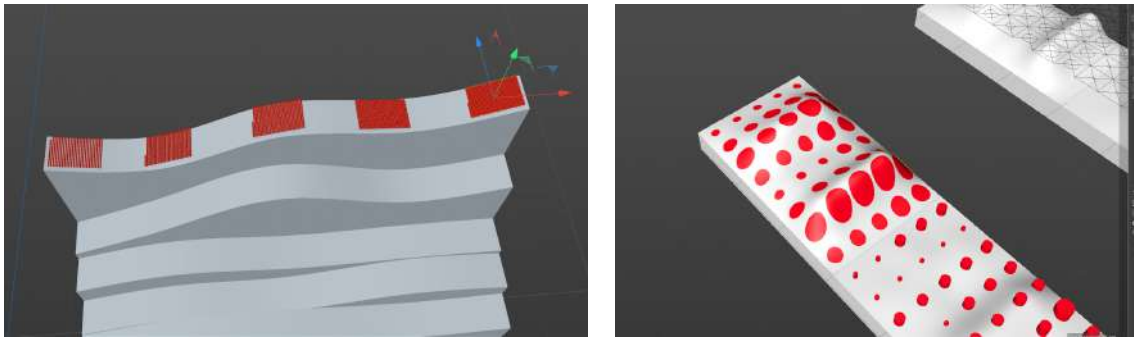


Fig2. Exploring ways to overlay company information onto the physical object. Cinema 4D screen captures. [1] Number of companies depicted through number of pins. [2] Number of companies depicted through circles area.

In parallel to this exercise, we explored ways to complement the information of the physical piece by giving a new look to the wood pieces, using filters, but also through the details-on-demand option. The filters allow each piece to be assigned the colour of its NUT II (i.e.. North, Center, Lisbon, Alentejo, Algarve, Islands of Madeira and Açores), while the details-on-demand option provides the exact numerical value within each piece (Fig.3.2). The changes to the physical object not only implied modifications to the configuration of the virtual objects at the visual level, but they also changed the symbolic dimension and the possibilities of meaning making in the virtual dimension. A clear example of these implications is evident in the 'slice-by-year' feature (Fig.4). Initially, the physical piece was designed as a single piece. In response to this configuration, the virtual dimension, , allowed simulating cuts in the physical piece by years, through animations (Fig.4). Cutting the piece by years resulted in a two-dimensional graph that allowed us to visualize the number of graduates and companies in each district and per year. With 'slice by year', the virtual component added to the physical piece, a new way of looking at the data being analysed - a traditional, two-dimensional way. This functionality remained, but with the physical piece no longer being integrated into a single piece, “slice-by-year” lost its original value.

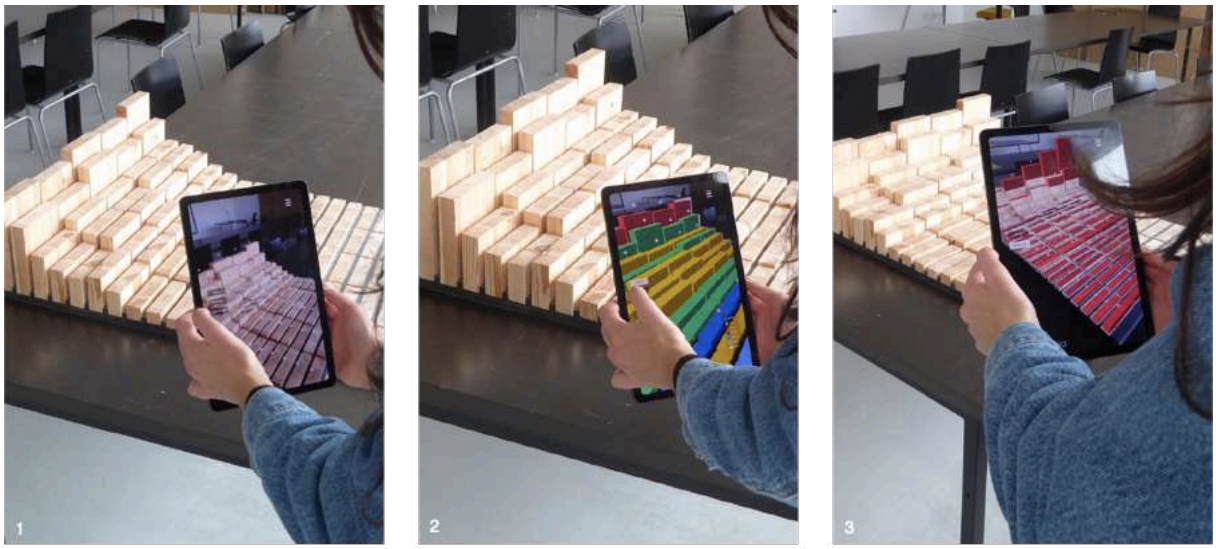


Fig3. app shows [1] the number of graduates in the physical object, [2] number of companies per NUT II region (organized in 7 colours), [3] intersection of number of graduates (physical object) and number of companies (in red) per year and district

In the version presented at the exhibition, the application (fig. X) allows the combination of three AR filters from the recognition of the physical object: (1) the 'NUTS II' filter attributes to the objects (physical and virtual) the colour of their corresponding geographical region; (2) the 'Companies' filter superimposes the model of the companies onto the physical object and (3) the 'slice by year' filter cuts the activated objects by year using 3D animation (Fig.4).

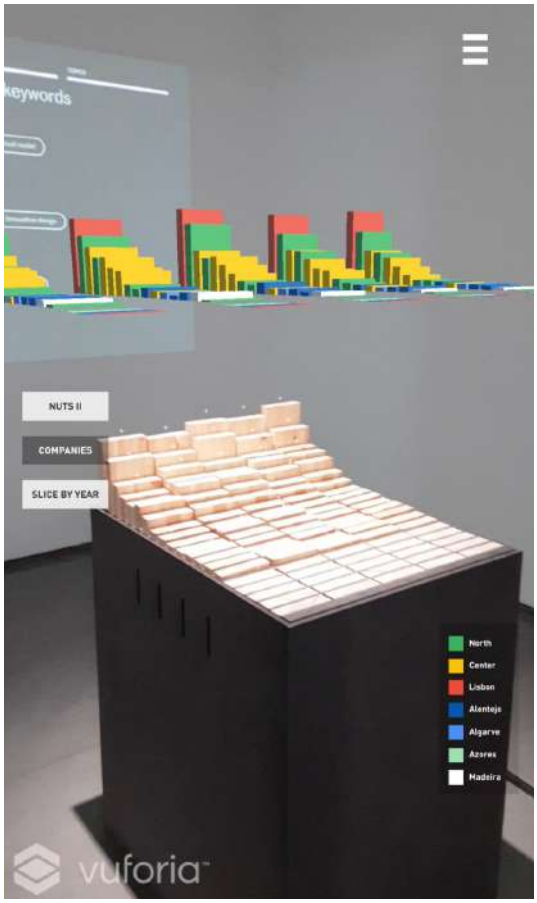


Fig4. GRAC mobile screen capture showing the slice by year feature at the exhibition room.

In addition to the filters, the details-on-demand interaction technique was also used: a '+' button appears on top of each physical piece to display the exact number on each piece.



Fig 5. GRAC final prototype combines the physicalization made of pinewood and laser engraved information; and AR application developed with Unity and Vuforia SDK.

5. Testing and reflecting about GRAC with users

Physicalization as an engaging device: The physical object turned out to be quite useful in capturing the attention of visitors and generating engagement: “I find it [physical object] more appealing than if it was just a sheet of paper. I think it's much more curious and interesting that way. If I was passing by I would stop to see it, much more than if it was a paper” (P21); "And so I really liked that idea of constructing the graph like that [referring to physicality]" (P7). In fact, the physical object conveys a strong aesthetic experience, mentioned by several participants, with the material inviting to touch and the three-dimensionality inviting participants to move around the piece, viewing the information from various perspectives. “In wood it is beautiful, yes, it's nice. It's good to touch, if we can touch it. It is good. Access to information is fast, reading information works well.” (P9). Understanding three-dimensionality was easier through the physical object than virtually, with several users reporting an immediate understanding of the information on the physical part. This ease of reading was also evident in their rich descriptive discourse about data.

Integration and complementarity of physical and virtual: Despite seeking total integration between the physical and the virtual, the app data representation seemed to replace the physical model with a virtual model, somewhat contradicting the idea of complementarity which was a pivotal concept while developing GRAC. This not intended substitution may have contributed to an issue frequently observed and confirmed through participants' discourse which is the difficulty in establishing an efficient integration between the physical wood piece and the corresponding virtual piece. Often, people would look through the screen while pointing at a particular piece of wood with their finger to confirm the year and district they were looking at. “Sometimes it's a bit hard to figure out what '+' the piece corresponds to.” (P3); “You have an increase there that I assume is... now the fifth one is... no, two to the left. That one! Aveiro! Yes.” (P8).

Visual language at the intersection of physical and virtual: Although the same visual language of the physical object (graduates) was used in the virtual model (companies), employing a white wireframe to outline the edges of the physical object in the app, users report difficulty positioning the companies graphic within the physical object, interpreting it as a whole. “Is this [virtual red piece] on top of the object or does it comprise the object and go even higher up?” (P1); “Maybe I'm not seeing correctly. But do those white lines mean anything?” (P6). From the observation and feedback, we

understand that the virtual dimension should avoid replacing the physical dimension. The hybrid experience will become richer the more it employs a vocabulary specific to the virtual layer.

Beyond the existing object: Some participants made design suggestions towards a greater interaction between the real environment and the virtual objects. One suggested the addition of a shadow projected by the user on the virtual piece, when pointing and touching the wooden pieces: "Sometimes it's a bit hard to figure out what else the piece corresponds to. (...) maybe the shadow could solve it. I don't know. (...) I don't know if this would be a possibility or not." (P3). The user suggested that reality, in this case the user's body, could affect the virtual experience. This kind of suggestion indicates the existence of some friction or resistance experienced while interacting with GRAC and the user's demand for a greater immediacy, ie. the desire for transparency, where the medium itself is effaced, and the user feels a sense of direct contact with the represented world.

The importance of context: The exhibition providing the background for GRAC proved to be crucial for contextualizing and introducing the topic of the Design ecosystem in Portugal, enabling the exploration of different types of questions and patterns. One of the participants suggested the possibility of adding layers of data beyond those presented, mentioning that it was a poster from the exhibition that gave him this idea: "It was that poster [pointing to the blue and pink poster that talked about higher education teachers in design]. (…) It's not just quantitative information, I mean, you can't really understand the number, but you can understand the dimension of things. You can understand the weight of gender in design. It's fantastic!" (P9). Moreover, some pre-tests were conducted without the exhibition, and the results are not as rich compared to tests conducted within the exhibition, with participants taking less time on each test and having more superficial speech. This type of hybrid artifact recovers the importance of the 'here and now' (Benjamin, 2012) of the object in an exhibition context (in this case not as a work of art, but as a design artifact).

5. Conclusions

Design research has already attempted to materialize data into artifacts (e.g. physicalization, infographics) and different media (story-based data driven websites) which usually explore one dataset. However, there are still few empirical cases that explore the design challenges of integrating different types of media into a single experience, especially if different datasets are combined. This study addresses this research gap via design and development of the GRAC artifact – a combination of physical and AR. In this context, AR does not substitute the real environment/object and asserts itself as a media that can add information to reality (Marques et al., 2021). This study details the design process to combine a physicalization and augmented reality application, reflecting about the implications and limitations.

This study also has limitations which in turn point to future research. First, this study draws design implications based on a single case of physical/virtual integration. Additional studies could focus on the aggregation of multiple artifacts that made this combination, thus reflecting on the limitations/advantages and implication of physical/virtual integration for designers. Second, as pointed out by several participants, data is always evolving and so should the artifact. Although virtual objects can be easily transformed and adapted, physical ones still do not hold this type of capacity - but are nevertheless essential parts of local-based aesthetic experiences. Finally, considering design as an activity of cultural mediation, it is important to explore if/how the transformation of data via the combination of physical/digital artifacts could have potential to construct creative future inquiry going beyond the use of data to support sense-making.

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