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The Role of Tangible Interaction to Communicate Tacit Knowledge of Built Heritage

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Abstract: Meanings and values of built heritage vary from factual and explicit meanings which are relatively easy to present, to more tacit knowledge, which is typically more challenging to communicate due to its implicit and often abstract character. In this paper, we investigate how tangible interaction influences the communication of this tacit knowledge of built heritage, and how it affects the experience of visitors. Through a between-group comparative study in a real-world museum context, we examined how the tangible characteristics of an interactive prototype museum installation influence how visitors perceive a particular story containing tacit heritage knowledge. The communicated story relates a historical journey in ancient Egypt to the physical and architectural characteristics of the entrance colonnade at the Djoser Complex in Saqqara. Our experimental conditions consisted of an interactive navigation (input) and a passive representation (output) components, ranging from traditional digital displays to fully tangible means of interaction. We report on our findings, which showed various differences and commonalities between our three experimental conditions. We conclude with a number of discussion points and design recommendations: (a) to strive for balance between navigation and representation modalities in terms of affordance and the required cognitive effort; (b) to take advantage of physical representation and grasping, such as conveying particular physical details and characteristics; and (c) to consider design aspects of embodiment, physical abstraction and materiality for future research or potential further development of communicating the meanings and values of heritage.

Keywords: tangible interaction; tacit knowledge; built heritage; communication; physical affordance; embodiment; Saqqara; museum studies

1. Introduction

Our built heritage forms a unique asset, as it expresses the richness and diversity of our common past. Heritage sites and monuments should therefore not be interpreted just as physical constructions, but as tangible artefacts that represent meanings and values that might even change over time. We therefore consider how the built heritage can be interpreted as a communication process [1], in which the different types of values and meanings can be perceived, understood and appreciated by a wide range of visitors. Typical values and meanings that originate from built heritage include factual and explicit meanings, such as shapes and forms, which are relatively easy to be graphically represented via text or images. Likewise, dimensions, which synthesize the proper understanding of the built heritage, are commonly communicated via drawings and sketches. Yet more intangible or tacit meanings and values, such as the skills, ideas and experiences that the heritage represents, are typically more challenging to communicate to visitors due to their implicit and often abstract character. Yet such tacit knowledge is particularly important to understand the complexity and richness of heritage as an experiential and communal concept that is not necessarily declarative or definitive. Tacit knowledge of built heritage includes, but is not limited to: (a) architectural qualities, such as how aspects of the work reinforce the oeuvre of a known or distinguished architect, the interrelationships of the different design styles within the artefact, the contributions to its environment, or particular structural or decorative aspects and their design process [2]; (b) cultural values, such as how the work has gained cultural significance with the passing of time, or how particular building characteristics illustrate specific societal developments; (c) aesthetic features, such as how the work corresponds to the sense of tradition and is manifested through an appreciation of cultural and historic characteristics [3]; or (d) symbolic significance, such as the symbolic aspects of what the work represents, or their embodied value in terms of their construction [4].

In particular, our research focuses on communicating tacit knowledge of built heritage. We are motivated by the emerging concept of heritage democratization [5], which states how communication forms a crucial matter in heritage, as an exceptional vehicle for spreading knowledge and heritage values by collectively facilitating access and awareness for extended protection [6]. By democratizing its communication beyond heritage professionals for conservation decisions [7], the significance of this tacit knowledge can be appreciated by a broader public such as to raise community awareness or to enable heritage visitors to appreciate heritage in more experiential ways.

During the past two decades, several emerging digital technologies already profoundly influenced the ways of disseminating and communicating cultural heritage [8]. These technologies vary in terms of their modality, immersion and integration into the physical manifestation of the heritage environment. For example, digital audio-guides in museums now offer immersive sound atmospheres that enrich the exploration of museum collections. Although these audio guides can be synchronized with individual trajectories [9], their individual "audio bubbles" [10] tend to isolate users insofar that they may hinder social or natural interactions between visitors themselves. Other technologies like digital displays focus on the communication of heritage values and meanings via the graphical user interface (GUI) such as via hand-held devices providing digital storytelling [11,12]; via large and sometimes interactive displays or multi-touch tabletops [13] that present textual or graphic heritage information, allowing multiple people to comprehend information and even enable the interaction of multiple people simultaneously, fostering different forms of socialization between them [14]; or even more flexible active presentation modalities, such as projections [15] that are able to engage multiple museum visitors in more body-centric and thus physical ways.

Tangible interaction is an interdisciplinary field of research, spanning a variety of perspectives, including Human-Computer Interaction (HCI) and Interaction Design. Its research tends to investigate how computational and mechanical advancements can be combined to allow novel forms of natural manipulation and full-body interaction with data and information [16]. In comparison to GUIs, tangible user interfaces (TUIs) are believed to be relatively more intuitive, as TUIs tend to communicate meaning through their physical affordances [17], such as by mapping information into physical shapes and forms, or into its material attributes (e.g., size, shape, texture, color, weight). Because of these affordances, which reveal the implied interaction possibilities through the physical design features in apparently seamless and natural ways, TUIs tend to require little experience or skills to be operated, and can function as both input and output mediums [18]. TUIs have also shown to possess significantly different qualities in comparison to commonly existing ways of heritage communication. For instance, TUIs tend to perform better in terms of recall because it requires multimodal ways of human perception to discover and decipher their meaning [19]. TUIs differ from touch surfaces in terms of their positive suitability in supporting collaborative and participative processes among users [20], while their explicit touch and manipulation affordances have shown to attract more visitors towards more extensive forms of exploration during interactive exhibits [21]. The design of TUIs focuses on how tangibles represents digital information and how it empowers users to interact with this information [22]. This information is often represented by metaphoric [23] or symbolic [24] forms via interaction modalities, which we call 'navigation' later in this paper. Because of these unique qualities, we believe tangible interaction forms a promising paradigm for communicating tacit knowledge of built heritage.

In fact, tangible interaction has already been scientifically investigated as a potential means to communicate different forms of heritage information. For instance, the European project meSch (mesch-project.eu) focuses on enabling forms of co-design between designers and heritage professionals by way of a do-it-yourself philosophy of making and experimenting. Recent outputs of this project include for instance, a book-like device that visitors carry with them during their visit in an outdoor heritage environment to support storytelling, as location-based auditory information is played when a magnetic bookmark is placed on a selected page of the book [25]. In museums, 3D printed replicas of original artifacts are used to trigger digital narrative content projected on museum display cases [26].

TUIs offer a spectrum of opportunities for museums with regard to the level of embodiment, focus of interaction, and targeting specific audiences to communicate the tangible and intangible values of heritage. First, applications of TUIs in museums vary in terms of how the museum artifact is embedded in the interface; from using the original artifact itself as an interaction device, such as triggering illuminations and auditory information by touching the artifacts [27], to a semi attached interaction, such as using a wooden magnifying lens with an integrated smartphone for allowing visitors to examine museum artifacts by pointing the lens close to them and then extra digital content (e.g., text, images or animations) is displayed on the smartphone [28], to more detached interaction when the original artifact and the interface are located in distant places in the museum for provoking visitors' curiosity to visit the artifact and to learn about it [29]. Second, communicating information and values of cultural heritage through tangible interaction could be explicitly integrated into sensorized objects by focusing on their physicality [30], or it could be implicitly integrated in a gesture or an action, focusing therefore on the act rather than the object itself [31]. By performing specific actions, the visitor implicitly understands and experiences an intangible value related to a certain object. These actions could be performed to navigate 3D models, to compare several objects, or to experience the physical material properties of an object [29]. Further, the tactile qualities of tangible interaction allow for interactive installations in museums that target specific audience [29]. For instance, the mix of materialities encourages creativity for playful exploration and allows for educational opportunities in a children's exhibition [32]. Moreover, the tactile exploration enables blind and visually impaired people to interact with heritage collections by touching specific hotspots on the artifact [33], or by navigating 3D surfaces via a smart ring in their fingers [34] to trigger voice explanations.

However, little is known on whether and how tangible interaction is effective in communicating knowledge or meaning, let alone in the context of revealing tacit knowledge of built heritage in a museum context. In order to investigate this issue and to benchmark different tangible interaction and feedback modalities, we conducted a between-group comparative study in a real-world museum context. As tacit knowledge, we chose a particular story that relates the physical and architectural characteristics of the entrance colonnade at the Djoser Complex in Saqqara to the potential meaning of the historical journey along the Nile in ancient Egypt. We investigated how this symbolic significance and other architectural qualities were communicated to museum visitors based on their interaction with three different experimental conditions. We also examined their engagement during interaction and how it affects communicating tacit knowledge of built heritage. Each of the tested experimental conditions consisted of an interactive navigation (input) and a passive representation (output) components. As such, the three conditions differed from each other by one of the tangible modalities, ranging from a traditional digital display interface to fully tangible means of interaction.

2. Context

Most ancient Egyptian antiquities are characterized by tacit knowledge like historical values as well as distinctive architectural qualities, which all predominantly represent symbolic significance through association and context. We chose to communicate the tacit knowledge of the Djoser pyramid complex in Egypt specifically because: (a) the antiquity department at the Royal Museum of Art and History in Brussels already possessed significant historical and archeological expertise of this particular site; (b) we discovered that its architectural layout and features are comprised of a rich variety of distinctive architectural qualities that could potentially be represented via tangible interaction, such as its spatial proportions, number and style of columns, etc. which individually (c) symbolize a specific historical story that is sufficiently compelling and interesting to be communicated to a large, lay audience. As such, our study was deployed in close collaboration with the Antiquity Department of the Royal Museum of Art and History in Brussels. The museum possesses the largest collection of Egyptian antiquities in Belgium, including a monumental scale model of the Djoser pyramid complex in Saqqara that dates back to 1943. The fabrication of this scale model was managed by the Egyptologist Jean-Philippe Lauer, who considered Saqqara as a life-long commitment [35]. Although the model was not publicly accessible at the time of our study, it might be featured in future exhibition designs, so that the empirical knowledge from our studies could form a foundation on which future tangible interaction approaches could be grounded.

The Djoser pyramid complex forms a mortuary precinct in Saqqara believed to be designed by Imhotep, one of the greatest known architects in ancient Egypt [36]. It was built for pharaoh Djoser around the mid-27th century BCE, and is recognized as the world's oldest large-scale stone structure. Its entrance colonnade consists of a limestone ceiling, loaded by pairs of limestone fluted columns composed of drum shaped segments, all reaching a height of 6.6 m. The columns are not free-standing, but attached to their side wall by masonry projections, hereby composing 42 individual *niches*, which are the spaces created between adjacent columns (Figure 1, right). The combination of complex architectural features of this impressive entrance colonnade carries a peculiar cultural meaning, as its particular physical layout can possibly be associated to the historical journey the pharaoh undertook along the Nile to visit each of the 42 *nomes*, the administrative territorial divisions of ancient Egypt (Figure 1, left), and their local gods. Some Egyptologists propose that each *niche* in the entrance colonnade represented a shrine where the *nome* gods of ancient Egypt were accommodated during the *Heb-Sed*, a festival celebrating the continued rule of the king through rituals that symbolically rejuvenate him [37], for opposing views see [38]. This working hypothesis is believed to be plausible because the number of *niches* and *nomes* are equal (42). As such, the architect Imhotep may have designed the architectural layout of the colonnade to portray symbolically the Nile River, and consequently the end chamber would represent the Delta region.

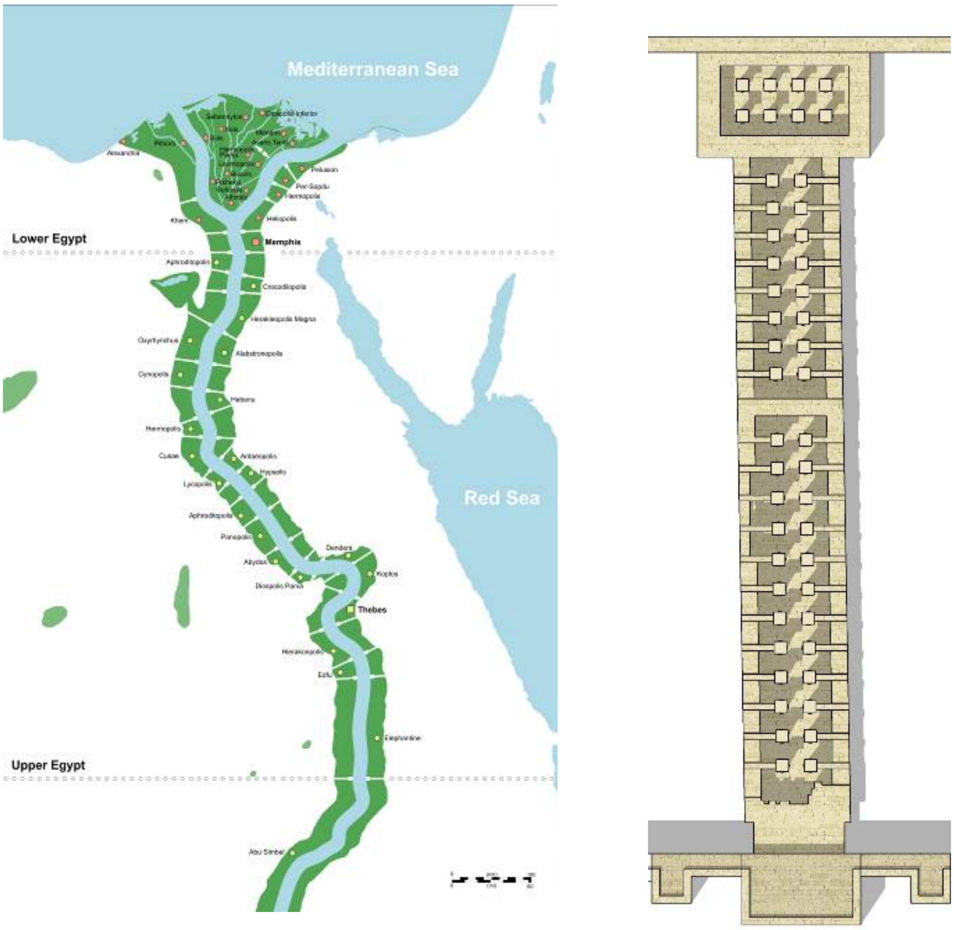


Figure 1. The chosen tacit knowledge; the historical hypothesis that the 42 *niches* in the entrance colonnade (**right**) represent the 42 *nomes* of ancient Egypt along the Nile River (**left**); the end chamber would have represented the Delta; and that the processing of pharaoh Djoser along the corridor and passing by each *nome* shrine would have been a ritualized version of the pharaoh's journey along the Nile to visit each of the *nomes* and their local gods.

In short, the historical hypothesis is that the processing of pharaoh Djoser along the corridor, passing by each *nome* shrine, represents and evokes a ritualized version of the pharaoh's journey along the Nile to visit each of the *nomes* and their local gods [39]. Our study hypothesis is that this tacit historical knowledge can be effectively communicated via tangible forms of interaction, which will lead to more collaborative forms of interaction and more profound recall of tacit heritage qualities by general museum visitors.

3. Methodology

In order to recognize the causal influence of tangible interaction on the communication of tacit knowledge of built heritage, we based our experimental approach on a between-group comparative study design. This means that we compared the impact of different tangible interaction designs with each other, in a way that avoided participants to interact with more than one interaction approach so that no learning effects or other kinds of bias could occur.

3.1. Experimental Conditions

The evaluation study consisted of three different conditions. Each condition was comprised of a distinct interactive navigation (input) and a representation (output) component that differed in terms of modality as summarized in Table 1 and as illustrated in Figure 2.

Table 1. Navigation and representation components of the three different conditions.

	Touch-Dix	*Tang-Dix*	*Tang-Phys*
Navigation	touch screen	tangible installation	tangible installation
Representation	2.5D digital display	2.5D digital display	3D physical rendition

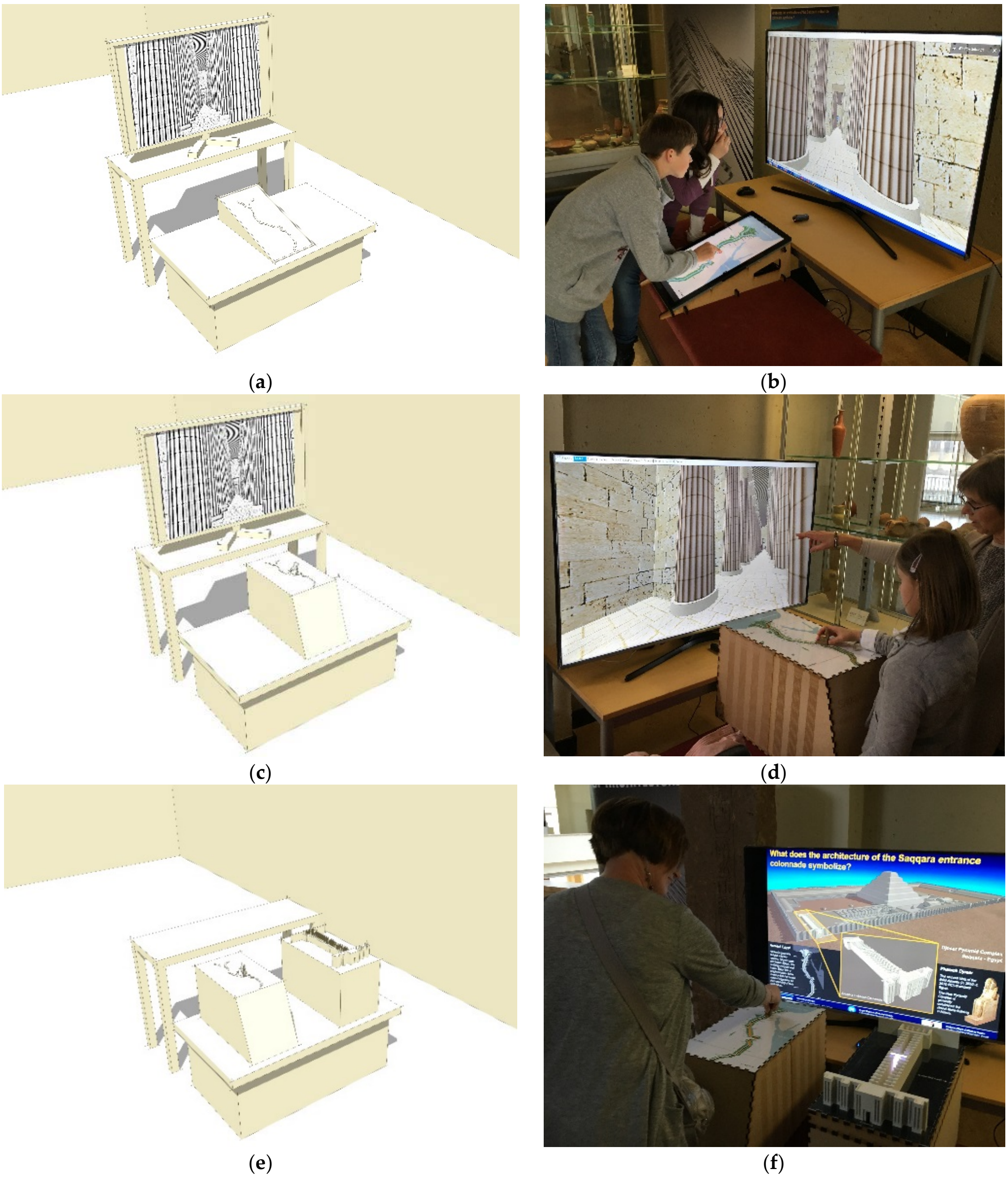


Figure 2. Different conditions for communicating the architectural story of the entrance colonnade of Djoser Pyramid Complex: (**a**) and (**b**) touch navigation and digital representation; (**c**) and (**d**) tangible navigation and digital representation; and (**e**) and (**f**) tangible navigation and physical representation (in this condition, the informative poster was displayed on the larger LCD display behind the installation).

In short, the *Touch-Dix* condition used a 'digital' modality in both navigation and representation components; the *Tang-Dix* condition used a 'tangible' modality for the navigation component; while the *Tang-Phys* condition included 'tangible' modalities for both components. The navigation component was based on interacting with a map of ancient Egypt that depicted the location of the territorial divisions of 42 *nomes*, as shown in Figure 1 (left). Participants were able to interact with the map either via moving around their finger on a common touch display (*Touch-Dix*) or via physically moving around a miniature 3D-printed statue of pharaoh Djoser on the map (*Tang-Dix* and *Tang-Phys*). In turn, the representation always consisted of a view of the entrance colonnade that dynamically changed according to the user input retrieved from the navigation component. The modality of this view either consisted of a 'digital' approach, i.e., a common LCD display depicting a 2.5D walk-through view of a rendered 3D model of the colonnade (*Touch-Dix* and *Tang-Dix*); or a 'tangible' approach, i.e., a physical scale model of the colonnade featuring a row of LED lights that lit up according to the navigation input, which users were able to pick up and touch (*Tang-Phys*).

3.1.1. *Touch-Dix* (Figure 2a,b)

The navigation modality in this condition occurred via a touch-enabled LCD display. Participants dragged a small 'you are here' icon along the Nile as depicted on a map of ancient Egypt. The position and rotation of this icon was directly translated to that of a camera viewpoint inside a virtual 3D model of the colonnade that was simultaneously displayed on a larger LCD screen in front of the smaller touch-enabled display (Video S1). The real-time connection between the touch display and the 3D world was accomplished via the Edddison plugin (edddison.com) within the SketchUp application. A printed poster (A2 size) located next to this installation summarily explained the historical context, and included a close-up view of the entrance colonnade, a concise bio of pharaoh Djoser, a map showing the unification of ancient Egypt, and an evocative question to visitors "what does the architecture of Saqqara's entrance colonnade symbolize?" (Figure S1).

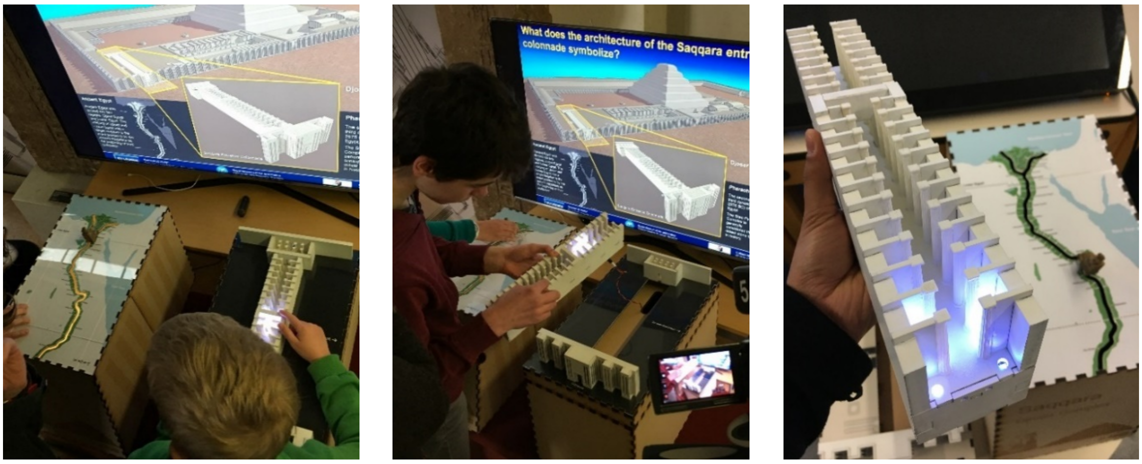
3.1.2. *Tang-Dix* (Figure 2c,d)

In the navigation modality of this condition, participants were invited to physically move a 3D-printed statue of pharaoh Djoser along a narrow slot representing the Nile River, which was equally shown on a map of ancient Egypt. Similarly to *Touch-Dix*, the relative position and rotation of the statue was directly linked to that of the camera viewpoint inside a virtual 3D model of the colonnade that was displayed on a large LCD screen. The relative location of the statue was tracked via a webcam underneath the map, which was then linked to the SketchUp model on the large LCD screen via a feature of the same Edddison plugin (Video S2). Identically to *Touch-Dix*, participants were informed of the historical context via the printed poster (Figure S1).

3.1.3. *Tang-Phys* (Figure 2e,f)

The navigation modality was identical to *Tang-Dix*, yet moving the statue along the Nile River caused a sequential row of LED lights to illuminate (Figure 3c) within a graspable and physical manifestation of the colonnade, to denote the position of the *nome* along the Nile with its corresponding *niche* (See the hypothesis in Figure 1). On a technical level, the distance of the physical statue was linked to a custom-developed electronic setup that controlled an Arduino LED strip that was integrated into the colonnade mock-up (Video S3). During this condition, the informative poster was displayed on the larger LCD display behind the installation (Figure 2f).

In order to better differentiate the aspects of immersion and interaction, the condition *Tang-Phys* was divided in two different sub-conditions. In the *fixed* sub-condition, the colonnade scale model was fixed unto the installation, meaning that participants were only able to look and touch the physical model from above (Figure 3a). In the *graspable* sub-condition, participants were allowed to pick up the model to look through it, potentially increasing the comprehension of spatial aspects [40] such as scale and proportionality (Figure 3b).



(**a**) (**b**) (**c**)

Figure 3. Illustration of the different sub-conditions of *Tang-Phys*: (**a**) Fixed: the colonnade scale model is fixed unto the installation; (**b**) Graspable: visitors are allowed to pick the model up; and (**c**) close-up view of the colonnade model from inside, showing the 3D printed fluted columns and the LED lights in each *niche*.

3.2. Evaluation Methods

The evaluation study deployed a mixed-method methodology, consisting of in-situ observations, semi-structured interviews, and a standardized user experience questionnaire.

3.2.1. Observation

During the experimental part of the study, all participants' interactions were video-recorded and observed, and then manually listed and analyzed in an Excel spreadsheet. The level of user engagement was derived by the duration of interaction, the apparent focus of attention while interacting and any form of social interaction with other person(s) nearby. The resulting observation data was chronologically mapped and then labelled in terms of user behavior, such as whether a participant focused on the navigation or the representation component, or both simultaneously; or whether they started discussing with each other; and whether these social interactions targeted the purpose of the installation or the sharing of their preliminary comprehension of it. We also logged any discussion with the interviewer, and whether and for how long they looked at the informative poster.

3.2.2. Semi-Structures Interview

After the experimental phase of the study, participants were invited to partake in a semi-structured interview that was audio-recorded. The questions focused on whether and how the participant comprehended the tacit knowledge of the colonnade, such as the symbolic relationships between the map of Egypt and the architectural colonnade layout. The interview also captured the participant's spatial comprehension of the colonnade layout, in order to benchmark how the architectural qualities of the space (e.g., dimensions and proportions, shape and flutedness of the columns) were perceived and internalized. For instance, participants were requested to describe the physical appearance (e.g., shape, number, color, material, etc.) of the columns when they voluntarily mentioned them during the interview. All participants were invited to estimate and report on the dimensions of the colonnade's width and height by sketching a cross-section of the colonnade on a grid paper that featured a human figure to illustrate the relative scale. In the case of a collaborative or group participation, each individual participant was asked to add his/her estimation on the same grid paper by a different color. Participants were also asked about their level of appreciation for these kind of installations, in an attempt to open up the interview towards more subjective answers that could explain the more quantitative responses before. All answers from the interviews were then manually analyzed using an

Excel spreadsheet, where we collected the understanding of the symbolic significance, and calculated the averages and median values for each condition, as summarized in Table 2.

3.2.3. User Experience Questionnaire (UEQ)

Subsequently to the interview phase, participants were asked to fill in a standardized user experience questionnaire (ueq-online.org). The UEQ has proven to be an efficient assessment of the user experience of an interaction design [41] and allowed participants to express their subjective feelings, impressions or attitudes in a statistically valid manner. The questionnaire consisted of six different scales with 26 items in total, covering a relatively comprehensive impression of user experience, including: (1) *attractiveness*, or the general impression of users, such as whether users liked or disliked it; (2) *efficiency*, such as whether users were able to use the installation efficiently, and whether its user interface looked organized; (3) *perspicuity*, or whether the installation was easy to understand in how it can be used; (4) *dependability*, or whether the user felt in control of the interaction in terms of security and predictability; (5) *stimulation*: whether they found it interesting and exciting to use; and finally, (6) *novelty*, in that the installation was considered to be innovative and creative.

3.3. Study Setup

The evaluation phase of this study commenced with a low-fidelity test session at our research lab with only a few participants. This test was followed by a two-day pilot study in the real museum environment, before we carried out the large-scale study during approximately two weeks. All participants first signed an informed consent form to confirm that they voluntarily participated and that the results of this research can be used only for scientific purposes.

3.3.1. Lab Study

Six volunteers (i.e., research associates not directly associated with this research) interacted with the three different installations in differing orders for around 10 min. Open interviews gauged whether they were able to intuitively use the installations, understood the symbolic link between the colonnade and the map, and remembered some of the architectural qualities. The subsequent analysis of their feedback led to several technical (e.g., the way the LED lights lit up), methodical (e.g., the phrasing of questions) and ergonomic (e.g., the table height of the installation, the graphical and textual readability of the map) alterations.

3.3.2. Pilot Study

The two-day pilot study occurred in the main showroom of the Egyptian collections at the Royal Museums of Art and History (Figure 4). It aimed to reveal any obvious usability or other user experiential issues within an ecologically valid context, such as whether lay museum visitors could intuitively understand how to interact with each installation. Each condition was introduced by a brief explanation about the general context of the colonnade (i.e., location and historical period) and the purpose of interacting with the installation (i.e., to explore the architectural symbolism of the entrance colonnade). The pilot-study consisted of 13 participants, participating individually or in group, including couples and groups of children on a museum school trip. The results and implications of this pilot study were briefly reported in [42].

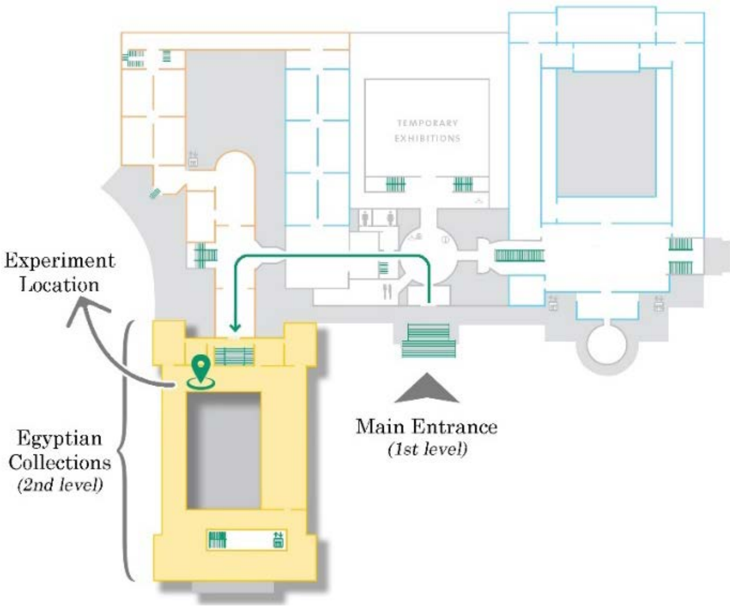


Figure 4. Floor plan of the Royal Museums of Art and History in Brussels, indicating the location of the experiment in the main showroom of the Egyptian collections at the Antiquity Department.

3.3.3. Final Study

Based on the results of the pilot study, several more modifications were implemented, such as: (1) the informative poster was printed in a larger size (A2 instead of A3) to be more prominently visible; (2) the 7″ tablet computer was replaced by a larger 21″ touch screen to increase the usability and accessibility of the navigation input; (3) the 21″ output display was replaced by a 52″ version to increase its prominence and general legibility; and (4) the evocative question was changed to be clearer about the symbolic significance of the entrance colonnade. The final study was conducted during five days at different times of day (mornings and afternoons during weekdays and weekends) over a total period of two weeks in order to reach varying types of museum visitors. Naturally, the three conditions were equally distributed over time in a random order to avoid that specific conditions were only tested by specific types of visitors (e.g., young pupils) or that learning effects occurred between museum visitors.

4. Results

The final comparative study involved a total of 42 participants, almost evenly distributed over the three different conditions (13 *Touch-Dix*, 14 *Tang-Dix*, and 15 *Tang-Phys*), who participated individually (10) or in groups (32), including couples, friends, or parents with children on a family museum visit. Only one group composed of two visitors do not know each other who socially engaged only in the sake of participating in the experiment. Participants varied in terms of gender (i.e., 4 males, 14 females, and 24 mixed groups of males and females), age range (i.e., children, teenagers, adults, and elderly), and the purpose of their museum visit (i.e., 2 school or university visits, 13 family visits, 13 local tourists, 13 international tourists, and 1 museum staff member). Based on the observations, interviews, and the user experience questionnaire, our findings are categorized into aspects relating to the communication of tacit knowledge and the user engagement.

4.1. Communication of Tacit Knowledge

This section describes how differences in the navigation and representation features of TUIs impact its ability to communicate tacit heritage knowledge in a museum context, including its symbolic significance and architectural qualities.

4.1.1. Comprehension of the Symbolic Significance

Our results indicate that the level of understanding of the symbolic relationship differs between the three conditions. In *Touch-Dix*, 39% of the participants (5, N = 13) immediately mentioned the link when they were asked about what did they learn from interacting with the installation, e.g., *"I think I was quite fast in understanding that link . . . for me, it was quite clear"* (participant 18). Another 39% of the participants (5, N = 13) described the link when they were asked more specifically during the interview about the corridor's symbolic representation. The remaining participants (3, N = 15) considered it difficult and commented on its complexity after it was explained to them *"you see a corridor and a lot of pillars, but to link it to the Nile is too far"* (participant 21).

Condition *Tang-Dix* proved more challenging, as there were only 3 participants (N = 14) who mentioned the symbolism immediately when they were asked what they learned from their interaction. However, participants found this insight not easy: *"I was moving this control (statue) through the river, and at the same time I was thinking why I am moving on the river, it was not related to the display . . . I think it is not easy to make a connection"* (participant 6), whereas 5 participants (N = 14) in the *Tang-Dix* condition only described the meaning during the interview when they were asked more specifically about the corridor's symbolic representation. For instance, *"if you only put this in front of visitors, nobody will get it"* (participant 11).

In contrast, condition *Tang-Phys* succeeded better in conveying the symbolic significance as 14 participants (N = 15), of which 10 in *graspable* sub-condition (N = 10) and 4 in *fixed* sub-condition (N = 5), mentioned the symbolic meaning when they were asked about what they learned from their interaction: *"it was evident when we are moving, the light is moving, so it was the Nile. As the Nile is the spine of Egypt, then it is Egypt"* (participant 27). Participants noted that they gained this knowledge only by interacting with this condition, as *"I did not know it was represented by the building. Now, because I saw the lights, I understand why the building was built"* (participant 30). Some participants reflected even upon the larger context of this insight. For instance, in *Tang-Phys* condition a participant mentioned that *"it was clear that this building was [built] at a unification period"* (participant 27), as he linked the story to the ancient Egyptian history when Egypt was divided into two regions, a historical fact that was also illustrated in the informative poster (Figure S1).

With regard to prior experience, we had 10 participants who previously visited the Saqqara site, as indicated in Table 2. Our results show no direct effect on the intuitive understanding of the symbolic meaning of the story (i.e., none of them from *Touch-Dix* (N = 3), only one from *Tang-Dix* (N = 4), and 2 from *Tang-Phys* (N = 3)). Further, it was challenging to extract the age-related differences regarding the understanding of the symbolic significance, as for instance all children visitors participated in groups with adults or elderly. Among groups with children, 3 groups intuitively understood the meaning from *Touch-Dix* (N = 4), 1 from *Tang-Dix* (N = 2), and 3 from *Tang-Phys* (N = 3). We noticed that the role of interacting with devices was dedicated mostly to children, while parents were focusing more on the poster and the map to understand the meaningful relationship; e.g., a parent from *Touch-Dix* condition: *"I was looking at the image (poster) and the map, not at the 3D model"* (participant 42).

4.1.2. Communication of Architectural Qualities

Participants described the colonnade as a linear space with a large number of columns and unclosed chambers between them (*niches*). When they were asked to estimate the number of the columns in the corridor (44), their answers in digital display conditions (*Touch-Dix* and *Tang-Dix*) were relatively correct, estimating their number as (53, avg.; 45, median) in *Touch-Dix* condition, and (51, avg.; 50, median) in *Tang-Dix* condition. However, in condition *Tang-Phys*, they tended to overestimate the number of columns (69, avg.; 49, median).

- **Spatial dimensions and proportions**

The participants' perception of the length of the colonnade varied from the actual length (56 m) to relatively large overestimations towards hundreds of meters. The average and median of their estimations per each condition were calculated and listed in Table 2. The average in the conditions of digital representation was quite convergent; 187 m in *Touch-Dix* and 162 m in *Tang-Dix* (medians are 150 m, and 75 m respectively). In *Tang-Phys* condition, the average of their estimations was 308 m because of a few outliers (median is 100 m). Although most participants initially hesitated to sketch the colonnade's dimensions on the grid paper due to a sense of social embarrassment or self-perceived poor drawing skills, all participants eventually sketched the requested section of the colonnade (Figure 5). Some of them even voluntarily used this opportunity to depict specific details, such as the ceiling's levels (Figure 6b) and the fluted columns (Figure 6c). Participants varied in estimating the height from approximately double the standard floor height, which is relatively correct (6.60 m), to somehow overestimations till 12 m in all conditions. However, their perception of the width varied between the digital representations conditions to the tangible scale model, as indicated in Figure 5 and Table 2. The estimated width in *Touch-Dix* and *Tang-Dix* conditions corresponded well with the actual internal width (i.e., inside) of the colonnade, whereas in the *Tang-Phys* condition, the external width (i.e., including the width of the outer walls) was perceived instead, as illustrated in Figure 5. Moreover, we calculated the width-to-height ratio in order to evaluate participants' perception of the proportional relationships of the space instead of absolute values of dimensions, as people tend to perceive spatial dimensions improperly through digital displays because of the limited field of view [43]. As such, we discovered that the ratio estimations conformed to the previous results, as illustrated in both Table 2 and in Figure 5.

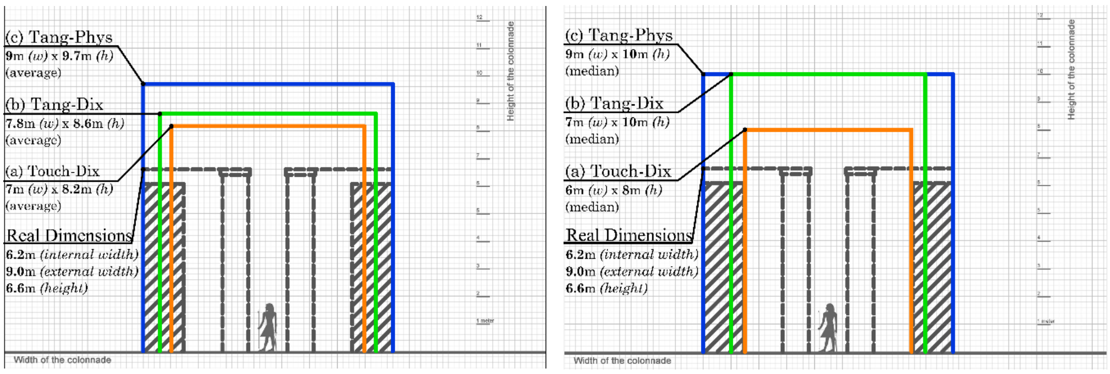
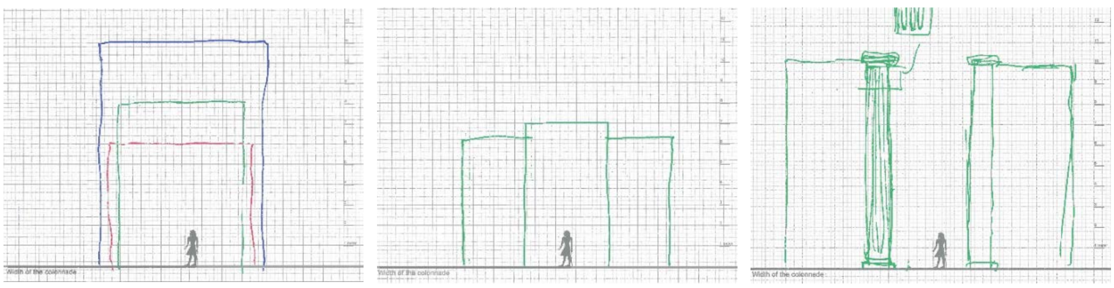


Figure 5. Calculated average (on the **left**) and median 'middle value' (on the **right**) of the estimated dimensions for the three conditions compared to the real dimensions; *Tang-Phys* (in blue), *Tang-Dix* (in green), *Touch-Dix* (in orange), and the actual dimensions (in black).



(**a**) (**b**) (**c**)

Figure 6. Samples of participants' estimation of the colonnade dimensions; (**a**) sample from *Touch-Dix*; estimating the dimensions in different colors of a group participation; (**b**) sample from *Tang-Dix*; perceiving the ceiling's levels in both main corridor and side *niches*; and (**c**) sample from *Tang-Phys*; perceiving the fluted columns and sketching their details.

Since spatial estimations seem to vary significantly between participants, making potential generalizations from these results is complex. Even in a group of multiple participants there existed different estimations of the spatial dimensions (e.g., Figure 6a). For the more traditional digital representations, some participants perceived the steps of the ceiling (e.g., Figure 6b), an observation that did not occur in *Tang-Phys* as the physical model was fabricated as a cross-section of the building, having no ceiling.

- **Shape, color and materiality of columns**

In the digital representation conditions (i.e., *Touch-Dix* and *Tang-Dix*), most participants (22, N = 27) correctly described the columns as having a rounded shape. Moreover, 10 participants (N = 13) in *Touch-Dix* condition and 8 participants (N = 14) in *Tang-Dix* condition mentioned that the columns were not smooth, but were fluted with vertical grooves. In condition *Tang-Phys*, some participants (5, N = 15) thought that the columns had a square or a rectangular shape, a perception that might well be the result of the top view that highlighted the square caps rather than section of the columns. *"Normally, columns in ancient Egypt are cylinders, but these are not. They were made of lines and angles. I even have the impression that they are not circular. But now thinking logically, I haven't seen any rectangular columns, they are always kind of circular, although the upper part (cap) could have been rectangle or square"* (participant 27). However, 9 participants in *Tang-Phys* condition (N = 15) mentioned that the columns were rounded and fluted, with one participant even drawing a detailed view of this flutedness as shown in Figure 6c. It is worth mentioning that within the *graspable* sub-condition of *Tang-Phys*, 7 participants (N = 10) perceived the flutedness of columns, while only 2 participants (N = 5) perceived it in the *fixed* sub-condition.

Participants also perceived other architectural qualities, such as the color (i.e., beige) and the materials (i.e., sand stone) in the digital representation conditions. However, as those qualities were not readily visible in condition *Tang-Phys* as the scale model was fabricated as a white, monotonous sculpture, we do not consider these for further analysis.

Table 2. Quantitative results of the final study in terms of user profiles, communication of tacit knowledge (symbolic significance and architectural qualities), and user engagement.

		Touch-Dix		*Tang-Dix*		*Tang-Phys*	
User Profile	Participants (n).	13		14		15	
	Participation type (individual, group).	1	12	4	10	5	10
	Regularly visiting museums (n, %).	12	92.3%	14	100.0%	12	80%
	Familiar with interactive designs (n, %).	5	38.5%	8	57.1%	7	47%
	Previously visited Saqqara (n, %).	3	23.1%	4	28.6%	3	20%
Symbolic Significance	Participants who intuitively understood the symbolic meaning of the story (n, %).	5	38.5%	3	21.4%	14	93.3%
	Participants who understood the meaning only after asking questions about the representation (n, %).	5	38.5%	5	35.7%	1	6.6%
	Total participants who understood the meaning (the link between the map and the building).	10	76.9%	8	57.1%	15	100%
Architectural Qualities	Estimated number of columns (avg., median); original number is 42.	53	45	51	50	69	49
	Estimated length of the corridor (avg., median); original length is 56 m.	187 m	150 m	162 m	75 m	308 m	100 m
	Estimated height of the corridor (avg., median); original height is 6.6 m.	8.17 m	8 m	8.62 m	10 m	9.71 m	10 m
	Estimated width of the corridor (avg., median); original width is 9 m (external) and 6.2 m (internal).	6.95 m	6 m	7.79 m	7 m	9 m	9 m
	Calculated ratio width to height (avg., median); ratio is 1.36 (external width) and 0.92 (internal width).	0.890	0.75	0.954	1.0	0.965	0.9
	Participants who perceived the fluted columns (n, %)	10	76.9%	8	57.1%	9	60%
User Engagement	Time of interaction (avg., median).	179 s	130 s	182 s	165 s	180 s	160 s
	Level of appreciation:						
	Don't like (n, %).	2	15.4%	0	0%	0	0%
	Neutral (n, %).	2	15.4%	5	35.7%	0	0%
	Like it (n, %).	5	38.5%	7	50%	9	60%
	Like it very much (n, %).	4	30.7%	2	14.3%	6	40%

4.2. User Engagement

This section describes the engagement of users in terms of their apparent focus of attention during interaction, their replies on the user experience questionnaire, and their forms of engagement and appreciation.

4.2.1. Chronological Analysis

Participants focused their attention on varying aspects during the interactive exploration process of each condition. Figure 7 demonstrates the chronological analysis of the three conditions, each row in the figure maps the interactions of a single participant along a horizontal timeline. Consequently, more yellow (i.e., focus on representation) can be noticed in condition *Tang-Dix*, while the green color (i.e., focus on navigation) can be noticed more during the interactions with conditions *Touch-Dix* and *Tang-Phys*. These patterns denote that condition *Tang-Dix* encouraged participants to focus more on the representation element (digital display), while the other two conditions (*Touch-Dix* and *Tang-Phys*) allowed participants to distribute their attention on both the representation (i.e., the digital display and 3D physical rendition) and the navigation (touch screen and tangible installation) elements. Moreover, we found a correlation between the visual attention of participants and their understanding of the cultural knowledge. As participants' focus of attention in *Tang-Dix* was less on navigation, and more on the digital representation on the screen (Figure 7); *Tang-Dix* condition attained the lowest percentage of understanding the story as indicated in Table 2. In contrast, the simultaneous focus of attention between navigation and representation in *Tang-Phys* resulted in better understanding of the symbolic significance of the colonnade.

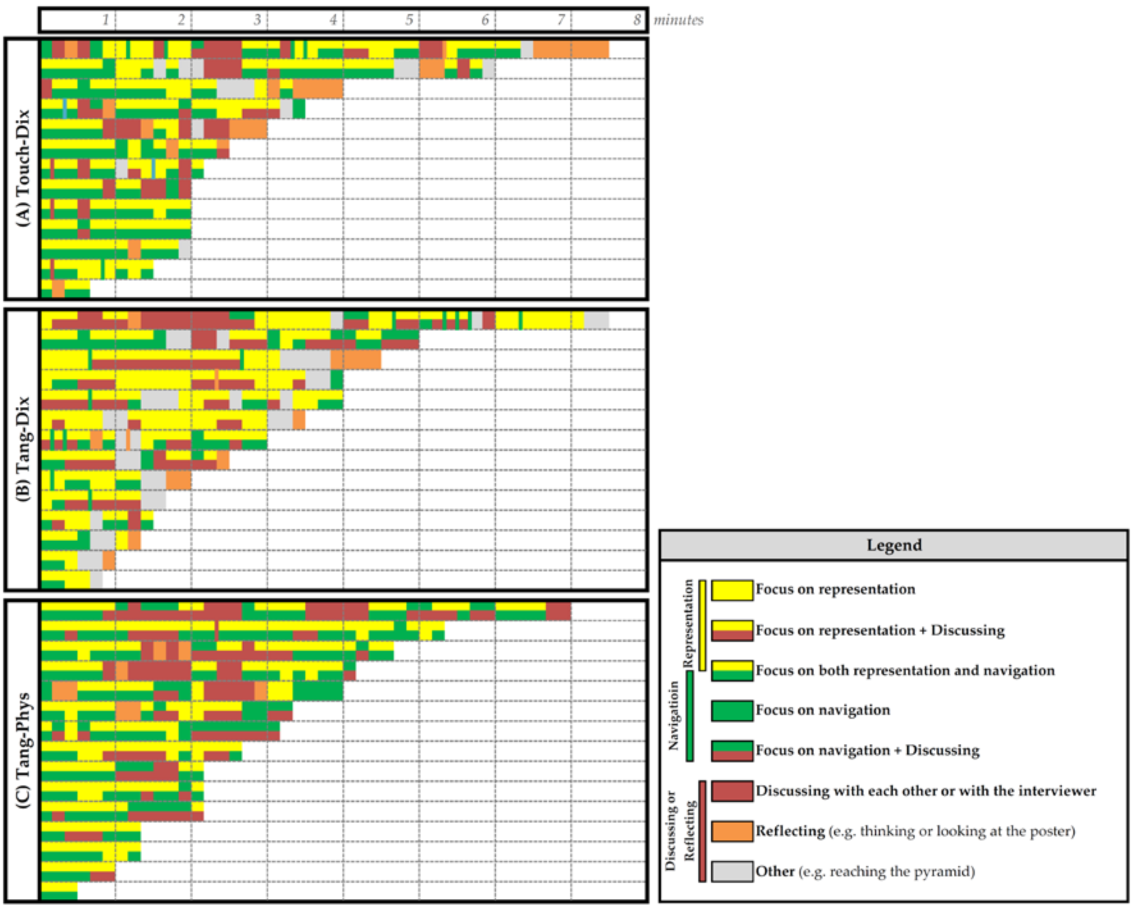


Figure 7. Chronological analysis of the participants' focus of attention while interacting with the three conditions.

Although all three conditions had the attention of a relatively similar number of participant groups (i.e., 12 in *Touch-Dix* (N = 13), 10 in *Tang-Dix* (N = 14), and 10 in *Tang-Phys* (N = 15)), the social interaction between the participants themselves was more noticeable during condition *Tang-Dix*. In contrast, there was somewhat less interaction in condition *Tang-Phys*, while in condition *Touch-Dix* the social interaction between the participants was much less than with the other two conditions.

4.2.2. User Experience Questionnaire (UEQ)

All UEQ items are scaled from −3 (representing the most negative answer) to +3 (representing the most positive answer, when 0 is a neutral answer). The Alpha-Coefficient value showed a high consistency for the items of attractiveness, stimulation, and novelty scales in all conditions. In contrast, the value was lower than 0.7 for the perspicuity scale in *Touch-Dix*, in efficiency scale in *Tang-Dix*, and in dependability scale for all conditions, meaning that these questions were probably misinterpreted or interpreted in a direction that does not reflect the intention of the participants within the context of UEQ [44].

As shown in Figure 8, the three conditions were statistically compared on the basis of the means for each UEQ scale. As the differences between the conditions are not significant for each of the scales (p-value is >0.05 in t-test), statistically valid generalizations are impossible. However, the results might still demonstrate some tendencies and trends in how each condition performed. For instance, *Tang-Phys* is more positive in attractiveness, perspicuity, efficiency and dependability scales, while *Tang-Dix* shows a positive performance in stimulation scale, and *Touch-Dix* in novelty scale.

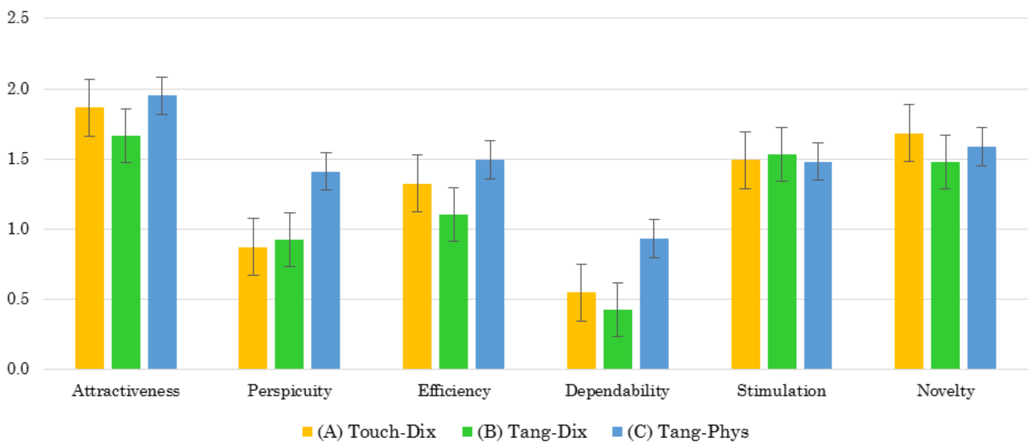


Figure 8. Comparison among the three experimental conditions concerning the scales of the UEQ (the error bars represent the 95% confidence intervals of the scale mean).

4.2.3. Engagement and Appreciation

In general, individual participants spent less time interacting (133 s, avg.; 85 s, median) in comparison to groups of participants (195 s, avg.; 180 s, median), as the discussion between group members encouraged them to explore the installation more. When comparing the different conditions, participants spent more time in case of tangible navigation; i.e., *Tang-Dix* (182 s, avg.; 165 s, median) and *Tang-Phys* (180 s, avg.; 160 s, median), compared to *Touch-Dix* (179 s, avg.; 130 s, median).

While the UEQ results demonstrate no significant differences between the conditions for all of the UEQ scales, participants seemed to have interpreted and appreciated the conditions differently. For instance, the concept of gaining new knowledge was mentioned 7 times in the context of *Tang-Phys* condition (N = 15) *"I like it because I learned something new"* (participant 38), and the concept of interactive experience in museums was mentioned 4 times in the same condition *"actually I like this installation very much because it is smartly done"* (participant 33). The condition *Tang-Dix* seemed less appreciated by participants (Figure 9), as 7 participants (N = 14) thought it required more explanation to be more appreciated, *"if you have explanation on the side, it may be clear"* (participant 12) and *"I like it now when* *you tell me the story, but before . . . not"* (participant 7). We have the impression that participants seemed to even less appreciate the *Touch-Dix* condition (Figure 9), mainly because of the lack of immersion when looking at the 2.5D representation of the colonnade *"it was too simple to grab my attention, and I was not immersed in it"* (participant 42), and possibly because they felt a bit frustrated *"oh, we tried every direction, and we see only columns"* (participant 21).

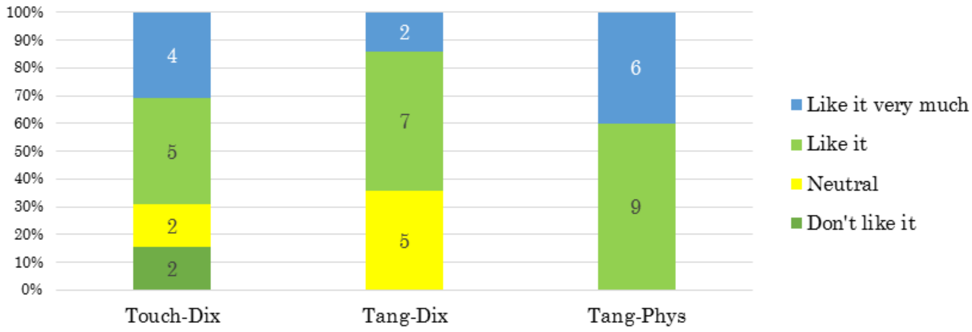


Figure 9. The percentage and number of participants with each level of appreciation for the three conditions.

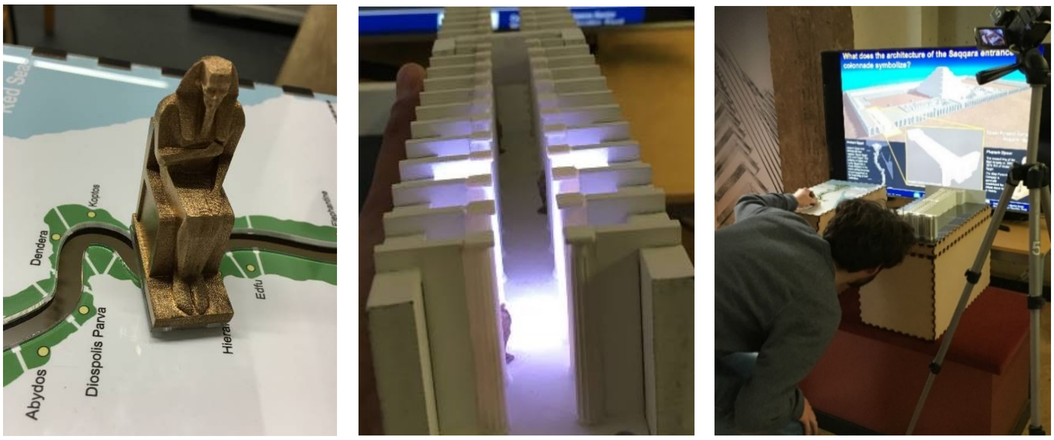
5. Discussion

In this section, we discuss the implications of our findings from this study with relevance to future research or potential further development of communicating heritage via tangible interaction. On the whole, one could note that *Touch-Dix* participants estimated the spatial features like dimensions (i.e., internal width) and quantity of major architectural elements relatively well. The condition *Tang-Dix* was better in stimulating social interactions among participants, who focused more on the output medium. Finally, the results of *Tang-Phys* show that it was better in conveying the symbolic significance of the colonnade, and it was more positively judged in the UEQ. Participants in that condition were more accurate in estimating the external width of the colonnade. In the *graspable* sub-condition, many perceived particular physical characteristics, i.e., the flutedness of the columns.

5.1. Role of Navigation

The design of our installations defined a new vocabulary of actions (e.g., similar to [26,29,30,32]), and the visitors were required to perform these actions in order to achieve certain goals (i.e., capturing the cultural knowledge). All three conditions were specifically designed to communicate the same tacit heritage knowledge by allowing participants to construct a meaningful link between an interactive navigation and the dynamic representation. Yet we observed that the actual effectiveness of linking and sense-making depended on the cognitive effort required to operate the tangible interaction interface, which consisted of the simultaneous use of an input (navigation) and output modality (representation). More specifically, the touch display in condition *Touch-Dix* proved harder to discover and then to operate, particularly when combined with a visual-centered output modality. We observed that the touch display affordance was mainly provided via the navigation component, while the visual attention of participants was constantly required in order to observe the relative position of their finger on the map, displayed on the screen (i.e., flat glass surface). In contrast, moving a physical object (i.e., the 3D printed statue of the pharaoh) along a groove possessed sufficient intuitive affordances and tangible guidance so that most visual attention could be dedicated to the output modality (representation) in *Tang-Dix* condition.

Accordingly, we believe that an equilibrium needs to be sought between the affordances and cognitive effort required when combining tangible interaction navigation and representation modalities. As participants' focus of attention in *Tang-Dix* was less on navigation, and more on the digital representation on the screen (Figure 7); *Tang-Dix* condition attained the lowest percentage of understanding the story as indicated in Table 2. In contrast, the seamless integration of navigation and representation in *Tang-Phys* resulted in better understanding of the symbolic significance of the colonnade. For instance, participants were able to do two simultaneous actions; tactile navigation and bringing their eyes to eye-level in the scale model (Figure 10c). This was possible because the two actions are relatively usable and not requiring visual focus. The link between navigation and representation could cause a sort of distraction if it is not well considered in design [29]. More specifically, only a single modality should require the conscious discovery of new affordances from the user, or require much and continuous cognitive effort to be operated. Yet the choice of these modalities might well depend on the specific focus or narrative of the intended communication. For instance, when intending that museum visitors should focus on the Nile, a touch display might be more suited.



(**a**) (**b**) (**c**)

Figure 10. The different embodied metaphors of *Tang-Phys* condition; (**a**) the 3D printed statue of the pharaoh moving along the Nile River, (**b**) the fluted columns are physically printed in the 3D model, and (**c**) people feel 'inside the space' by looking through it.

5.2. Role of Physical Representation

The level of realism, the physical construction and the manipulation features of a 3D scale model influences how people observe and remember architectural qualities, particularly when compared to a 2.5D interactive walk-through rendering. In the condition of physical representation (i.e., *Tang-Phys*), most participants understood intuitively the symbolic significance between the colonnade and the map. We believe that *Tang-Phys* enabled the communication of the symbolic significance because of the direct link between the movement of the statue along the Nile and the corresponding lights in the physical colonnade, that was easy to perceive as *"the parallelism of the colonnade and the map was too easy … with lights, it is evident"* (participant 38). As the digital representation conditions (*Touch-Dix* and *Tang-Dix*) reached a relatively lower percentage of participants who readily understood this symbolic significance (as shown in Table 2), understanding the link between the navigation and representation was more ambiguous and more challenging, probably because *"it was contradictory to move the control (statue) through the river, and at the same time to see the building"* (participant 6) from *Tang-Dix* condition. On the other hand, we observed several unexpected results in *Tang-Phys* condition, particularly regarding how participants perceived or remembered certain architectural qualities. For instance, participants perceived the spatial proportions differently. The average estimated width of the colonnade in *Tang-Phys* condition was more or less the correct external width including the width of the outer walls, whereas the length was somehow overestimated. The shape of the columns were perceived by 6 participants (N = 15) as non-circular. The colors and materials were less well perceived when using the physical model in comparison to the other conditions, *"I cannot understand the materials form this model … ancient Egyptian buildings did not have marble, so it is limestone"* (participant 27). We hypothesize these observations were mainly due to the particular physical properties of the scaled model of the colonnade. To allow for visual investigation from the top, the model lacked a ceiling, which in turn caused people to observe the length from above. In addition, the columns were 'cut through' at their very top end, which are square. Finally, people perceived the 'external' width including the thickness of the walls, whereas the walk-through view only allowed a view from inside.

We propose that future comparative experiments should have quasi-identical levels of representation abstraction in both the digital renderings as the physical models, and that spatial estimation questions could potentially be fine-tuned by asking participants to also draw the thickness of the walls and ceilings (Figure 10b). Yet we also wish to point out how seemingly trivial issues like opening ceilings or vertically sectioning a building can easily become misconstrued by visitors. As a result, an equilibrium needs to be found between the positive qualities of tangible interaction via physical representations and the actual level of realism that can be fabricated within obvious constraints of financial costs, robustness and historical accuracy. While often absolute realism is wished for, abstraction and ambiguity is a well-known design method to engage users to take responsibility in interpreting its meaning and functionality [45].

5.3. Role of Grasping

We believe that grasping a physical model, bringing it closer to one's eye and observing it from different angles facilitates the communication of correct scale and more detailed information. In the *graspable*-centered sub-condition of *Tang-Phys*, all participants understood the symbolic significance of the story, led to more precise communication of the architectural scale (i.e., width of the colonnade and proportion), and to more accurate estimations of the number of fluted columns and their shapes in the *graspable* sub-condition, particularly compared to the identical sub-condition during which participants could not grasp the physical model itself (i.e., *fixed*).

This evidence encourages further developments in allowing visitors to grasp physical models or replicas for better communication of the tacit knowledge or the finer details of heritage artifacts. However, to enable tangible forms of interaction, graspable models must be equipped with sensors (e.g., touch, orientation) or actuators (e.g., lights, motors) that are subtly embedded almost or wirelessly connected. In addition, such technological interventions should be meaningful, respectful and intuitive to be understood [46]. In addition, the technology itself could potentially disturb an immersive experience of the heritage communication. For instance, during our study, some participants were curious to discover the hidden technology driving the installation in the *graspable* sub-condition, probably because of the visible wiring. Furthermore, interactive objects require affordable and robust forms of technology, which cannot be simply stolen or damaged, and thus issues of cost and ease of replacement should be well considered [26].

5.4. Role of Material Characteristics

The intrinsic multimodal characteristics of tangible interaction requires taking into account characteristics that reach well beyond the graphical, including aspects such as embodiment, physical abstraction, and materiality (i.e., texture, weight, friction, etc.)

We believe a persuasive part of tangible interaction is its ability to offer participants the opportunity to decipher its affordances through different forms of embodiment, in order to allow them to discover the interactive features as well their potential meaning in forming a historically valid narrative. To entice a sufficient level of curiousness and engagement, this discovery process should be non-obvious yet sufficiently simple that people feel encouraged to explore all the hidden functionalities without frustration. Within our design, we therefore exploited the concept of embodiment, which is considered one of the main attributes of TUIs because it supports learning unconsciously [47]. According to [48], embodiment plays a constitutive role in communicating heritage information when it is entangled through context and environment, which enables visitors to get more involved in historical stories [49]. We considered several forms of embodiment when designing the *Tang-Phys* condition. For instance, we made a physical representation of the Djoser pharaoh which was able to be moved along a groove representing the Nile River (Figure 10a), embodying his journey along the Nile. The physical representation model showed the space from above, embodying the architectural qualities of flutedness by 3D printing them (Figure 10b). Overall, the small physical model embodied the spatial experience of the colonnade when the model was grasped and viewed on eye-level, so that the columns and small statues appeared as they were 'in the space' (Figure 10c).

Likewise, we propose that the concept of physical abstraction plays a crucial role in the imagined potential of more embodied forms of representation, as a crucial difference exists between the abstracted neutral aesthetic of a model fabricated out of white, thick walls in condition *Tang-Phys* versus the more realistically colored stone brick textures on the digital 2.5D models in the other two conditions. Consequently, participants tended to differ in opinion in terms of the ideal level of abstraction, as some *Tang-Phys* participants complained about too much abstraction in the physical model, *"I have a difficulty in imagination . . . I have to see something in 3D to form a real image about it"* (participant 25), whereas others (from *Touch-Dix*) actually wanted a more abstract form of visualization for the digital renderings: *"you can gain a better sense of information if you look at the colonnade from a top view"* (participant 41). For some participants, the geometric and 3D-aesthetic of the 2.5D rendering made it look like a 'game': *"it did not look very well . . . the quality looked a bit (like a) video game"* (participant 7, *Tang-Dix*).

Tangible interaction requires the material construction of objects, making the concept of materiality relevant for both the navigation (input) and the representation (output) modalities, as the power of material characteristics enable heritage visitors to acquire the cultural meanings [29]. According to [50], materiality emphasizes the visitor's sensations and personal interpretations of heritage information through the physical objects they interact with. For instance, the texture (i.e., rough versus glossy surface) of the physical model probably impacted how people imagined the spatial qualities of the colonnade, and the materials they imagined the colonnade to be of marble *"a rough colonnade, maybe made out of marble"* (participant 26). The experienced weight and friction of moving the pharaoh along the groove also played a role in the general experience of the installation *"I like it because I can move the pharaoh along the Nile"* (participant 38), and *"with the colors, I prefer this part [navigation] because I interact and touch the statue"* (participant 36) from *Tang-Phys*.

Overall, one could argue an equilibrium needs to be sought towards the average preferences of the public at large in terms of deciding the embodiment, abstraction or materiality. As when too much emphasis is put on the information, the physical object dissolves into meanings [51]. Yet, the mentioned concepts are also potentially powerful design aspects that could become exploited for more explicit design goals in steering useful forms of tangible interaction. For instance, the actual embodiment of narratives and historical facts could be made more ambiguous to allow visitors to guess their metaphorical meaning, whereas a varying level of abstraction could relate to the corresponding level of historical accuracy of current heritage knowledge. Likewise, heavy or glossy objects could guide the attention of visitors towards more precious or historically valuable aspects of a specific site or objects.

5.5. Shortcomings and Limitations

In our study, the experiments were deployed for a relatively short time with a limited number of participants. Due to the corresponding small sample size, the results of the UEQ did not show any significant statistical differences among the conditions. We also realize that the conclusions might be limited to conveying information by ways of tangible interaction that links direct navigational input controlled by users unto locative information that has a metaphorical meaning. At the same time, we believe that most of our findings can be generalized towards many other forms of tangible interactions that are meant to communicate information towards a lay audience.

We used only low-fidelity prototypes in our experimental conditions, which is known to lower the expectations of participants [52]. This observation also was demonstrated by how many participants expected 'more', particularly in terms of the information that was offered: *"you see only this corridor, but if it is linked to information of these [the nomes], that could be very interesting"* (participant 21) from *Touch-Dix*; as well as in terms of interactive features: *"it would be better if during the interaction, the person in the 3D model gives us some explanations"* (participant 40) from *Tang-Dix*. With regard to the experiment setup, the informative poster was displayed in *Tang-Phys* condition on the large LCD display behind the installation instead of hanging it on the wall in the other two conditions (Figure 2d–f). This setup might affect the results because the display was larger and placed in a more prominent location, although the chronological analysis (Figure 7) does not show more focus on the poster in this condition, but this could be due to the manual observation and analysis. Additionally, due to language barriers, only few families involved their children in answering the questions during the interview and all the internal discussions among families were in their own language. Accordingly, it was challenging to report on the age-related differences in terms of how children understood the symbolic significance and how they comprehended the spatial aspects. Moreover, on busy museum days with large crowds, our installation might not be ideal, as queues could form. It could be ameliorated by choosing a social approach, one that allows people to share their experience with each other. For instance, multiple scale models could be used and light up. Furthermore, according to the concept of participatory museum and connecting visitors [53], we believe that incorporating a TUI in our prototype might well increase the interactions among museum visitors who do not know each other to actively engage and to socially interact, not only among families [54]. However, due to the limited number of participants and the short time of the experiment, we only observed and mapped the discussion and social interaction among the visitors who knew each other in advance and arrived in groups (i.e., family visits or group of friends). Accordingly, we recommend that the influence of these kinds of installations on social interaction in a museum context should be further investigated.

6. Conclusions

In this paper, we conducted a between-group comparative study to investigate how tangible interaction influences the communication of tacit knowledge of built heritage and how this affects the experience of visitors in a real-world museum context. Our three experimental conditions showed different findings regarding the communication of a particular story, which relates a historical journey in ancient Egypt to the physical and architectural characteristics of the entrance colonnade at the Djoser Complex in Saqqara. Our findings indicate how the communication of tacit heritage knowledge in museum environments could benefit from interactive physical models instead of introducing digital 3D models. Digital displays stimulate social interaction among visitors, and enable them to estimate relatively well the internal width of the colonnade and the number of columns. While the physical scale model was better in conveying the symbolic significance of the colonnade, and it was more positively rated in terms of attractiveness and perspicuity. When allowed to grasp the physical model, visitors were also more accurate in estimating the external width of the colonnade, and many of them perceived particular physical characteristics, i.e., the flutedness of the columns.

We concluded our paper with a set of discussion points and recommendations for future research or development of alternative approaches to communicate the meanings and values of heritage. Such as, when combining tangible interaction navigation and representation modalities, an equilibrium needs to be sought between the affordances and the required cognitive effort, depending on the specific focus or narrative of the intended communication. We discussed how the level of realism, physical construction and manipulation features of a 3D scale model influences how people observe and remember architectural qualities. Grasping tangible models proved to effectively communicate correct scale and more detailed information, such as proportions and the shape of columns. Aspects of embodiment, physical abstraction and materiality were also discussed as powerful design characteristics to be exploited for more explicit design goals in steering useful forms of tangible interaction.

Supplementary Materials: The following are available online at http://www.mdpi.com/2571-9408/1/2/28/s1, Figure S1: The informative poster that was located next to the installations in the three experimental conditions, Video S1: The experimental condition *Touch-Dix*, Video S2: The experimental condition *Tang-Dix*, Video S3: The experimental condition *Tang-Phys*.

Author Contributions: Conceptualization, E.N., V.B, H.H. and A.V.M.; methodology, E.N., R.M.R. and A.V.M.; software, E.N.; formal analysis, E.N., R.M.R. and A.V.M.; investigation, E.N.; resources, E.N., V.B., H.H. and A.V.M.; data curation, E.N., R.M.R. and A.V.M.; writing—original draft preparation, E.N.; writing—review and editing, R.M.R., V.B., H.H. and A.V.M.; visualization, E.N.; supervision, R.M.R. and A.V.M.

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