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SABLIER : a Tangible Interactor to Navigate through Space and Time

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ABSTRACT

Historians use spatio-temporal navigation for their models and studies of historical evolutions and events. Their findings can then be exhibited in cultural mediation centers or museums. The latter, both to facilitate the transmission of knowledge and to make their exhibitions more attractive, are now exploiting new technologies. Indeed, digital systems allow, among other things, visitors to navigate spatially and temporally in virtual reconstructions of historical environments. We propose to combine these virtual representations with a tangible interface to provide visitors with an immersive experience and engaging interactions. To do so, we have set up a co-design process involving cultural mediation actors (museum directors, historians, etc.). The result is SABLIER, a tangible interactor to navigate through space and time based on the interaction metaphors and natural affordance of an hourglass. Finally, we have conducted an evaluation of the acceptability of our interactor, whose results are positive.

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**; *Virtual reality*.

KEYWORDS

Tangible User Interface, Cultural Mediation, Virtual Reality

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1 INTRODUCTION

Sablrier /sablrije (French) - Hourglass (noun) [masculine]: a glass container that contains sand that moves from an upper to a lower

part through a narrow opening in the middle and is used for measuring time [39].

Since antiquity, humans have created and used different instruments to measure time. From the calendar to keep a track of years to the clock to keep track of the time of the day, still today people use these instruments. Considering especially the passage of time, people used clepsydra or hourglass for centuries.

The work that we present in this paper is based on the analogy of an hourglass (that we call SABLIER) to navigate through time and space when interacting inside a digital space.

On the one hand, with the advent of technology, users can control the time inside digital spaces. The examples or use cases involving these actions are very varied today. For instance, temporal navigation is useful when watching a movie or listening to a music album. The user can pause the playback, speed up the broadcast or even select a specific chapter or song. For that, different metaphors have been proposed, for example, the manipulation of a timeline [22] or the direct manipulation of elements (e.g., objects seen in videos) in the digital environment [13]. These metaphors have been applied to different domains, such as data visualization [3, 27, 45] or simulation of complex systems [2, 7], and in different environments, whether 2D [25] or 3D [31].

On the other hand, spatial navigation is often seen in video games where the user has to move and find its way through a digital environment or in GPS application when planning a trip. With a 2D Graphical User Interface (GUI), the user handles controllers such as keyboard, mouse, or joystick to either move an avatar or interact with graphical elements [34]. In the case of 3D immersive interfaces, notably those presented in Virtual or Mixed Reality, other metaphors have appeared, such as pointing in a direction [8], grabbing the environment, walking while being tracked by the computer system [41] and, more recently, teleportation by pointing to the destination [9].

One field that uses both spatial navigation and temporal navigation is the field of History. By definition, History is the study of past events that took place in specific temporal and spatial contexts. To study these spatial and temporal contexts, historians use ontology models such as *PeriodO* [40], *Dolce* [16] and *CIDOC-CRM* [11]. While *PeriodO* defines a single long-term timescale based on the notion of period/landscape, *Dolce* and *CIDOC-CRM* define two timescales: 1) long-term evolutions and 2) short-term evolutions.

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Long-term evolutions are described by landscapes which are the association of a spatio-temporal volume and sets of procedures, artifacts and actors. Short-term evolutions are described by procedures and activities. Since our research is carried out in collaboration with cultural heritage experts, we will rely on these two timescales.

Furthermore, historians works are often exhibited in cultural heritage institutions or museums. The latter, both to facilitate the transmission of knowledge and to make their exhibitions more attractive, are now exploiting new technologies. Indeed, digital systems allow, among other things, visitors to navigate spatially and temporally in virtual reconstructions of historical environments¹²³. However, interacting simultaneously with time and space on several scales is a complex task for visitors. Like [12], we consider that embodied interaction, thanks to a greater involvement of the body than the interactions presented above, allows a better understanding of spatial and temporal evolutions. We therefore propose to associate to these virtual representations a tangible interactor to provide an immersive and engaging experience.

In this paper we first study the characteristics of Tangible User Interfaces (TUI) allowing to improve the user's experience in a cultural heritage context and also the spatio-temporal navigation functionalities already implemented in the literature (section 2). This study, completed by formative workshops (section 3), allows us to propose a new interactor enabling an automatic and generic association to an exhaustive set of spatio-temporal navigation functionalities in a cultural heritage context (section 4). In order to validate our hypothesis, we have conducted an evaluation of the acceptability of our interactor (section 5). We then discuss our results and propose some future work (section 6).

2 RELATED WORK

Our work aims to propose a TUI that will allow a user to navigate through space and time on multiple scales. In this section we present previous works implementing spatial and/or temporal navigation metaphors.

2.1 Interaction metaphors for Spatio-Temporal Navigation

ChronoViz [15] is a system to synchronize videos, temporal data streams and handwritten notes. Each data stream is synchronized with a timeline and notes are displayed at the temporal position of their writing. *ChronoViz* proposes three interaction metaphors for temporal navigation: 1) VCR-type controls, 2) navigation by events (e.g., the writing of a note), 3) the direct manipulation of a temporal variable (e.g., graph of a simulated flight). Besides, *ChronoViz* allows spatial positions to be displayed on a map. Selecting a spatial position controls the temporal position of the data streams.

Lilija *et al.* [31], based on [13], propose to control time by direct manipulation of virtual environment elements. Thus, a user can select an element, see its trajectory and navigate through time by moving it along that trajectory. The authors note, however, that

direct manipulation is not suitable for all scenarios and that the concept requires the user to be actively involved with the interaction, which can be tiring in complex scenarios.

Photoportals [29] builds on the metaphor of digital photography to enable the sharing of spatial and temporal references in virtual environments. Photos and videos taken by users with a tangible interactor (a camera) allow them to navigate spatially and temporally by moving through them. In this work, Kunert *et al.* rely on [19] to allow the replay of activities that have taken place over time in the environment. Although these works make it possible to navigate through space and time, they only allow it on a single timescale (short-term evolutions). Moreover, tangible interactions only concern the capture of the environment and not spatio-temporal navigation.

Bennett *et al.* propose *ChronoTape*, a system to assist genealogical research by providing a tangible representation of family history [6]. *ChronoTape* is a paper tape on which dates are indicated. The tape can be associated with digital documents (e.g., notes, images). The user can navigate temporally by browsing the tape. Note that this proposition does not deal with spatial navigation.

This sub-section shows that research has been carried out to propose interaction metaphors for spatio-temporal navigation in WIMP interfaces, TUIs, or in virtual environments. However, none of these works allows, at the same time, to navigate spatially and on several timescales as, for example, those used in cultural heritage. The following subsection presents works proposing to navigate spatially and temporally in a cultural heritage context.

2.2 Spatio-Temporal Navigation in Cultural Heritage context

TimeMachine Oulu [36] proposes to use a Personal Digital Assistant (PDA) and a GUI to display a reconstruction of the city of Oulu in Finland. The user can navigate spatially in the digital environment by physically moving around the real city and temporally by choosing the year he wants to observe through graphical buttons. The user navigates from year to year by time increment. The graphical reconstruction then automatically adapts to reflect the user's navigation. In this application, the user's position in the real environment is determined by the PDA's GPS, which allows large-scale positioning but does not allow navigation within the buildings observed on the GUI. Temporal navigation through the use of incremental buttons does not induce a limit in the number of available dates. However, as the number of dates can be large, it does not allow for a hierarchy of years, by period for example, which would speed up navigation.

On the contrary, Koebel *et al.* proposed a Virtual Reality application to navigate inside a specific building [26] and not in a large open area. *Biennale 4D* is a Virtual Reality reconstruction of the Swiss pavilion at the *Biennale di Venezia* exhibition. In this immersive environment, the user can move spatially by teleportation and, to a lesser extent, walk in its immediate environment. The authors propose to use the metaphor of the time machine as a temporal navigation tool. Indeed, the user can interact with a virtual cube which allows him to select the year he wishes to observe. The authors selected four editions of the exhibition, each year being represented

¹<https://en.chateauversailles.fr/long-read/queens-hamlet>

²<https://www.romereborn.org/>

³<https://www.noovae-studio.com/EN/projets/medieval-city/>

by a face of the cube. Because the time machine is represented by a virtual cube it implies that the number of available dates is limited.

Instead of using a virtual object to navigate through time, Gaugne *et al.* propose to link the temporal and spatial navigation. In *Evolusion* [17] the user is offered the possibility to explore the history of Western music from antiquity to the present day. Because each period is represented by a room, the user changes the observed period by moving from a room to another one.

2.3 Tangible User Interfaces for Cultural Heritage

The appearance or shape of an object can provide clues to its use or function. These concepts, borrowed from the definitions of affordance [18, 35], can be found in many works related to Tangible User Interfaces (TUI) since they involve the use of physical objects to interact with elements of the digital world [24]. Because they improve engagement and creativity [20] they are valuable tools for cultural mediation applications. In this sub-section, we present some works related to the use of TUI in cultural heritage contexts. We categorize them according to their affordance, their shape and their functions.

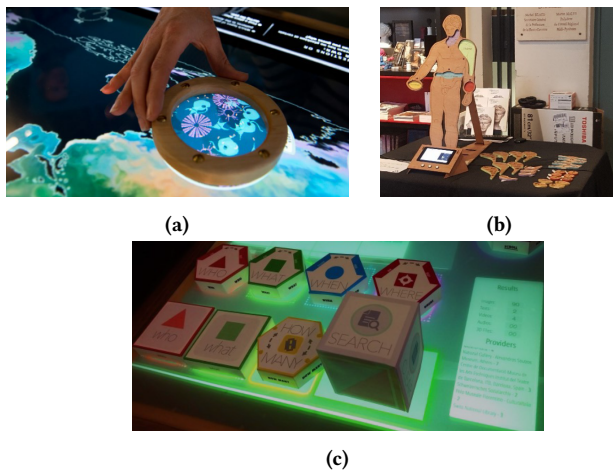


Figure 1: Examples of TUI in context of museum. (a): Ma *et al.* [32]; (b): Rey *et al.* [42]; (c): Pereda *et al.* [37]

The first category consists of digitally augmented objects inspired by the real world that are used in the same way as the real object. The visitor uses a tangible interactor that has exactly the same shape as a regular object. In addition, the user manipulates the tangible interactor to perform the same function as they would with the regular object. The digitally augmented tangible interactor must be spatially tracked in the real world in order to identify the information to be provided. For this purpose, different tracking systems can be used like QR codes, inertial units, interactive tabletops and so on. The second aspect of the digital augmentation is the display of information. This information is presented in several ways: directly on the interactor or on a remote screen.

For example, *The Loupe* [10] gives visitors the opportunity to use a magnifying glass-shaped interactor equipped with a camera

to detect artifacts in an exhibition. The interactor is also equipped with a screen that displays information about the detected object. This information is more or less detailed depending on the distance between *The Loupe* and the observed object. In the same category, Ma *et al.* [32] proposes to manipulate lens-shaped objects to observe microscopic elements (phytoplankton). The positions of the lenses are detected by a multi-touch tabletop. As shown in Figure 1a, the latter also displays the information to be provided.

This type of tangible objects is very affordant, easy to use and requires little time to learn. However, in the context of a complex application allowing many kind of interactions, it is not realistic to use one object per interaction.

The second category we identified includes objects that are more or less affordant but are not used as the real object from which they are inspired. In contrast to the first category, the object, because of its characteristics, carries only information used by the digital environment, and it is the state of this environment that decides on the interaction to be performed. Note that the technologies for tracking the interactor and displaying information are similar to those of the first category.

Petrelli *et al.* [38] propose to use tangible replicas of everyday objects from the Second World War. Each object represents a particular profile (soldier, civilian and civil servant) and, when placed in a particular location, identifies the multimedia content related to the profile. While this application allows users to control the content during the visit, other applications allow them to control the visit route. For instance, *Build Your Own Hercules* [42] allows a group of visitors to personalize their visit according to the time available, the age of the visitors or their interests. As shown in Figure 1b, each criterion is represented by an object (token [44]) that is positioned on a tangible representation of Hercules. Each token is representative of the involved criterion (e.g., the time available for visiting is represented by a token representing a watch). These first two TUI use objects whose shape recalls the information carried. For more genericity in the application domain, it is possible to use objects which do not carry information on the specific content but on more abstract concepts. For example in [37], the objects used represent search fields on a database. They are placed on an interactive tabletop to create a query, for instance WHAT : paintings; WHO : Picasso; WHEN : 1935 (Figure 1c).

In the context of cultural heritage, previous work has shown that the use of TUI and the intrinsic affordance of the used object reduces learning time. However, in these works, either the objects allow only one type of interaction or the form of the proposed interactors is strongly linked to the application cases. On the other hand, the works offering the visitors to navigate spatio-temporally allow to move physically either on the scale of a city or on the scale of a building, and to navigate temporally on a single timescale. However, they do not allow the hierarchisation of the observed periods, nor the navigation in the dynamics of the simulated activities in the digital environment. Moreover, to our knowledge, no work proposing spatio-temporal navigation in a context of cultural heritage has been carried out using TUI.

In the following section, we present the setup of our formative workshops whose objectives are to, first define the affordance criteria of a generic TUI for spatio-temporal navigation in a cultural

heritage context and then to identify exhaustively the associated functionalities.

3 FORMATIVE WORKSHOPS

In order to propose a relevant tangible interactor to navigate through space and time, we set up a co-design process involving cultural heritage experts. Indeed, our work is based on a use case whose objective is to study the history of two bridges that followed one another in time (the first one was destroyed in 1944 and the second one inaugurated in 1954) and spanned over a military arsenal. First, we conducted a primary workshop to identify the functionalities that would allow users to navigate through space and time. Then, we carried out an ideation and prototyping workshop with the aim of proposing tangible interactors that would realize these functionalities.

3.1 Definition of the functionalities

Sixteen participants (including eight women) took part in this first formative workshop. Among them, four were HCI researchers and twelve were cultural heritage experts: one cultural heritage institution director, one collection manager, two curators, two researchers in history of science, three researchers in archaeology, one software developer of cultural heritage applications, and two mediators. They had between four and thirty years of experience ($\mu = 15.4$; $SD = 8.1$) working on designing cultural heritage application or working directly with the general public. This workshop was not time-boxed to let the participants discuss and present their point of view and lasted three hours.

During this workshop, we used the user stories tool, borrowed from the scrum agile methodology [21]. The first task was to identify the different user profiles potentially involved in the use of spatio-temporal navigation tools in cultural heritage institutions. At the end of this first step, six profiles were identified:

General public (*abbrev.* GP): Group of people seeking to share an experience without necessarily trying to learn something;

Audience with knowledge (*abbrev.* AwK): Person or group going to the museum or cultural heritage institution with the objective of deepening their knowledge about the subject of the exhibition;

Group with didactic intention (*abbrev.* GwDI): Group composed of learners and a teacher whose objective is to relate a teaching to the exhibition;

Mediator (*abbrev.* M): Person making the link between knowledge (about an object or a concept) and a target audience;

Researcher (*abbrev.* R): Specialist in a field who needs to navigate temporally to observe the effects of temporal evolutions on a studied system;

Art restorer (*abbrev.* AR): Person needing to navigate between different stages of the life cycle of an object in order to determine the treatments to be carried out to restore the object.

We then asked the participants to individually write user stories involving spatial and temporal navigation. To write these user stories, the instructions were to follow this format: "As a {profile}, I would like {functionality} in order to achieve {objective}".

A total of 69 user stories were written, for instance : "as a visitor from the general public, I want to change the speed of time to observe the movement of the tide and its effects on the sea level". All these user stories were then presented to the participants. Then, they collectively identified 23 functionalities from these user stories. Some of the identified functionalities have similar effects on the environment but do not offer the same operational approach. For instance, it was proposed that the users could navigate between landscape by selecting either a specific year or a specific event. These two functionalities are grouped into the elementary functionality F2: "navigating between different landscapes". In the end, from these 23 functionalities we propose 11 elementary functionalities presented in Table 1. According to their relevance for spatio-temporal navigation, the 11 elementary functionalities are classified into three categories. The first category includes the seven primary functionalities (F1 to F7, highlighted in green in Table 1) which are directly linked to spatial or temporal navigation. They were involved in most of the user stories (for instance: F1 was cited 15 times, F2 was cited 38 times). F8 and F9 compose the second category, they are important for cultural heritage applications but secondary for spatio-temporal navigation (highlighted in blue in Table 1). Finally, the third category contains functionalities that are used for managing the environment (highlighted in mauve in Table 1). These functionalities are not involved in spatial or temporal navigation. They are also part of the least cited functionalities being involved just once in the user stories.

3.2 Ideation and Prototyping

The second workshop aimed at proposing and prototyping several tangible interactors allowing spatial and temporal navigation. Because of this objective, 16 participants (including 6 women) with various backgrounds and expertise (*i.e.*, engineering, mechanical design, cultural heritage, psychology, and human-computer interaction) were involved. The workshop took place in three phases. First, we took 50 minutes to explain how the workshop would happen and to present the spatio-temporal navigation functionalities described in Section 3.1. Next, we conducted a brainstorming session whose objective was to answer two questions: 1) How to represent time in a tangible way? 2) Which interactions should be associated with each functionality? This brainstorming session lasted one hour and was followed by a 30-minutes discussion of the results. Finally, we carried out a prototyping session based on the results of the brainstorming session. The participants had one hour to design a low-fidelity tangible interactor. Then the participants presented the design of their prototype with its intended interactions. Including the different breaks, the workshop lasted for 4h30.

During the brainstorming session, participants were asked to answer the two questions mentioned above. During this session, we first presented our representation of time. Indeed, we consider time on two distinct scales: a short-term scale, linked to the procedures of human activities, and a long-term scale, linked to the different periods of time, also called landscapes, that we find in the functionalities presented in Table 1. Finally, concerning the answers to the brainstorming questions, they are in fact reflected in the prototypes proposed by the participants that we present below.

Id	Functionality	Description	Interested user profiles
F1	change the speed of time flow	slow down or speed up the speed of time flow in the VE to observe a step in more details or gain time	GP; AwK; GwDI; M; R
F2	navigate between different landscapes	change the landscape shown in the VE to observe another place or time	GP; AwK; GwDI; M; R; AR
F3	navigate spatially within a fixed landscape	change the viewpoint displayed in the VE	GP; AwK; GwDI; M; R
F4	navigate in the course of a procedure	select an action in order to observe the state of a system at an instant of a procedure	GP; AwK; GwDI; M; R; AR
F5	start the execution of a procedure	start (or stop) the execution of a procedure in the VE	GP; AwK; GwDI; M; R
F6	select landscapes	select landscapes to navigate to later	GP; AwK; GwDI; M; R; AR
F7	select a procedure	select a procedure to obtain information and initiate execution	GP; AwK; GwDI; M; R; AR
F8	access information relating to a selected landscape	display information characterizing a selected landscape (e.g., start and end dates, milestones...)	GP; AwK; GwDI; M; R; AR
F9	superimpose several temporal states	display several landscapes at the same time in the VE (navigate in several landscapes simultaneously)	GP; AwK; GwDI; M; R; AR
F10	define timescales	define or redefine the timescales used to perform activities or represent landscapes	R; AR
F11	create a landscape according to two dates	create and add a new landscape in the application	M; R; AR

Table 1: Summary of the 11 elementary functionalities to navigate through space and time (green : seven primary functionalities, blue : two secondary functionalities, mauve : two optional functionalities.)

During the prototyping session, the participants could work alone or in a group. Their objective was to design a tangible interactor and its interactions, as well as building a low fidelity prototype using play dough, paper or Lego bricks. Seven participants decided to work alone, three groups of two and one group of three were formed, either by affinity or because the participants had similar ideas. At the end of the prototyping session, 11 low fidelity prototypes and their interactions were proposed.

3.2.1 Proposed Interactors. Out of the eleven prototypes, four took inspiration in everyday objects linked to the passing of time: a clock (P3, Figure 2a), an hourglass (P4, Figure 2b), an ephemeris (P9, Figure 2c) and a concentric calendar (P7). Four were designed around two distinct independently moving parts, such as wheels or cubes (P1; P5; P6; P11, Figure 2d). One was based on a map and used tokens (P8) and the two last were designed as generic (not related to space and time) interactors (P2; P10).

3.2.2 Prototype Evaluation. Following the prototyping workshop and in order to identify the interactor that we should implement, we set up an evaluation of each prototype according to two criteria: affordance and usability. The affordance criterion evaluates whether the shape of the interactor (in our case the low fidelity prototype) suggests to the user how to manipulate it. Affordance concerned the whole interactor and was evaluated once for each prototype. The usability criterion was split into three sub-criteria according to the ISO 9241-11 standard :

Effectiveness : Does the interactor enable the user to achieve his objective, to carry out the intended task?

Efficiency : Is the interactor easy to use, does it require much effort to use?

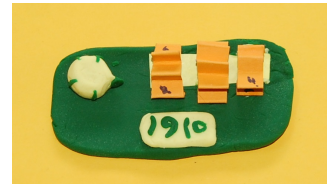
Satisfaction : Is the interactor pleasant to use?



(a)



(b)



(c)



(d)

Figure 2: Sample from the 11 proposed prototypes. (a) Prototype n°3, (b) Prototype n°4, (c) Prototype n°9, (d) Prototype n°11

These three sub-criteria were evaluated for each functionality the prototype implemented.

To evaluate the prototypes, we called on 10 cultural heritage experts (5 women), notably those who had taken part in the first formative workshop (4 of them took part in this evaluation). All the participants had over 5 years of experience in cultural heritage ($\mu = 13.0$; $SD = 7.0$).

Note that, we initially planned to have the assessors come to our research laboratory so that they could manipulate the low-fidelity prototypes. However, due to the national restrictions in place to fight against COVID-19, this possibility was ruled out.

This is why we decided to conduct this evaluation online. More concretely, we asked the participants to fill in a questionnaire. It was associated with a document describing, in depth, the functionalities described in the first formative workshop, the prototypes and their intended interactions. Each of the criteria was rated on a scale of 1 (very low) to 5 (very high). Once the questionnaire was completed, we conducted an interview to gather qualitative feedback [33]. Note that, after asking the experts for their consent, we recorded these interviews for post-processing analysis. Although not time-boxed, the interviews lasted between 30 minutes and 1 hour for a total duration of 5 hours ($\mu = 39min\ 22s$).

Nevertheless, due to the online aspect of the evaluation, we decided to focus our analysis on the more subjective criteria: affordance and satisfaction.

We then verified whether a prototype stood out from the rest by using a Kruskal-Wallis test [28]. This did not show any significant differences between the prototypes neither on the affordance criterion ($p = 0.11$) nor on the satisfaction criterion ($p = 0.19$).

For this reason, we also adopted a qualitative approach by analyzing the verbatim recorded interviews, focusing on both the affordance and satisfaction criteria.

Regarding affordance, three experts (E*) noted that a circular shape reminded them of time as opposed to a cube. For instance: *"it speaks more to me when it's round, it clearly reminded me of an audio or VHS cassette"* (E5); *"I find that a cube is not adapted to time at all"* (E4). Besides, four experts specifically indicated that an hourglass shape (see Figure 2b) suggests the manipulation of temporal concepts: *"when we think of time, we inevitably think of an hourglass"* (E1); *"the hourglass is also an interesting idea; the time aspect is well identified by the hourglass"* (E6). Overall, the shape of the interactor and its association with time is a point that was raised by the experts: *"It is less obvious to make this association of ideas between this object and time"* (E6) about prototype n°9 (see Figure 2c), *"this tool is reminiscent of time"* (E4) about prototype n°4 (see Figure 2b).

As for satisfaction, some experts mentioned that they preferred to perform simple interactions *"because there is a simplicity of use"* (E7 on his positive assessment of prototype n°5 satisfaction) such as rotating or moving the interactor: *"there is nothing simpler than putting the object where you want it"* (E1), *"it seemed very understandable to me because there is this system of discs, we understand that a disc turns"* (E2). However, E1 pointed out that *"using the same button for several actions bothers me"*. This indicates that the number of actions for each interaction should be limited.

The quantitative results did not show any significant differences between the prototypes according to the affordance and satisfaction criteria. Nevertheless, the qualitative results of the experts' interviews allow us to issue guidelines for the design of a tangible interactor to navigate through space and time in a cultural heritage context. On the one hand, the relationship between the interactor shape and time is a specific element to be considered. On the other hand, the interactor should offer simple interactions and also limit the number of actions per interaction.

The evaluation by the cultural heritage experts could not clearly designate the best prototype to implement, even if we have design guidelines. Therefore, we also completed this evaluation by adding engineering criteria such as technical feasibility, assumed cost of

manufacture, variety in interaction modalities, and the presence of visual feedback integrated into the interactor. Again, each criterion was rated from 1 to 5 in order to be consistent with the experts' evaluation. We then averaged the scores for each interactor to compare them.

As a result of this evaluation we find that, amongst the 11 low-fidelity prototypes, the best compromise between satisfaction, affordance, and the additional criteria is prototype n°4 (Figure 2b). Moreover this interactor is one of the everyday life objects category. As we have seen in Section 2 this implies less learning time for the user. This prototype is shaped like an hourglass and proposes, in particular, that the user manipulates the speed of time by tilting and turning the interactor. We then decide to implement a fully functional version of this interactor, that we call SABLIER. This implementation is presented in the next section.

4 WORKING PROTOTYPE IMPLEMENTATION : SABLIER

4.1 Requirements

For our working prototype, according to the guidelines (Section 3.2.2), we want to keep the affordance of the hourglass metaphor both in its form and in its use. For this reason, our interactor should not only look like an hourglass, but also function similarly to be as close as possible to the metaphor. First, we want it to be sized so that the user can manipulate it with one hand, as a classic hourglass could be. Second, the user should also be able to find the functioning of an hourglass through the interactions.

Like a regular hourglass, the user can observe the flow of sand in one direction or the other if the hourglass is turned upside down, tilt it to reduce the speed of the sand flow or lay it down to stop the flow. By analogy, we can link the use of a standard hourglass to one of the proposed functionalities such as F1 (see Table 1): changing the speed of sand flow controls the speed of time flow. To go further than the use of a regular hourglass (tilt), we propose to augment our prototype with three additional interactions: tap, move and rotate as shown in Figure 3. To do this, our prototype will have to rely on a system capable of detecting the user's hand and also a tracking system to detect its position and orientation.

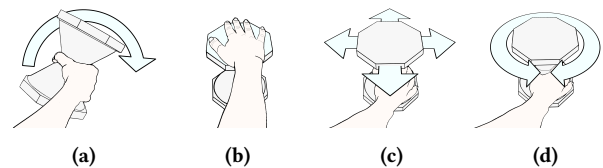


Figure 3: Possible interactions. (a) tilt, (b) tap, (c) move, (d) rotate

4.2 Electronics

In order to meet all the requirements presented above, we have equipped SABLIER with these following electronic components:

- an inertial unit with a gyroscope, an accelerometer and a compass to sense the tilt angle of the interactor

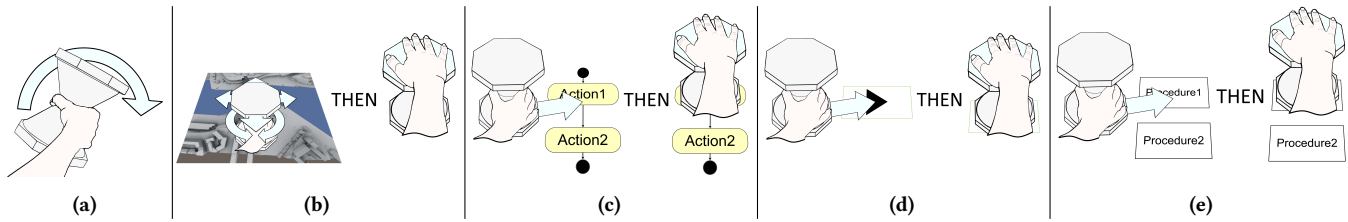


Figure 4: Proposed interaction for each functionality. (a) F1, (b) F3, (c) F4, (d) F5, (e) F7

- a NeoPixels LED strip mainly to imitate the sand flow and give a visual output on the side
- 12 (6 on each face) unique NeoPixels LEDs giving a visual output on the top and bottom faces
- 12 inductive sensors going along with the LEDs, placed on top and bottom faces, in a circular shape to detect a tapping interaction (and eventually a sliding interaction not currently exploited) from the hand of the user
- a Raspberry Pi Zero to control the above mentioned components
- a 12V @ 3000 mAh LiPo battery with a voltage step-down regulator to 5V (to power the Raspberry Pi)

4.3 3D modeling

We designed SABLIER to look like a real hourglass and in order to integrate all the electronics inside.

Because the battery is the most heavy component, we designed the electronics support pieces (Figure 5b and 5e) to keep the battery in the center. That way, when manipulating SABLIER, the user won't feel any difference in the weight distribution. These pieces also have sockets to hold the LEDs and the inductive sensors. The piece (e) has indeed sockets to hold the Raspberry Pi Zero and the inertial unit.

Moreover, the part presented in Figure 5c is designed so the LED strip can easily be attached on the side. The main body (Figure 5d) is also translucent, so the light from inner LEDs can get through. The hoods (Figure 5a) are also designed in order to use different type of tracking markers (e.g., NFC, QR Code, Multitouch Pattern, Infrared optical markers, *etc.*) according to the tracking system used. The hoods could be easily replaced, depending on the tracking method chosen.

Finally, the different parts are arranged as shown in Figure 5 to form SABLIER.

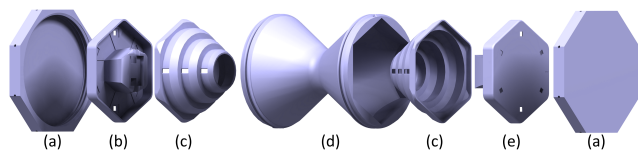


Figure 5: SABLIER mounting range : (a) hood, (b) A-face LEDs and inductive sensors support, (c) side LED strip support, (d) SABLIER main body, (e) B-face LEDs and inductive sensors support and battery socket

4.4 From SABLIER to a Tangible User Interface

Following the example of the TUI proposed in the relative work section (Section 2), we propose to couple SABLIER to an interactive tabletop. Coupling SABLIER with a tabletop interface is a complementary approach that first allows the user to put our augmented hourglass on the tabletop so he can free his hands as he would do with a conventional hourglass but also to have a complementary display on the tabletop.

As shown in Figure 6, the GUI displayed on the tabletop is separated into three areas. The upper left area (n°1) is a dynamic top view of the digital environment. The upper right area (n°2) is a menu that can display the list of procedures in the environment or the progress of a selected procedure. The lower area (n°3) is a timeline representing the different landscapes available.

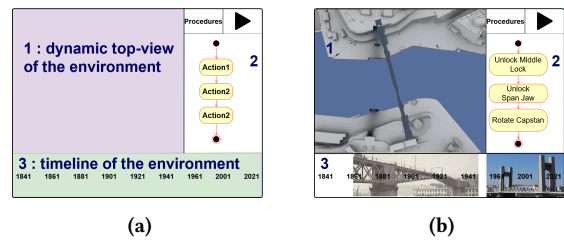


Figure 6: Implementation of the GUI for a cultural mediation use case (area n°1 : dynamic top-down view of the environment, area n°2 : menu showing either the list of procedures or the diagram of a selected procedure, area n°3 : timeline of the different landscapes).

By placing SABLIER on the different areas and validating with a tap, the user can interact with the interface elements. For example, placing the interactor somewhere on the dynamic top view area and validating will take the user's point of view to the location (with the orientation) of the hourglass (Figure 4b). In a same way, the user can control procedures by selecting them and temporally navigating inside them through the procedure area (by placing SABLIER on the desired action, and validating with a tap as shown by Figure 4c). When a procedure is selected, the progression of the procedure is illustrated by simulating the flow of sand inside an hourglass. This simulation is carried out by the brightness level of the LED strip running along the entire height of SABLIER. Finally, the user can navigate between landscapes through the bottom timeline.

4.5 TUI & Immersive Situation for Cultural Heritage

In a cultural heritage context such as ours, adding a highly immersive system to tangible interactions can engage a user as much as a visit to a physical museum [5]. Among the highly immersive systems like Head-Mounted Display and CAVE-like systems, the latter have the advantage of immersing the user in VR while letting them directly see the real tangible interactor.

From the user's point of view, as shown in Figure 7, adding a table-like object into a CAVE may obscure part of the screen. The virtual content that the user sees on the tabletop is then the wrong one. Indeed, the user is looking at the virtual content originally projected at floor level, distorted by the table-like object (Figure 7a). Instead, the user should see the content in the direct continuity of his field of vision: the content of the hidden area (Figure 7c).

Hence, we implemented a shader that recalculates the projected image to display a copy of the occluded content on the tabletop according to its shape. Figure 7b shows the perceived content from the user's point of view without the projection mapping shader, and Figure 7d with it. Moreover, this projection mapping also works with non-planar surfaces, as long as these are not tangent to the projection cone.

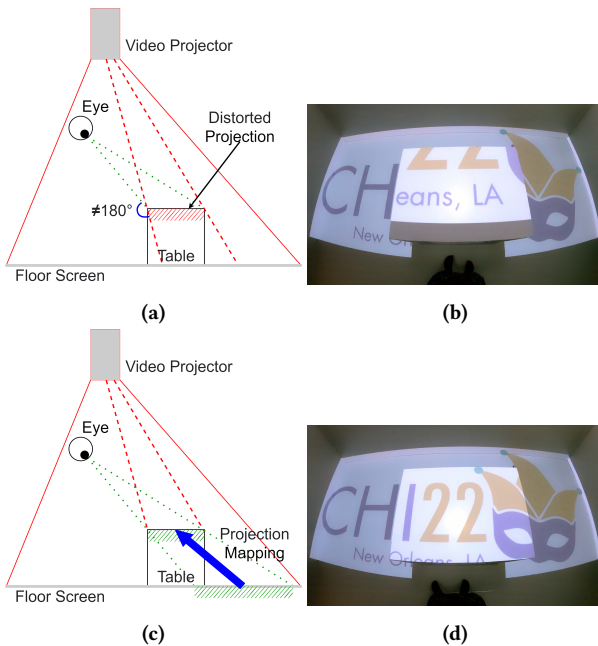


Figure 7: Comparison of perceived content from the user's point of view without and with projection mapping. Without projection mapping, diagram (a) resulting photo (b). With projection mapping, diagram (c) resulting photo (d)

5 EVALUATION OF SABLIER ACCEPTABILITY

To evaluate the validity (ability of the user to realize the functionalities) of our proposal as well as its perceived usefulness and ease of use, we conducted a user evaluation. In this study, we asked

participants to use SABLIER to navigate spatially and temporally within a virtual environment. In this section, we describe the participants and the experimental protocol. We finish by presenting and analyzing the collected data.

5.1 Participants

25 people aged 19 to 62 ($\mu = 38.4$; $SD = 14.4$) took part in this evaluation. The group of participants consisted of 14 men and 9 women, among those who wished to specify their gender. Of the group, 36% reported visiting museums more than 4-6 times per year and 56% reported visiting museums 1-3 times per year. All the participants were considered as General public (GP) profile (cf. Section 3.1).

5.2 Procedure

The experiment was divided into three stages. The first one was to introduce the virtual environment of the experiment, its historical context and the CAVE. It was important to introduce the CAVE because not all participants had the same experience with Virtual Reality (VR). Indeed, out of the 25 participants, 11 had never had any experience with VR, 4 had tested VR devices occasionally (1 to 3 times a year), 6 use them regularly (4 times a year to 3 times a month) and 4 use them in their daily life (at least once a week). Next, the GUI displayed on the tabletop was presented as well as all the interactions proposed by SABLIER (see Figure 3) and its implemented functionalities (F1, F3, F4, F5, F7).

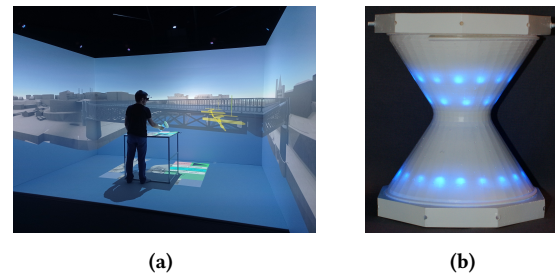


Figure 8: (a): User manipulating SABLIER in an immersive situation. (b): Photograph of SABLIER with the internal LED strip on.

During the familiarization phase, after the presentation of all the elements composing the TUI, we let the participants get acquainted with SABLIER outside the evaluation environment. During this phase, participants were invited to manipulate SABLIER without time constraints, and discover all its interactions (tilt, tap, move, rotate, see Figure 3) on a generic version of our GUI displayed on the tabletop. The experimental situation is illustrated on Figure 8a.

In the second step, the scenario was presented and detailed to the participants. The scenario asks the participants to realize seven tasks: 1) selecting a procedure (F7), 2) starting its execution (F5), 3) slowing down the flow of time (F1), 4) stopping the execution (F5), 5) moving the point of view of the scene (F3), 6) selecting an action of the procedure in progress (F4), and 7) reversing the time flow (F1). Then, we let the participants follow the scenario without any time constraint.

Variable	Question	Agrees	Net Top Box
PU1	Using this interactor in a museum would enable me to navigate through space and time more quickly.	64,00%	40,00%
PU2	Using this interactor would improve spatio-temporal navigation.	76,00%	64,00%
PU3	Using this interactor in a museum would increase my comprehension of the spatio-temporal evolutions.	80,00%	56,00%
PU4	Using this interactor would enhance my effectiveness in navigating through space and time.	68,00%	52,00%
PU5	Using this interactor would make it easier to navigate through space and time in a virtual environment.	88,00%	64,00%
PU6	I would find this interactor useful in a museum.	96,00%	84,00%
PU		80,00%	48,00%
PEU1	Learning to operate this interactor would be easy for me.	96,00%	76,00%
PEU2	I would find it easy to get this interactor to do what I want it to do.	80,00%	56,00%
PEU3	My interaction with this interactor would be clear and understandable.	88,00%	72,00%
PEU4	I would find this interactor to be flexible to interact with.	96,00%	72,00%
PEU5	It would be easy for me to become skillful at using this interactor.	96,00%	88,00%
PEU6	I would find this interactor easy to use.	96,00%	88,00%
PEU		88,00%	64,00%
V1	I managed to navigate spatially in the virtual environment.	76,00%	60,00%
V2	I managed to select a procedure.	100,00%	96,00%
V3	I managed to select a particular action in a procedure.	100,00%	96,00%
V4	I managed to run a procedure.	100,00%	100,00%
V5	I managed to slow down the speed of time.	92,00%	88,00%
V		100,00%	80,00%

Table 2: Share of positive answers to questions on Perceived Usefulness (PU), Perceived Ease-of-Use (PEU) and Validity (V)

Finally, the participants had to answer two questionnaires. The first one was built on the model of the Technology Acceptance Model (TAM) questionnaire [1], adapted to our situation. Some questions in the TAM asked participants to evaluate our proposition in comparison to existing systems. For these questions we asked participants to evaluate SABLIER against systems they already had the opportunity to use in museums or in virtual environments. We proposed a second questionnaire to check the validity of the interactor. The participants were asked if they have succeeded in doing each of the functionalities involved in the scenario. Each item from the two questionnaires were on a 7-point Likert scale.

Throughout this experiment, we ask the participants to express their thoughts out loud in order to take notes. These notes allowed us to put the results of the questionnaires into perspective and get more qualitative data on the strengths and weaknesses of our proposition.

5.3 Results

In order to validate the acceptability of our proposition, we first analyze the results regarding the evaluation of the usefulness and ease of use of SABLIER. Then we look at the answers to the second questionnaire on the success or failure to achieve each of the proposed functionalities.

5.3.1 Perceived Usefulness (PU) & Perceived Ease of Use (PEU). Table 2 shows the share of positive responses (score above 5) in the third column and the difference between the share of participants who definitely approve (scores of 6 or 7) and the share of participants who definitely do not approve (scores of 1 or 2) in the fourth column.

The results of our study show that participants perceived our interface as useful for navigating spatially and temporally within a digital environment. Indeed, 80% of the participants (20 out of 25) rated the Perceived Usefulness (PU) of SABLIER positively. More

concretely, this result represents the number of participants who responded, on average above 5. The other 5 participants were neutral (in average between 3 and 5). The lowest rated question was about the ability of SABLIER to enable quick spatial and temporal navigation (PU1), only 64% of the participants (16 out of 25) agreed with this proposition, 5 participants gave a neutral answer and the 4 last disagreed. The improvement of efficiency (PU4) was evaluated positively by 68% of the participants (17 out of 25) while 19 participants indicated that SABLIER would improve spatio-temporal navigation (PU2). Almost all participants (24 out of 25) considered that our interface proposal would be useful in a museum (PU6).

The assessment of the Perceived Ease of Use (PEU) of SABLIER shows that our interactor was widely regarded as easy to use and learn. 88% of the participants (22 out of 25) Perceived the Ease of Use (PEU) positively, the other participants were neutral. 96% of the participants (24 out of 25) considered it would be easy to learn to use SABLIER (PEU1) and to become skilled in its use (PEU5). 88% of the participants (22 out of 25) felt that their interactions with our interactor would be clear and understandable (PEU3). 80% of the participants (20 out of 25) found it would be easy to get SABLIER to do what they want to (PEU2).

For each of the questions on the Perceived Usefulness and Perceived Ease of Use of SABLIER, the Net Top Box (see Table 2) is positive which means that the proportion of strongly positive responses predominates over the proportion of strongly negative responses.

In addition, we can calculate an overall TAM score coherent with the SUS and UMUX scales by calculating $SABLIER_{PU}$ (see Equation 1) and $SABLIER_{PEU}$ (see Equation 2) and averaging them (see Equation 3) according to Lewis [30].

$$SABLIER_{PU} = (AVERAGE(PU1, PU2, PU3, PU4, PU5, PU6) - 1) * (100/6) \quad (1)$$

$$SABLIER_{PEU} = (AVERAGE(PEU1, PEU2, PEU3, PEU4, PEU5, PEU6) - 1) * (100/6) \quad (2)$$

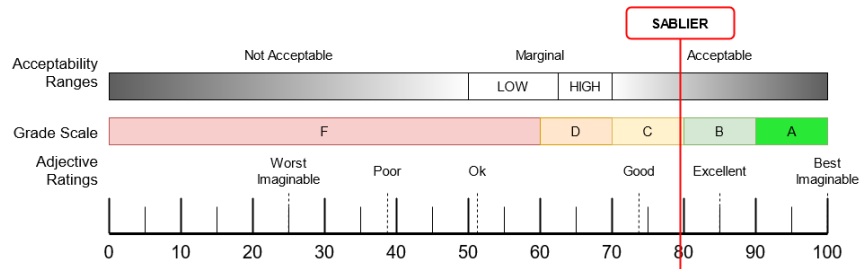


Figure 9: Representation of the SUS/UMUX Scale and the position of SABLIER on this scale.

$$SABLIER_{TAM} = AVERAGE(SABLIER_{PU}, SABLIER_{PEU}) \quad (3)$$

This gives us $SABLIER_{PU} = 76.78$ and $SABLIER_{PEU} = 83.00$, we get an overall score of $SABLIER_{TAM} = 79.89$. According to [4] this score places SABLIER in the acceptable range of the SUS scale (Figure 9).

5.3.2 Validity of SABLIER. In order to verify the validity of SABLIER for the functionalities we proposed in this evaluation, we asked the participants to rate the ease with which they performed each interaction. The results (lowest section of Table 2) show that all participants felt successful in performing the functionalities.

For each of the variables related to the validity of SABLIER, with the exception of V1, at least 92% of the participants (23 out of 25) considered that they had successfully performed the associated functionality. With 76% of the participants (19 out of 25) considering that they could easily change their point of view in the virtual environment (V1), spatial navigation was the least well perceived functionality.

6 DISCUSSION AND FUTURE WORK

According to Section 2, works proposing spatial and temporal navigation metaphors generally provide single scale temporal navigation [6, 13, 17, 31]. Furthermore, Tangible User Interfaces have shown many advantages for the cultural heritage domain in terms of attractiveness [32], engagement [5] and are preferred to the use of phones in a museum context [38]. With SABLIER, our TUI proposition builds on these advantages and offers users the possibility to navigate spatially and temporally on several scales.

Regarding the evaluation of affordance and satisfaction of the low-fidelity prototypes by the cultural heritage experts, the results did not reveal any significant difference. However, a qualitative approach allowed us, based on the analysis of the experts' interviews verbatims, to issue some guidelines for the design of a tangible interactor to navigate through space and time. Although we have taken these guidelines into consideration for the implementation of SABLIER, it would be necessary to evaluate and validate them with, for example, the implementation of other prototypes.

The results of the SABLIER acceptability evaluation presented in Section 5 show that our TUI is perceived as acceptable by the users (see Figure 9). In addition, during this evaluation, participants indicated that SABLIER was "much more efficient" (P9), "easy to learn because there are only a few buttons" (P4) and "easy to get used to, even for children or the elderly" (P11). These comments are in line with

those expressed by the experts during the video interviews (Section 3.2.2). From their perspective as museum visitors, participants mentioned that SABLIER was "super nice for cultural mediation" (P2), could "really have an interest in museums" and that "if you put that in a museum people will never leave" (P18). It should also be noted that the participants appreciated the hourglass shape because "the hourglass object gives a very concrete representation of time" (P20), and "for mediation, I think it's really nice" (P2). These comments confirm that the association between the interactor shape and time is an important criterion.

According to the result of the Table 2, the participants felt that they were able to carry out the functionalities. Nevertheless, some negative aspects were highlighted. Indeed, spatial navigation was the least well perceived functionality, as P5 mentioned "it is easy to navigate through time, more difficult through space". In order to improve spatial navigation, participants suggested adding visual feedback of the user's position "on SABLIER top face to know where you are specifically on the map" (P21) and also to use SABLIER top face as a magnifying glass because "it hides what's underneath" (P5). These suggestions are made possible by our projection mapping shader. Furthermore, although the GUI dynamic top view already allows users to maintain visual contact with the virtual environment, it would be interesting to display this visual feedback in a 3D World-In-Miniature [14, 23, 43]. Moreover, although included in the immersive environment (CAVE), the tangible workspace (tabletop) separated from the visualization space can cause the user to shift their gaze between these two spaces. While this aspect was not raised by any of the participants in our evaluation, we are considering setting up an alternative that displays a dynamic and transparent replica of the tangible workspace in the visualization space.

Besides, some participants indicated that SABLIER "is too heavy" (P3), however, one of them specified that it was easily gripped: "the hourglass is quite heavy but easily grasped" (P14). Similarly, some participants reported that SABLIER was "too big for the map" (P4). Both of these problems are related to our electronic design. Indeed, the size and weight of SABLIER are mainly constrained by the internal electronics. In a future iteration of SABLIER, we could design a specific electronic board allowing us to save space and review the sizing of the power supply battery and thus, reduce the size and weight of SABLIER.

Finally, SABLIER could also be evaluated within cultural heritage institutions. This evaluation would be focused on the improvement of the user experience and how SABLIER can help the different

user profiles (see Section 3.1) better understand multiscale temporal evolutions.

7 CONCLUSION

In this paper, we presented SABLIER, a tangible interactor allowing a user to navigate spatially and temporally in a digital environment. This interactor results from a co-design process with cultural heritage experts. This process relies on two formative workshops. During the first one, we identified the functionalities to implement. Following this first workshop, we conducted an ideation and prototyping workshop whose goal was to propose tangible interactors that would allow the implementation of the functionalities identified by the experts. To identify the interactor we would implement, we evaluated the proposals of the second workshop on the criteria of affordance, user satisfaction and engineering. The result of this process is SABLIER, an hourglass-shaped tangible interactor allowing a user to navigate spatially and temporally. Unlike the works presented in Section 2, SABLIER is a generic interactor which is not bound to a specific application case. It also allows interaction and navigation on several timescales, one scale associated with temporal landscapes and the other associated with human activity procedures. We conducted a first evaluation in order to verify the acceptability of our proposition as well as its validity. The results of this study show that SABLIER is perceived as acceptable in the context of a cultural heritage application.

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