An evolving museum metaphor applied to cultural heritage for personalized content delivery

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Abstract The aim of this article concerns adaptive and personalized navigation in a cultural heritage database. The theoretical grounding of the proposition relies on cognitive science, particularly constructivism and enaction. The navigation is conducted via an intelligent interface through a 3D "living" museum metaphor. The purpose of this interface is to recommend dynamic cultural heritage objects according to a user profile that is computed online from the interactions that a user has with these objects. To this end, objects are linked to semantic structures that represent relations between cultural heritage concepts. The user profile is described in terms of cultural heritage interests. A prototype of this principle is used to evaluate some of the basic hypotheses of this proposition.

Keywords visual metaphor · real-time adaptation · profiling techniques · personalized database exploration · virtual museum

1 Preamble for the reviewer, relative to UMUAI submission

- What is the main research question that your planned submission addresses ? *How can we personalize cultural heritage data exploration "in line " through a co-construction paradigm (i.e., during the exploration and not from a predefined user profile)?*
- What makes your research results important and worth being reported in a top-ranked journal (as opposed to a conference) ? *This paper presents an global study compound of some results: 1) a model that includes the*

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interactive environment and an evolving representation in response to the user's interaction , 2) its implementation, and 3) an evaluation of the results. Each part could be a conference paper on its own. Moreover, to the best of our knowledge, the model is highly original because it is based on an evolving in-line visual metaphor.
- Why does your planned submission fits into the scope of UMUAI ? *The work is focused on a cultural heritage application (and we are applying for a special issue on this subject) and aims to improve interface personalization (which is a main concern of the journal).*
- What are the main limitations of your approach ? *It is not extended to collaborative exploration of data. The evaluation is limited to specific hypothesis and doesn't cover all the purpose of the proposition.*
- What is the relationship of your work to the closest 2-3 publications by others ? (also cite them):
  *In (***dos2004adaptive***), Santos and Osorio proposed an approach named "AdapTIVE," which is applied in the commerce domain. This approach is close to ours in terms of navigation and adaptation. However, in our case, the environment evolves progressively according to the user's interaction, which is not true for AdaptTIVE. Our approach allows guidance of the user exploration and control of the complexity of the data. A similar approach proposed by Bonis et al. (***bonis2013adaptive***) is also applied in the cultural heritage field. The main difference with our approach is in the mechanism used for the generation of the environment. Bonis et al. organize the positions of the objects according to the user's center of interest, but the structure of the environment is guided only by semantic information. In our case, the structure of the environment is based on an intersection of semantic information and the user's center of interest, which evolves during the exploration. In (***stock2007adaptive***) Stock et al. proposed an interactive and adaptive interface dedicated to the museum visitor. In their approach, animated agents help motivate visitors and focus the visitors' attention when necessary. The authors' objectives are to generate automatically adaptive multimedia documentaries on mobile devices and post-visit according to the interests of visitors, which are determined by their behavior and choices during their visit.The relationship with our work is the notion of adaptive generation. In our case we generate a 3D environment which is the support of content while they generate multimodal documents.*

2 Introduction

Current technologies allow direct access to databases that may contain thousands of items providing cultural heritage information (objects, events, places, characters, and items related to religious, economical or military heritage). These databases are complex not only because of their considerable size but also because of the numerous relations, implicit or explicit, that exist between the items they contain. It is possible to use these data to augment the understanding of the societies that produce them. Search via keywords is not sufficient because the goal is not to find specific information but rather to grasp the relations that exist between items. These relations provide a reading context that sheds light on the information itself. This goal can be advanced by the design of an itinerary that highlights the relations between different items. One important point is that during an exploration of the data, the user's concern is not precise and may be erroneous. The user's focus will gradually be refined during the exploration and according to the user's interests and the user's evolving understanding. Furthermore, as the amount of data is substantial, the user may miss relevant information or relations relating to his questions. Thus, the personalization of navigation in a cultural heritage database is crucial in this context. A key point is to consider the evolution of the user's center of interest during his exploration resulting from encounters with novel information. Similarly, it is possible to improve the introduction of novel information to favor the evolution of the user's center of interest by considering certain knowledge. This knowledge is defined by incorporating expert knowledge of certain domains with the user's center of interest. In this paper, we will introduce a system that provides this capability during the exploration of a cultural heritage database. We discuss an enactive or co-evolutive system in the sense that it favors the evolution of the user's center of interest and the user's understanding through his interactions with the system. Enaction is a cognitive science paradigm, similar to constructivism in psychology, that considers the coupling between cognitive agents and their environment, the basis of the construction of knowledge and the circular dependencies between these elements. These features characterize the proposed system as an enactive system. In (**DeLoor2009b**) we present our positioning in cognitive science by defining the notion of enaction-based artificial intelligence. The present work take part on this positioning. More concretely, the user interface is a virtual museum with a number of rooms that evolves during the user's visit and according to his behavior as a museum visitor.

To present this work, we begin in Section 3 with a survey on data representation, particularly from a cultural heritage perspective, and on the personalization of recommendation systems. This survey justifies the originality of our proposition, the main features of which we present in Section 4. We illustrate its functioning in Section 5. Section 6 presents the model underlying the approach and its formalization. Section 7 then presents an evaluation of the model. This evaluation shows that the system is able to follow the user's center of interest in real time and to adapt its own evolution to that of the user. The evaluation also shows that the user understands and appreciates the system's proposition. Finally, Section 10 stresses the limitations and perspectives of this work.

3 Related work

Helping the user to explore the data involves retrieving relevant information according to his interests and providing him with a global view of the links within this information, particularly to continue the exploration. This process is promoted using tools and methods, including, on the one hand, the organization of the presentation spaces according to the contents and/or the behaviors of the users and, on the other hand, how the information is delivered to the users.

One approach to exploring the data is to give the user the ability to indicate what information is most relevant to him; users explicitly mark their interest (or lack of interest) in certain elements of information. Kelly et al. (**kel2006**) note two drawbacks of this approach: the cognitive load induced by the notation and the risk of appearance of context traps.

In another approach, the information elements are described according to several dimensions (or facets), such as a spatial dimension, a temporal dimension or a thematic dimension. Facets offer several entries into the database and several points of view on the information contained therein. The exploration of a database is performed by the successive application of filters according to different dimensions. A hierarchical structuring of the values of each dimension allows the user to refine these queries as his exploration progresses. Dörk et al. (**dor2008**; **dork2012navigating**) proposed to use neighborhood relations in each dimension to recommend new information elements to be interested the user and thus to continue the exploration of the database. They call this mechanism "weighted brushing". The difficulty of this approach lies in the manual creation and updating of the different dimensions.

An approach to supporting the exploration of the database is to establish neighborhood relationships between similar elements of information. The idea is to organize the data presentation space according to the content of the database to be explored. Bonis et al. (**bonis2013adaptive**) and Damiano et al. (**dam2015**) considered ontologies that formally describe the domains the databases address. Ontologies are used to structure the information space (and thus neighborhood relationships). The membership relationships of the information elements to the categories defined by the concepts determine how the information space is populated by the information elements. Stock et al. (**stock2007adaptive**) evaluate the centers of interest of the user to generate a personalized summary of his visit. To do that, the system (PEACH) propagates values among a graph of concepts. This propagation is triggered explicitly by the user or defined implicitly by the system according to an analysis of the user's behavior. Another approach uses clustering algorithms. Each element of information is characterized by a vector computed from a set of keywords. Sjöberg et al. (**sjo2006**) applied a self-organized map of Kohonen to create a set of clusters distributed on a 2D grid to understand the structure of a large image collection. To this end, they considered graphical attributes extracted automatically from images and annotation given by human contributors. In the same vein, Aviles Collao et al. (**avi2003**) and Kaipainen et al. (**kai2008**) proposed the use of soft ontologies to explore cultural heritage resources. Soft ontologies are a geometrization of folksonomies. They interactively support several points of view with respect to a collection of objects or events represented in the form of 2D plots.

A common problem encountered in exploratory search is identifying the user's needs to adapt the traversal of the data.

Many approaches focus on the exploitation of semantic links between data items to achieve more relevant results that are returned by word queries. There are many exploratory tools applied in different domains, as presented by Goodchild et al. (**li2014towards**), Nuzzolese et al. (**nuzzolese2017aemoo**) and Poco et al. (**poco2014similarityexplorer**). Sun et al (**7108039**) proposed a topic-oriented exploratory search that allows the user to discover associations and knowledge.

In a completely different approach, some authors proposed to continue the exploration of the data based on statistical learning. As part of the visit to cultural heritage sites, Albanese et al. (**alb2004**) proposed the use of a neural network to predict the keywords describing the next place to reach. The neural network is trained offline from a corpus of visits. In other works, the predictions are obtained using Markov chains or collaborative filter systems (**Boh2007**).

The use of user profiles not only restricts the information elements to be presented to the user but also defines how to continue the exploration of a database. Veron and Levasseur (**veron1983**) proposed a user classification according to 4 classes also reused by other authors (for instance, (**Chittaro2004AVT**)). Each of these classes, represented by an animal (ant, grasshopper, butterfly, or fish), is characterized by the behaviors of its users—their movements, the time they spend in front of the exhibited works, and the nature of these works. Sookhanaphibarn and Thawonmas (**soo2010**) presented a formalization of each class via a function of probability of presence in a point compared with a work. Kuflik et al. (**kuflik2012**) experimentally validated the classification presented in (**veron1983**). Sparacino (**spa2001**) did not simply propose an ontology of visitors; she proposed the use of Bayesian networks to classify visitors according to the time they spend in front of exhibits. In this work, Sparacino used other networks to characterize the content to exhibit according to different criteria, including the class of the considered visitor.

Athukorala et al. (**ath2016**) presented a system that can classify the research style of the users (two classes were considered: exploratory and lookup search) and to adapt the search engine's parameters so that the search results best match the user's expectations. In addition to the algorithm for the retrieval of relevant information, the design of the interface is a challenge for data exploration. Conventional search engines consider queries expressed as text, and search results are given as lists of texts and images. This form makes it difficult to interpret the results and to express queries. Several works advocate the use of graphical representation to exploit the abilities of the human visual system to detect patterns and relationships between objects. Keim (**kei2002**) described many algorithms developed to explore large databases. One of the key points in visual data mining is to find the right method of mapping data attributes onto graphical attributes (pose, size, color, and texture). Donalek et al. (**don2014**) suggested that we cannot understand anything if we cannot somehow visualize it.

According to Svanaes et al. (**sva2013**) we create meaning through physical interactions with the surrounding world. Virtual reality allows more natural interactions by immersing the users in the data (employing a helmet, sensors able to track the body, and the gestures of the user). This approach promotes more direct access to the data that considers the body of the user, particularly considering the continuous interactions between this body and its environment (hence the graphical representation of the data). One of the principles of virtual reality is that placing data at the human level helps make sense of those data. Azzag et al. (**azz2005**) presented VRminer, a 3D interactive tool to explore multimedia data. The user can navigate naturally within the data and select information for a more detailed description. However, the system does not adapt to the user. Teras and Raghunathan (**ter2015**) discussed the need for embodied perception and interaction to be able to understand big data.

However, excessive data can cause the user to become lost. Meta-data can help him navigate to the data most relevant for him. These meta-data can be explicitly represented in graphics form (e.g., labels) or implicitly using metaphors. A metaphor is a meta-model of environments familiar to users, allowing the association of a meaning with objects of these environments. For example, in a 3D environment, a room groups similar objects. A door between two rooms encourages the user to move from one group of objects to another, even when the door is closed. Several metaphors of navigation and presentation have been studied: metaphors of books and libraries (**car1996**), museums (**kou2012**), cities (**spa1999**), a mountain landscape(**rob1998**), and a island landscape (**boy2002**).

In our work, we are interested in how to mutually influence the user and the data exploration system in terms of the refinement and discovery of information through the interface. This approach implies a need to coordinate the recommendation and interaction processing.

4 Positioning

As we briefly mention in the introduction, the originality of our proposition relies particularly on three aspects: 1) The proposition is dedicated to exploration and not to researching information. 2) It evaluates the profile of the user in real time during this exploration. 3) It uses an interface that evolves continuously according to the user's behavior and that relies on a 3D metaphor. This proposition is inspired by constructivism and enaction paradigms (**Piaget1951**; **Varela-1993**) . These paradigms consider that the knowledge and the sense making of living beings are constructed from their interactions with their environment and, more drastically , from the circular dependency between them. According to this stance, and taking enaction as a type of recommendation, our interface relies on two principles:

1. **Co-construction:** The personalization of the navigation in the database is driven by a strong coupling between the user and the database. More precisely, the user and the representation of the data influence each other continuously. The system proposes information according to an analysis of the user behavior and of the interactions of the user with the data. If the user is inactive, the system must be able to propose information to attract his interest. We can find similar propositions in, for instance, (**stock2007adaptive**) with the system PEACH. It also evaluates the user profile in realtime. However, the co-construction principle of our approach implies that the adaptation of the environment is done in realtime during the exploration (that is not the case for PEACH which computes a summary of the visit at its end). We can also find common idea with (**dork2012navigating**) (VisGets). VisGets proposes information from an analysis of user's interactions (it uses the notion of facet that is close to our notion of semantic dimension). The difference with our proposition is mainly on the fact that our system is pro-active while VisGets is reactive. Another important difference is on choices made for the visualisation
2. **Embodiment:** The user is situated within the information. He can move and naturally interact with it. This situated aspect relates to the role of links between actions and perceptions in the understanding of our "own world" (**noe**). Then, the user explores the information in the strictest sense; relevant information for him is close to him, and similar information or information elements that are linked together are also close together and make clusters in the environment. The user can approach or move away from information and spend time in front of it to acquire new knowledge. Embodiment also allows for an implicit proposition of information representation that is considered potentially relevant by the system to favor co-construction. A similar proposition could be found in (**Wang**) with the system CHIP, which personalizes and embodies a visit from a user profile. However, CHIP computes the environment before the visit. It's not an online co-construction.

These two principles are implemented through the metaphor of a 'living' museum. This museum evolves and grows according to the interactions of the users (see figure 1). According to a real-time analysis of the interactive behavior of the user, certain heuristics guide the museum's evolution, resulting in a co-evolution between user and data presentation. Moreover, the embodiment is reflected by the fact that the user is situated within the virtual museum and that the data are incarnated with poster presentations whose presence has relevance according to the links that exist between them.

The long-term objective of this research is to help people understand complex facts or situations related to cultural heritage such as events, places, objects, religions, mentalities, business, and wars, which are all local information linked together. These links make it possible to obtain a global understanding of a civilization or a historical evolution, for instance. The short-term objective of this study is to present and evaluate models and algorithms developed

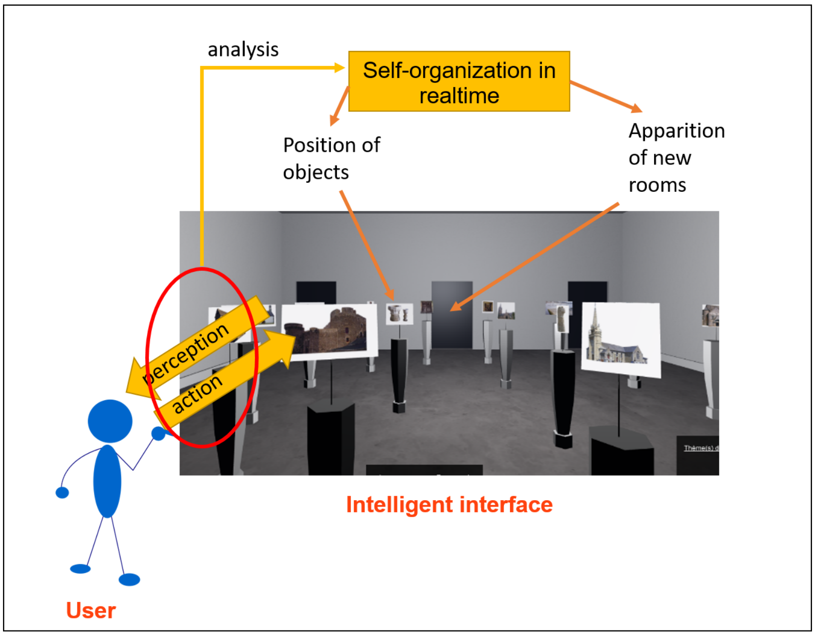

Fig. 1 Main principles of our proposition: Co-construction is obtained from the analysis of the user's behavior and a self-organization of the evolving museum. Embodiment is relative to the incarnation of the data and the situation of the user relative to the data.

to obtain a self-adaptive and real-time growing virtual museum. The choice of a virtual museum derives from the fact that we mainly address the cultural heritage domain. However, as we will show, the model is far enough generic to be applied to other growing metaphor. For example, we applied it to ACM publications (see section 6.4). In this case, it may have been possible to replace display stands by shelves and rooms by bookcases. The prerequisite of the metaphor is only to be based on cells that can contain objects and the use of passages from cells to cells. Then, the model is able to propose dynamically new cells populated with new objects as well as new passages between these cells.

5 Example

Before the presentation of the underlying model that we designed to realize our proposition, we believe that an illustrative example that concretely explains different steps during an exploration of a user may be useful:

– Figure 2: At the beginning of the exploration, the user is in one room, and the doors that allow access to other rooms are closed because these other rooms are not "instantiated." The creation of these rooms and the opening of the corresponding doors depend upon the behavior of the user.

Each time new rooms are constructed, they will similarly have new closed doors, a process that can be repeated indefinitely. A room is associated with one or more topics. Here, the topic of the first room, chosen randomly, is *"battlefield"*. The objects in this room have a strong relationship with this topic.

- Figure 3: The user consults information about one of these objects. Here, the object is characterized by *"battlefield* but also by other topics: *"murder"*, IX^{th} *century*, and *"Rieux"* (a city in France). This approach allows the user to discover information about a specific place or a particular period.
- Figure 4: The user takes a tool for keyword visualization and selects the term *"Economy"*. He continues to visualize and to consult information in this *room*.
- Figure 5: After a certain period of navigation, one door is opened on a new room. The topic attributed to this room is *"Economy"*. This room prompts the user to discover new objects that are strongly linked to economy.
- Figure 6: Because the user does not enter the previously created room, another door is opened that leads to another new room that has three topics: *"Market"*, *"Rieux"* and *"IX^{th} century"*. These last two topics are among the concepts that characterized the objects consulted by the user in the *first room* and *"Market"* is an element that allows another vision of the concept of economy. The user decides to enter this room, which has three new doors allowing access to other rooms.
- Figure 7: The user stands in front of one door. He thus implicitly asks the system to suggest a new room. It does so by creating a room and by opening the corresponding door. The topics attributed to this room are *Marine* which corresponds to commerce (*"Market"*), *"Saint Hélene"* which is a city in the same region as *"Rieux"*, and *"X^{th} century"*. These three topics are close semantically to the concepts that characterized previous rooms. This process continues in Figures 7 to 10. The process shows the capabilities of the system to refine its proposition according to the user's behavior but also its capability to propose topics that were not intentionally sought by the user and that will influence his next behavior.
- Figure 11: The system provides the user an opportunity to navigate in time through a specific door. He can access a room with the topic *"$XVIII^{th}$ century"*. The room allows, for instance, the user to compare objects from two periods that have other topics in common. However, the user stays in the room with the topic *"XIX^{th} century"* and consults certain heritage objects. Because the heritage objects in these rooms present characteristics that correspond not only to the *"XIX^{th} century"* but also to others, the user may be influenced by other objects that are considered far from his initial centers of interest. At this stage, he consults information about ship models in the *"XIX^{th} century"*. In response to this behavior, the system influences him to discover different types of models by creating a new room with this topic.

Fig. 2 Entrance hall(topic: battlefield).

Fig. 3 Consultation of certain objects in the *entrance hall*.

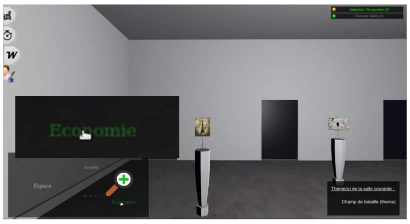

Fig. 4 Use of navigation tool, selection of one keyword: *Economy*.

Fig. 5 Creation of new room with abstract topic "Economy".

Fig. 6 Creation of new room with a detailed topic.

Fig. 7 Creation of a new room semantically close to Fig.6 in term of category in heritage field, region and period.

Fig. 8 Consultation of objects classified in many categories of heritage field.

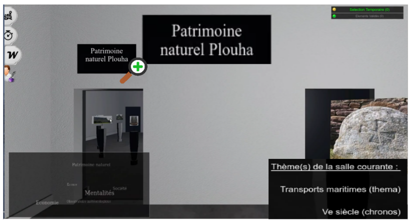

Fig. 9 Creation of a new room with a topic different from the centers of interest of the user.

Fig. 10 Creation of a new room with a topic that characterizes the time period.

Fig. 11 Creation of a new room semantically close to Fig. 10 in term of a certain period of time.

This example has illustrated the notion of co-evolution that we defend: The user is influenced by the system through propositions that are more or less in relation with his initial interest. In return, the system tries to suggest new heritage objects corresponding to his centers of interest while introducing some novelties. The resulting museum is specific to the user and to the evolution of his interest during his visit.

6 Model

6.1 Main components

In the model, the general operation of our proposition relies on two spaces (see figure 13): the interaction space and the recommendation space.

The **interaction space** is a three-dimensional environment structured in rooms (embodiment of the notion of clusters). A graph represents the relation of adjacency between rooms. At the beginning, the museum contains only one room. All of the interactions of the user are recorded in a list of traces that is used by the recommendation space.

The **recommendation space** is composed of the database, certain semantic representations of cultural heritage concepts and different processes that allow the real-time evaluation of the user profile and a real-time proposition of new data to represent according to the traces that come from the interaction space. More precisely, each semantic representation is a graph for which the vertices are cultural heritage concepts and edges are semantic relationships. These graphs are also used to represent the relationships between concepts and cultural heritage objects in the database. Currently, we use three graphs:

– **Thema** is an anthropological representation of cultural heritage. This concept is close to an ontology such as CIDOC-CRM but is simpler according to the constraints and specificity of our industrial partner. The partner edits books on cultural heritage (**flohic**). His editorial line presents articles according to an anthropological vision. Although it is not the purpose of this paper to discuss this choice, we can provide an idea of the resulting concepts. For instance, concepts could be *Mentalities, Religions, Trades,* *Status, and Castles*. Links are of the type ***is a***. Figure 12 illustrates an extract of this semantic representation. In fact, the semantic representation contains 945 concepts. Each data element of the database is tagged with one or more of these concepts.

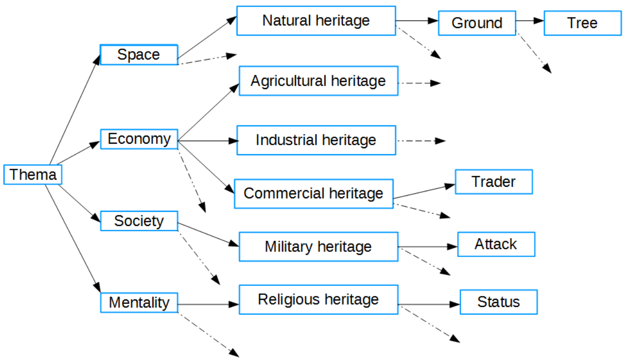

Fig. 12 Extract of the semantic structure *Thema*. The complete structure contains 945 nodes.

- **Chronos** is a representation of time. Concepts are ordered (*before, after*) as well as hierarchical (*during, overlap*). Indeed, different granularities are used, such as *age, centuries, year, days*.
- **Topos** is a representation of the geographic position of the data on a map. These positions allow the definition of an adjacency graph. Each vertex is a place, with each edge representing a distance between the two places that it connects. Technically, this graph is not fully represented in memory but is partially computed when necessary.

These graphs are used to compute the user's center of interest. To this end, real numbers are associated with each vertex and each edge. These values are computed according to the interactions of the user with the data, which can be interpreted as a degree of interest of the user for a concept at one moment. It is possible to update all of the edge and vertex values because each data element has some relation to different concepts of the graphs. Then, the computed values represent the assumed interest of the user in concepts or links between concepts. The values can be interpreted as a user model.

6.2 Temporal evolution principles

The coupling between the user and the data is obtained via three steps executed in a time sequence by the system:

1. The system computes dynamically the *style* and the *profile* of the user from the trace of interactions. We use a taxonomy of visitors inspired by

(**veron1983**). For instance, a visitor can be assimilated to an ant when he meticulously observes each data element and each room of a museum. Alternatively, he can be assimilated to a grasshopper when he ignores a great deal of the data. For us, the style of the visitor is considered (according to (**veron1983**), butterfly and fish visitors are possible intermediate types, but in our case, we need not make such a precise profile because the system is able to adapt in real time to its evolution). The profile is relative to the concepts that are assumed to be of interest to the user.

2. The system defines the concepts that appear more relevant at a given moment. To this end, it considers the profile and the style of the user and the semantic relations included in the semantic structures (recommendation engine in figure 13).
3. The system selects data in the database linked to the more relevant concepts. Data are sent to the interaction space, which will represent them in the 3D environment in new rooms (Sampling in figure 13).

The research of the relevant concepts relies on a bio-inspired metaphor: pheromone diffusion and spreading activation. This meta-heuristic is generally used for optimization or classification to reinforce certain paths in a space (**Dorigo**).

The next section will detail and formalize all of these elements.

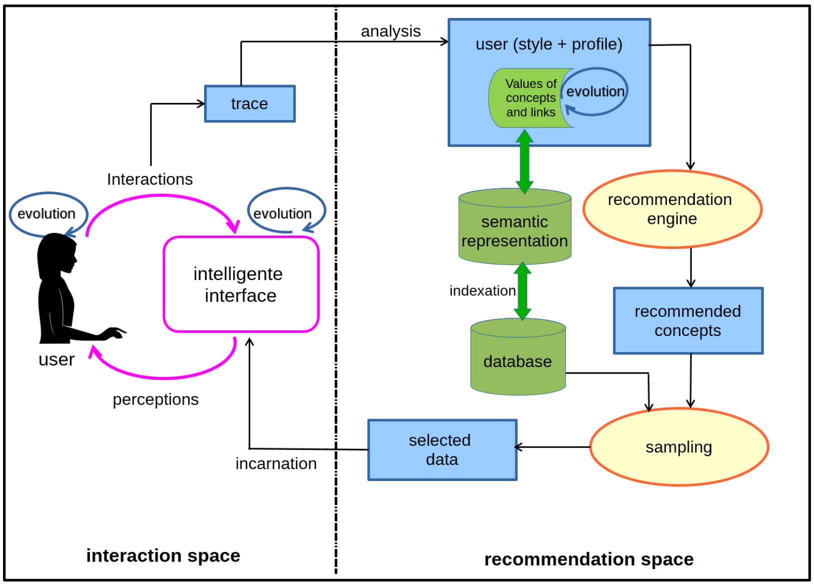

Fig. 13 Main components of the principle of our proposition.

6.3 Formalization

6.3.1 Interaction space

The interaction space IS includes a model of the environment, a model of interactions and a model of traces. Real-time evolution of these models is provided by the user's interactions and an incarnation of the relevant data that come from the semantic space.

The model of the 3D environment is a graph $Env = \{C_{IS}, R_{IS}\}$ where :

- C_{IS}, a set of cells.
- R_{IS}, a set of edges that link cells to each other and that represents the topology of the environment. In our case, each cell represents a room of the museum.

Each cell can contain a certain number of entities with which the user can interact. The set of such entities is named $InteractEntities$. Concretely, the elements of the set can be a cultural heritage object that is in the database, interactive tools provided by the environment (topos, chronos, and thema; see below) or even the doors of the museum. Each entity e of the environment is associated with a set of semantic concepts C_e.

An interaction of the user with an entity e is represented by a triplet: $Interaction = (C_e, \eta, t)$:

- η is the type of the interaction. A type is, for example, *selection* or *displacement*. However, it can also be a "*passive*" interaction such as *observation of an object or a text during a certain amount of time*. The number of possible types of interactions depends upon the implementation of the graphical interface (3D web page, virtual environment, immersive environment or even a 2D web site could be represented by this model). To generalize, we must consider only that each type is associated with a specific 'strength'. This strength characterizes the *a priori* importance that the user imputes to entity e_i when he interacts through $Interaction$.
- t is the time when the interaction has been realized.

Consequently, during his exploration, the user generates a $Trace$ of all of the interactions he had with the different entities in the environment. Formally, $Trace$ is a sequence $[Interaction_1, Interaction_2, ..., Interaction_n]$

6.3.2 Recommendation space

The recommendation space is composed of semantic structures denoted SS (in the final application we have 3 semantic structures: chronos, topos and thema but the principle is applicable to any number of semantic structures) that are linked with the data of the database and with all of the entities with which the user can interact in the environment (set $InteractEntities$).

From these structures, and according to the $Traces$ of the user, an interpretation process computes a set of relevant concepts. The style of the user can be used to parameterize the function that computes these concepts (see below). These concepts will be used as such which will characterize the next new room of the environment. Moreover, because each data item in the database is linked with the semantic structures, a function determines relevant data that will populate this new room.

Each data item in the database and each element in the environment is linked to semantic structures.

There are two kinds of entities represented in the environment. The first one are objects which correspond to the item of the database and the second one are different interactive tools (map, rooms and doors of the museum, chronological fresco ...) which allow the user to indicate place, time or keywords. Both kinds of entities are linked to concepts of semantic structures. Formally, we denote C_e the set of concepts which corresponds to an entity e in the environment.

We denote SS the set of semantic structures, each of them is a graph, so $\forall ss \in SS, ss = (C_{ss}, R_{ss})$ where:

- C_{ss} is a set of vertices representing concepts in ss,
- R_{ss} a set of edges representing relations in ss.

Different functions are defined on these structures:

- $distance : C_{ss} \times C_{ss} \rightarrow \mathbb{R}$. The value of $distance(c_i, c_j)$ depends upon the type of concepts represented (ss). For instance, for the **Thema**, the value is the minimum number of edges in R_{SC} that are necessary to cross in the graph to join c_i to c_j. For **Chronos** and **Topos** a mathematical function is used that computes duration and distance between c_i and c_j respectively.

6.3.3 Recommendation's steps

The recommendation uses the trace of interactions to evaluate the relevance of each concept $c \in C_{ss}$ for all ss in SS. Figure 14 illustrates this process that we explain below.

We formulate four research questions:

- The more a user interacts with a concept (through the entities in the environment linked with this concept), the more this concept and concepts close to it in the semantic structure can be relevant for the user.
- If the user successively interacts with two different concepts, the path in the semantic structure between these two concepts contains concepts that might interest the user even when the two concepts are distant in the semantic structure. Such concepts can be distant from the concepts with which the user has interacted.
- If a concept is close to concept that is considered relevant from the previous hypothesis, it might be relevant to the user, even when he has not interacted with it or with concepts close to it.

– A concept not related to interactions becomes increasingly less relevant.

To consider these hypotheses, we decompose the relevance of a concept from three *relevance parts*. The first associates a weight with the concepts of the different semantic structures through the diffusion of *relevance* from the last consulted concept to concepts close to it. We name this relevance the **relevance from user proximity (RUP)**. The second associates pheromones with the edges that constitute the path between two concepts successively consulted by the user. We name this relevance the **interactive proximity relevance (IPR)**. The third is the **semantic proximity relevance (SPR)** which considers that if a concept is relevant, concepts semantically close to it might be relevant. This last part is not exactly the same as the **RUP** because it is independent of the user interaction. There are no dependencies between these three relevance parts and they are computed independently of one another. Thereafter, the **final relevance (FR)** is computed, from the previous parts. It is possible to set the function that computes **FR** to each of the three relevancies a greater or lesser extent. These settings can be modified according to the user style (see below).

To realize these principles, we use the pheromone metaphor. **Asynchronous processes**, triggered by the interactions of the user, introduce relevance values and pheromones into the semantic structures. A simulation loop allows for **synchronous processes** that manage the evaporation of pheromones. These principles allow consideration the dynamic of the user's activities. Hence, a concept not consulted for a long time will have a weight that decreases slowly. Figure 14 illustrates the global mechanisms and can be used to support the following explanations:

6.3.4 RUP computation

For the first part of relevance, we define $RUP : (c, t) \rightarrow \mathbb{R}$ value of a concept c at step t.

Asynchronous processes:

When the user interacts with an interactive entity e in $InteractEntities$ at time t, an asynchronous process introduces an interaction $(C_e, \eta, t) \in Trace$.

For each c in C_e, $RUP(c, t)$ is updated with the following equation:

$$RUP(c, t) = RUP(c, t-1) + \lambda(\eta)(1 - RUP(c, t-1))$$

where $\lambda(\eta)$ is an augmentation rate that depends upon the type of the interaction (η). This equation ensures that $RUP(c, t) \leq 1$.

The diffusion to neighbors of c is performed if the value of $RUP(c, t)$ exceeds a threshold th_{RUP}:

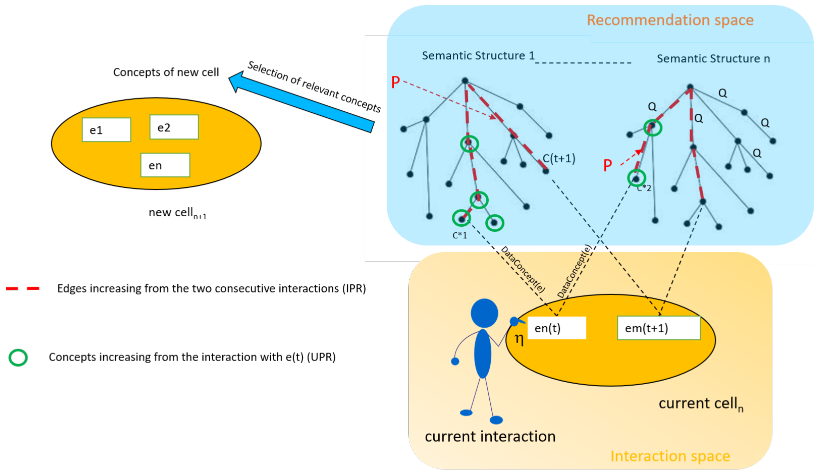

Fig. 14 Illustration of the functioning of the algorithm when the user interacts with an entity e_n and then with an entity e_m. c_1^* and c_2^* are such of e_n in two semantic structures. Green circles show concepts close to these concepts that most likely be affected by a change of UPR, and red dashed lines correspond to the path on which pheromones will be increased and increase IPR. SPR is not evolving from interactions.

Given ρ, the proportion of relevance extracted from $RUP(c, t)$:
if $RUP(c, t) > th_{RUP}$ then: $RUP(c, t) = RUP(c, t)(1 - \rho)$, and for each c_n neighbors of c in the semantic structure: $RUP(c_n, t) = RUP(c_n, t - 1) + RUP(c_n, t) * \rho/m$ when m is the number of neighbors of c.

Synchronous processes:
To prevent all RUPs from progressively reachinges the maximum value for each concept and to assign greater importance to recent interactions compared with the oldest, the relevance of each concept is decreased by a small value at each execution of the simulation loop of the system:
for each concept c of a semantic structure, $RUP(c, t) = RUP(c, t-1) * (1 - \epsilon)$

6.3.5 IPR computation

Concerning the second part of the computation of the relevance, pheromones are associated with each edge of the semantic structures. We use the path that separates the two last concepts with which the user interacted:

Asynchronous processes:
When the user interacts with a concept c^* and given c_1 as the previous concept, P is the shortest path that links c_1 and c^* in the graph. Given $Q(edge, t - 1)$ the pheromone level of an edge $edge \in P$ at step $t - 1$, this level will be increased as follows:

$Q(edge, t) = Q(edge, t-1) + \delta/|P|$, where δ is a parameter that represents the reactivity of the system to the user interaction and $|P|$ is the length of P.

The interactive proximity relevance due to two consecutive interactions of two concepts belonging to the same semantic structure ss is $IPR : (C_{ss} \times C_{ss}, t) \rightarrow \mathbb{R}$ and is the average of the pheromone level of each edge in the path P:

$IPR(c, c^*) = \sum_{edge_i \in P'} Q(edge_i, t)/|P'| * Q_{max}$, where P' is the shortest path between c to c^*, when Q_{max} is the maximum pheromone level encountered on the path P. By this equation, we ensure that $IPR \leq 1$

Synchronous process:
Concerning RUP and to consider the dynamic of the user, each simulation loop, the pheromone rate is decreased by a small value (evaporation): for all $edge \in SC : Q(edge, t) = Q(edge, t-1) * (1 - \epsilon_2)$

6.3.6 SPR computation

For the third part of the relevance, the semantic proximity relevance, we use the definition of (**wu1994verbs**) to evaluate the similarity of two concepts c and c^* in a semantic structure:
$SPR(c, c^*) = \frac{2*L(c^-, c_0)}{|L(c, c^-) + L(c^-, c^*) + 2*L(c^-, c_0)|}$

where the function L defines the number of edges between two concepts, c^- is the common concept between c and c^*, and c_0 is the root concept of the semantic structure. This definition ensure that $SPR \leq 1$.

6.3.7 Style computation

The evaluation of the style of the user (*grasshopper* or *ant*) is done by the semantic proximity between the last consulted concepts. So, it can evolve during the exploration. A high proximity corresponds to a *grasshopper* and a low proximity corresponds to an *ant*. We set empirically a threshold that defines the value of the proximity which separates these two styles.

6.3.8 Final relevance computation

The final relevance of a concept c at time t is determined with the following equation:

$$FR(c, t) = \sqrt{\alpha * \exp^{2*RUP(c,t)} + \beta * \exp^{2*SPR(c,c^*)} + \gamma * \exp^{2*IPR(c,c^*)}}$$

where c^* is the last consulted concept in the semantic structure. We use exponential functions because the values of relevance are more often close to 0 than to 1. This equation, while ensuring that FR remains less than 1, also more effectively accounts for the variability of SPR, RUP and IPR between simulation steps.

The parameters α, β and γ allow certain parameters of evaluation to be favored or penalized ($\alpha + \beta + \gamma = 1$). Once α is defined at the beginning of the exploration, it will not be changed during the exploration. This condition does not hold for β and γ. These both parameters change according to the style of the user: if the user is an ant, β will be set greater than γ. In contrast, if the user is a grasshopper, γ will be set greater than β.

This calculation is executed for each semantic structure (Topos, Chronos, and Thema) at each step.

6.3.9 Creation of new cells

New cells are created in two cases:

1. If the relevance of certain concepts (note that RC represents the set of relevant concepts) exceeds a certain threshold, the environment creates a new cell c which is considered an entity of the environment ($c \in InteractionEntites$). Thus, $c = (C_c)$ where $C_c = RC$
2. If the user asks for a new cell, concepts that have higher relevance are chosen for this cell. In practice, for the virtual museum, the user is considered to be asking for a new cell when he pauses in front of a closed room.

According to a sampling algorithm, certain amount of data d (depending upon the choice of the graphical metaphor) of the database, which has concepts (C_d) in common with cell (C_c) are chosen randomly to populate the new cell.

For the 3D virtual museum, each cell is a room that contains at maximum sixteen objects. A mass-spring algorithm is used to define the position of each data in these rooms. The springs rigidness between each data are proportional to the semantic distance between them.

6.4 Genericity

This model can be applied to any semantic structures and environments and suits the following conditions:

- The data of the database are linked with concepts in semantic structures.
- The graphical metaphor must be based on the notion of cells that contain data representations.

– Each interaction that the user can have in the environment is associated with a type, and each type is associated with a rate that corresponds to the effect of this interaction on the supposed interest of the user on the object he interacts with (variables η and $\lambda(\eta)$ in the formal model).

In the case of our example, the cells are rooms of the virtual museum and representations of the data are pictures and texts that describe the cultural heritage objects. To show the genericity of our proposition, we implemented three versions of this interactive evolving model of data exploration:

1. The cultural heritage database in the virtual museum presented in Section 5.
2. The cultural heritage database with a web-style interface. This version not only allows the genericity of the model to be shown but is also used to compare a 2D environment with a 3D environment (see Section 7). In short, mechanisms that are equivalent to visits to rooms or the selection of objects, such as the virtual museum presented in Section 5 , are permitted. The difference is that the representations of the objects and the rooms are represented flat (on a main frame). No perspective is possible, and no displacements of the user in a virtual space are allowed. The three green rectangles in Figure 15 represent the equivalence of the three rooms that can be accessed from the room in which the user is located in the virtual museum. These rectangles do not contain pictures, but they allow concepts that are associated with them to be displayed. As in the virtual museum, the user can click on a picture to obtain information about the corresponding object. He can click on a rectangle to consult the objects corresponding to concepts displayed on it (the new objects corresponding to the clicked rectangle will be displayed on the main panel, the concepts of the last clicked rectangle are those displayed on the orange rectangle, and the concepts of this last will be displayed on the bottom rectangle). Figure 15 shows this interface and the tools (on the right) that allow the user to indicate places that interest him. In fact, three tools (map, timeline, and keywords) can be used similarly to the 3D virtual museum.
3. The semantic structure of the Association for Computing Machinery (ACM; see `http://acm.rkbexplorer.com/`), with the metaphor of the growing virtual museum. The aim of this version was only to challenge the genericity, and it was convincing; the environment was able to present articles that change progressively with keywords and can exhibit the temporal evolution of this or that scientific thematic, for instance (see Figure 16).

7 Evaluation

7.1 Hypotheses

We evaluated our proposition according two aspects:

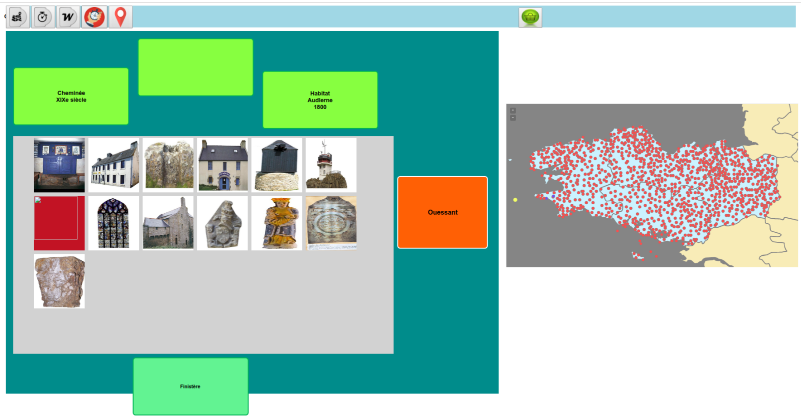

Fig. 15 Snapshot of the web page version of the exploration of cultural heritage data.

Fig. 16 Application of our proposition to the ACM library.

1. the adaptability of our system to the user, which includes objective measures of the behavior of the system and a subjective evaluation that allows the confirmation that the interpretations of the system about the user are correct. Ideally we should evaluate if the user understands the complexity of the data with our system and we should compare this understanding with users that doesn't use our system. However, this kind of evaluation is out of our reach. It needs a formalization of what it is the understanding of complexes data and how to measure it. Moreover, we have done these experimentations during the cultural heritage days to insure that participants had a minimum interest for cultural heritage. The drawback is that these participants were volunteers and were not come especially to pass an evaluation. They also had a limited time. All these points lead us to limit the evaluation on the adaptation ability of the system. In fact, it is justifiable by 2 points: 1) adaptation is a prerequisite to obtain a coevolution between

the user and the system and 2) according to the enactive paradigm, co-evolution is a prerequisite to provide understanding and sensemaking for a living being.

2. the user experience, including his understanding and appreciation of the system behavior, his feeling about the capability of the system to allow the discovery of interesting information to catch the attention of the user and feelings about the graphical representation. In particular, the enactive paradigm takes part on the trends of embodied cognition that considers that the situation of an agent into his environment is crucial to improve his sense making. 3D environments are more immersive than 2D Web pages. They situate the user among the data. His displacements in the environment have a direct impact on his perception of these data, affordances like doors, lights, distances could influence the behavior of the user. Different studies show that performances are better in 3D than in 2D. For example, Jennett et al. presented three experimentations in (**jennett2008measuring**) in order to compare the quality of experience in immersion and in non-immersion. Objective and subjective measures used for these experimentations allow them to conclude that immersion is not only a positive experience but also run high. To verify this hypothesis in the context of our works, we compared the two kinds.

   Our hypotheses are as follows:

- H1: The system adapts itself in real time to the users' centers of interest but is also able to influence these centers of interest and to help users to discover novel information:
  - h1.1: The system determines both the information close to the centers of interest of the users and the information that is far from these centers.
  - h1.2: The user perceives that the system proposes objects and room topics close to his center of interest.
  - h1.3: The system is able to propose objects close to the user's interest, even when the centers of interest change during exploration. This hypothesis does not consider the comparison between the user's point of view and the system, only the objective behavior of the system, by assuming that Hypothesis h1.1 is valid.
  - h1.4: The system is able to influence the user's centers of interest by proposing novelties that interest the user, a result not anticipated at the beginning of the exploration.
- H2: Our proposition, including the virtual museum metaphor, improves the user experience:
  - h2.1: The system allows for the discovery of objects that were not initially envisaged by the user but that are ultimately interesting to him.
  - h2.2: The 3D virtual museum facilitates a better perception of propositions made by the system than does a 2D web interface; for example, the clustering of similar objects is well perceived.
  - h2.3: The 3D virtual museum allows faster exploration of the data.

7.2 Experimentation description

To evaluate these hypotheses, we conducted two experiments during the *cultural heritage days*, two days during which museums and cultural heritage sites are free for visitors. We installed our setup in a cultural heritage site [1] (see Figure 17), providing an opportunity to test our system with people who are generally interested in cultural heritage.

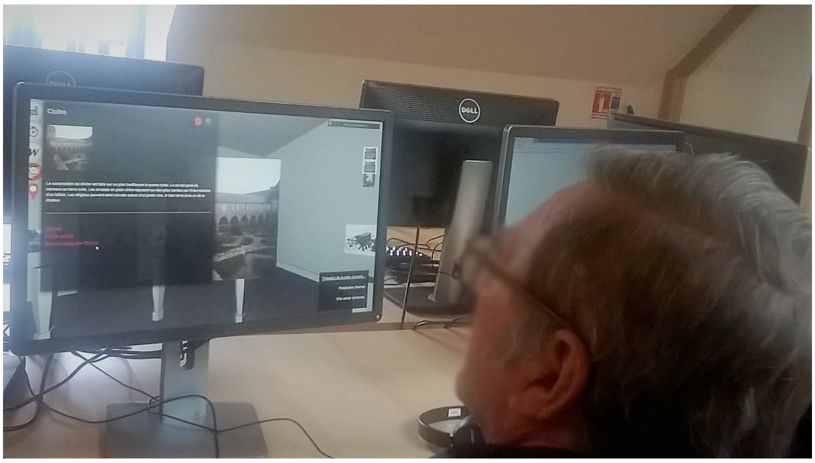

Fig. 17 Photo taken during the experiment.

The first experiment (Exp. 1) consisted of asking participants to explore the virtual museum for ten minutes exactly as though they were visiting a museum (we would have preferred to offer longer visits, but we soon found that people were not motivated to participate in an experiment when they knew that it would take 15 minutes plus the time to watch the learning video). There was no task to accomplish or goal to reach. We explained that the museum contains a great deal of cultural heritage objects about Brittany and that they must visit it. Initially, the participants were asked to watch a tutorial of the virtual museum that explained, for example, how to move, how to place an object in or retract an object from the virtual shopping cart, and how to use tools. When the participants were ready, they entered certain information (age, video game practice, and cultural heritage interest) and began the visit. In this step, we recorded different data such as the consulted objects, visited rooms, and interactions. We also recorded data to analyze the behavior of the algorithm— objects and rooms that are proposed to the user (associated with timestamps) and the 4 most relevant concepts that were assumed to belong to the centers of interest of the user. The 3 less relevant concepts and 3 other concepts randomly chosen such that they obtained a relevance between 0.1 and

[1] The Trevarez castle: `https://en.wikipedia.org/wiki/Chateau_de_Trevarez`

0.4 were also recorded. Then, subjects were asked to answer a single-choice questionnaire (similar to scale or qualitative modalities; see Table 1). We also used 4 points Likert scales. This choice could be criticable because it force the user to make a choice. However, has stated by (**krosnick2010**) it is sometime relevant to avoid a neutral proposition. It allows for the obtention of tendencies and to force users to be attentive and to not drop a question which seems too difficult for him. Users also answered open-ended questions to collect more details, opinions and feelings about the system.

The second experiment (Exp. 2) consisted of comparing the 3D virtual museum with a 2D web interface (in a randomized order). Subjects were asked to view a video explaining one interface. They then used the interface for 5 minutes. Next, the functioning of the second interface was explained. The subjects used it for 5 minutes. Finally, they answered a single-choice questionnaire (see Table 1) and an open-ended question.

Table 1 Questionnaire and data processing to evaluate the hypotheses. The third column indicates with which experiment each hypothesis is evaluated. When the evaluation is completed using the questionnaire, the questions and responses are indicated. Some hypotheses are evaluated from trace analysis.

Hypotheses		Exp.	Objective procedure or subjective questions
H1	h1.1	Exp.1	**q1.** During your exploration, were you interested in this concept (X) for a time? (Yes/Somewhat yes/Somewhat no/No).
	h1.2	Exp.1	**q2.** When new rooms were proposed, their themes depended on your interest about objects in the previous rooms. (Yes/No). **q3.** The themes of rooms are defined from your usage of the 3 tools (map, timeline and keywords). (Yes/No).
	h1.3	Exp.1	Trace analyses.
	h1.4	Exp.1	**q4.** Did you feel that the museum helped you discover objects that did not interest you at the beginning? (Yes/No). Trace analyses.
H2	h2.1	Exp.2	**q5.** The opening of doors in the 3D virtual museum promotes the discovery of new objects more than the blinking of the web page thumbnails. (I do not agree at all/ I do not agree/I do not know/I agree/I completely agree) **q6.** The application ensures that the more the objects have common points, the more they are grouped on the screen. In your opinion, which does so best? (3D virtual museum/2D web page) **q7.** The virtual 3D museum provides more exploration mark than the web page. (I do not agree at all/I do not agree/I agree/I completely agree) **q8.** Exploring data using the 2D web page is more efficient than using the virtual 3D museum (I do not agree at all/I do not agree/I agree/I completely agree) **q9.** I prefer to explore the data with (3D virtual museum or 2D web site).
	h2.2	Exp.2	Trace analysis

7.3 Results

7.3.1 Experiment 1

For any useful purpose, descriptive results are provided in section 11. Forty-five persons participated in the first experiment (Exp. 1)—24 females and 21 males. The median age of the participants was 42 years, the minimum age was 12 years, and the maximum age was 74 years. Of all participants, 71.11% had a level inferior or equal to 2 on a scale from 1 to 5 with respect to familiarity with video games. However, 86.6% of the participants had a level greater than or equal to 3 with respect to interest in cultural heritage. No significant correlations were found between the answers to the questions and age, familliarity to video game or interest in cultural heritage.

Data relative to h1.1.
Results from the questionnaire are as follows:

The first question (**q1**) asks the participant whether he was interested in a given concept for a time during his exploration. Ten concepts are proposed to the user. These concepts are randomly ordered, and they comprise the 4 concepts that were considered more relevant by the system (*Relevant*), the 3 concepts that were considered as less relevant (*Irrelevant*) and 3 other concepts that had a relevance between 0.1 and 0.4 during the exploration (considered ambiguous for the system: these thresholds of 0.1 and 0.4 were chosen from the observation of the relevance values during different test sessions). For each, the participant must select an answer from among the following: 'yes', 'somewhat yes', 'somewhat no' and 'no'. Table 2 shows the contingency table of the modalities of the system evaluation and the user evaluation.
An χ^2 statistical test confirms a significant relationship between the user's answers and the system evaluation (p-value of 1.505 e^{-12}).

User/System	Relevant	[0.1;0.4]	Irrelevant	Total
Yes	79	54	12	145
Somewhat Yes	46	32	29	107
Somewhat No	30	33	38	101
No	24	20	53	97
Total	179	139	132	450

Table 2 Contingency table comparing the evaluation of the user with the system evaluation in terms of interest in concepts.

Data relative to h1.2.

The second and the third questions ask the user whether he has the impression that the themes of the created rooms have a link with his interactions with the objects (**q2**) and the tools (**q3**).Thus, 62.22% of the participants answer 'Yes' to question **q2** and 53.33% of the participants answer 'Yes' to question **q3**. This difference is not significant because the p-values by a *binomial test* are 0.06758 for **q2** and 1 for **q3**.

Data relative to h1.3.
During the experiment, we recorded the concepts consulted by each participant through his interaction with the museum (selection of objects, crossing of rooms, use of tools, and reading of object notices) and the concepts proposed by the system through the creation of rooms over time. All these elements are characterized at least by one concept. Thus, it is possible to evaluate semantic similarity between them. Figures 18, 19, 20, and 21 represent different scenarios as follows:

- Axis: x-axis represents the time, and y-axis the *semantic distance* between two successive interactions of the user or two successive propositions of the system, denoted d_{O_i}, where $d_{O_i}(c, c^*) = 1 - s_{O_i}(c, c^*)$

  The calculation of $s_{O_i}(c, c^*)$ was conducted using the equation in Section 6.3.6. Therefore, the closer the y value is to 0, the more the current consulted/proposed concept is close semantically to the previous concept. In contrast, when the y-value shifts away from 1 the current consulted/proposed concept is semantically farther from the previous concept.

- Colors: For each curve, the semantic similarity measurement was applied only to concepts in the same semantic structure. For the user interaction, each ontology was represented by one color- red for topics, blue for time periods, and magenta for space. In Figure 18, the concepts recommended by the system and the concepts consulted by the user have the same colors if they belong to the same semantic structure. However, in Figures 19, 20, and 21, the colors of the recommended concepts are black. To achieve the best visualization, only black was used.

- Point style: The concepts consulted by the user were represented by circles, while the concepts proposed by the system were represented by stars. If two successive points were not connected by a line, the corresponding semantic structure was not concerned with a proposition or by an interaction. For the propositions, this situation occurs when no concept's evaluation *FR(c,t)* is superior to the threshold that defines its selection by the system (see Section 6.3.9). For a user, this situation occurs when his interaction is not related to the semantic structure.

The fourth set of figures presents the traces corresponding to the fourth typical scenario during the 10-minute use of the system the Exp. 1:

- Figure 18 corresponds to a user who is a *curious and scattered explorer*. According to the terminology of (**veron1983**), the user is a *grasshopper*. He frequently interacts (e.g., selects objects and moves toward new rooms) and often changes often concepts. We assume that this user did not have a precise center of interest. He explores and discovers various data. The recommendation of the system varies according to the interactions of the user (with *semantic distance* from 0.1 to 0.8 for the concepts of time (blue) and the concepts of topics (red) , and from 0.1 to 0.6 for the concepts of space(magenta)).

- Figure 19 corresponds to a user who is close to an *ant* according to the terminology of (**veron1983**). He is interested in specific information. We assume that this user has rather precise centers of interest. In this case, the system makes close recommendations but introduces certain shifts (0.3) between each of them to promote exploration.
- Figure 20 corresponds to a user who is a *calm explorer*. He is interested in specific information for a certain time and then (at time 300), he changes his centers of interest. The system adapts its proposition to this change. To expand the metaphor of (**veron1983**), we can say that the user is like a cat because he does what he wants and in a sense, he manipulates the system which follows him.

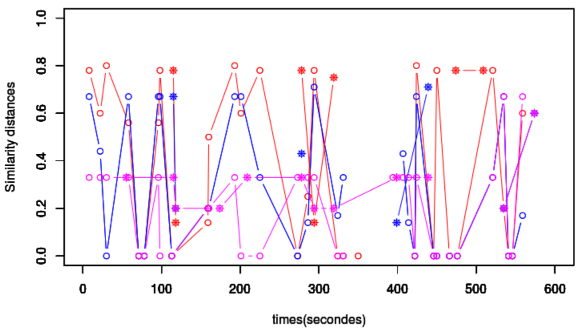

Fig. 18 Trace of a *'Grasshopper user' : curious and scattered data explorer.*

Data relative to h1.4.

Question (**q4**) is to learn whether participants agreed that the museum was able to propose objects for which the user would not have initially been interested but that finally are in line with his center of interest. Of all participants, 80% agreed with this assertion (see Figure 22). The p-value of a *binomial test* is 3.287 e^{-05} and confirms the relevance of this result. Trace analysis confirms the answer of participant concerning (**q4**). Indeed, figure 21 is an *influenced explorer*: He starts with rather close concepts but if the system proposed novelties (at t=230 for instance), he changes his centers of interest. This phenomenon is repeated at t=490.

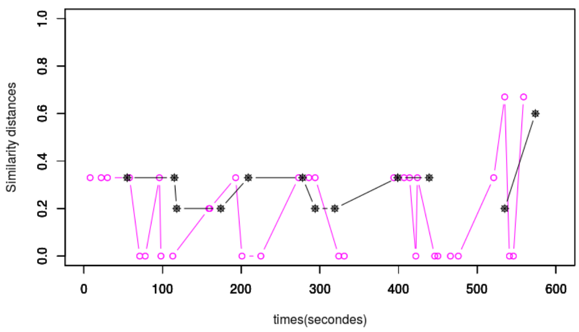

Fig. 19 Trace of a *'Ant user': deep data explorer.*

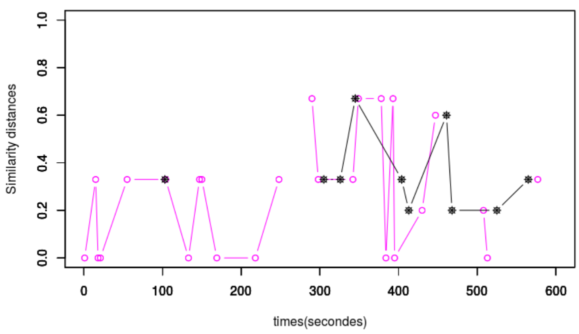

Fig. 20 Trace of a *'Cat user': calm data explorer followed by the system.*

7.3.2 Experiment 2

Thirty-one persons participated in the second experiment (Exp2) -16 females and 15 males. The median age of the participants was 41 years. The youngest was 17 years old, and the oldest was 75 years old.
This experiment consisted in particular of comparing the 3D virtual museum interface with the 2D web interface (see Section 6.4) on the following points: discovery of information (**q5**), grouping of information (**q6**), guiding (**q7**), effectiveness (**q8**), and preference (**q9**).
Half of the participants participated in the experiment on the 3D virtual museum and then on the 2D web interface. However, the other half of the participants participated in the experiment on the 2D web interface and then on the 3D virtual museum.

Data relative to h2.1.
In their answers concerning the improvement provided by the 3D versus 2D

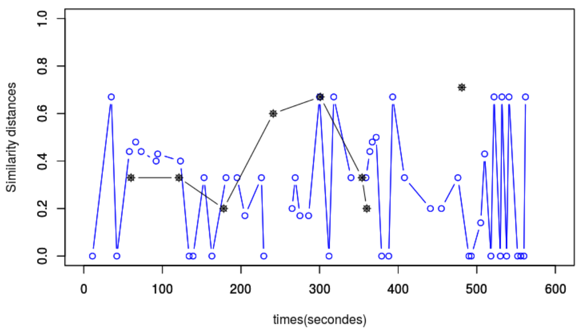

Fig. 21 Trace of an *'Dog user': influenced by the propositions of the system.*

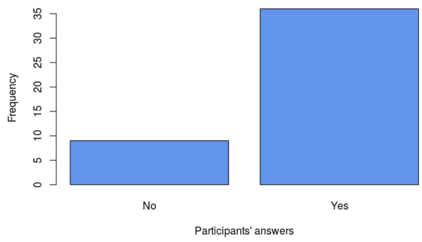

Fig. 22 Answers' distribution of having the impression that they were discovering interesting objects during their exploration, although they did not initially believe that these objects would be interesting for them at the beginning of the visit; **q4**.

on information discovery (**q5**), of all participants, 0% disagreed, 12.90% did not have an opinion, 38.71% agreed, and 48.39% completely agreed.

Because p-value of an χ^2 compliance test is 0.6553, these differences are not significant. Concerning the question on the grouping of information (**q6**), 84.64% of the participants confirmed that the 3D virtual museum is better than the 2D web page. The participant answer distribution is provided in Figure 23. This difference is significant because the p-value of a *binomial test* was 0.000439.

Concerning the landmark of exploration (**q7**), 25.80% of the participants disagreed that the 3D virtual museum provided more landmarks of exploration than the 2D web site interface, and 3.22% completely disagreed. However, 38.71% agreed, and 32.27% completely agreed - but the χ^2 compliance test returned a p-value of 0.5702, which indicates that these differences are not significant. We also asked each participant whether he agrees or not that the 2D web site is more efficient than the 3D virtual museum in terms of exploration (**q8**). The distribution of the answers of the participants was as follows:

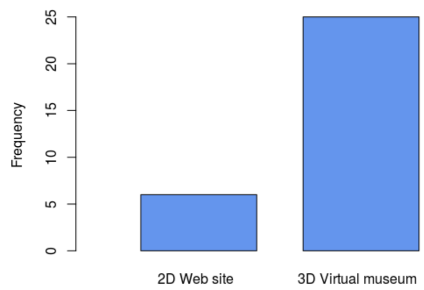

Fig. 23 Answers' distribution about **q6**: *The application makes sure that, in fact, the more the objects have common points, the more they are grouped on the screen. In your opinion, which does it best?*

12.90% of the participants completely disagreed, 41.93% disagreed, 38.71% agreed and 6.46% completely agreed. The p-value of an χ^2 compliance test was 0.5421.

The last question (**q9**) inquired into the preference in terms of the exploration interface. Respondents were allowed to choose "3D virtual museum" or "2D web site". According to their answers, 84.64% preferred to use the "3D virtual museum". To confirm this result a *binomial test* returned a p-value equal to $0.000439 \ll 0.05$.

Data relative to h2.2.
From the records of the explorations with the 2D web site interface and the 3D virtual museum, we can compare a great deal of information. The comparisons are presented in Figures 24 and 25. The first figure shows that the number of objects consulted by the participants was less in 2D than in 3D. A *Wilcoxon test* confirmed that the median in the 3D virtual museum in terms of consultation of objects was significantly different from the median in the 2D web site (p-value = 0.001356).

The second figure shows that the medians in terms of number of visited rooms in 2D and 3D are likely to be equal. Because the variances are different, we used the *Welch test* to compare the averages of the two samples. This test returned a p-value = 0.4734. Therefore, we fail to reject the null hypothesis and conclude that the averages of the numbers of visited rooms are approximately the same in 2D as in 3D (and close to 3).

8 Discussion

The results presented above allow the evaluation of our hypotheses from specific observations and statistical analysis of objective and subjective measures.

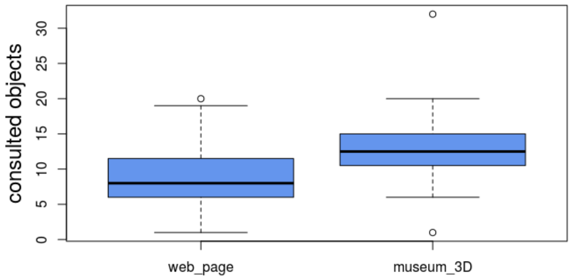

Fig. 24 Number of selected objects during exploration

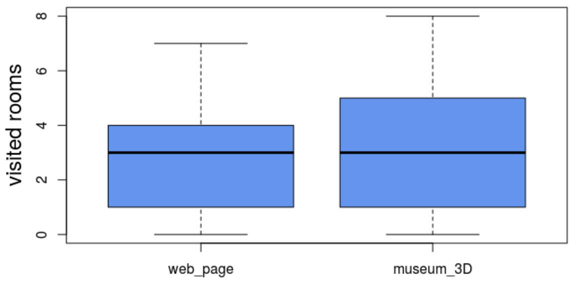

Fig. 25 Number of visited rooms during exploration

Certain answers to the open questions allow a reinforcement of the interpretation of the results. We have successfully recruited a large panel of participants in terms of ages and familiarity with video games. This characteristic is important when evaluating the answers to our questionnaire.

Concerning Hypothesis H1: traces in Figures 18 to 20 show the ability of the system to self-adapt to the user (Hypothesis h1.3). When the user was quite curious, the system proposed numbered novelties. Conversely, if the user focused rather precise concepts, the system followed him. The fact that the system can also influence the user (Hypothesis h1.4) is illustrated by Figure 21. Recall that a small proportion of random objects are introduced at each appearance of new rooms to promote discovery.

Another result is the confirmation of the role of the system from the participants point of view: they agreed that the system was able to identify their centers of interest (Hypothesis h1.1 , **q1**, Table 2). This result confirms that the combination of the ontologies, the observation of interactions and the spreading of pheromones provides an effective approach. However, even when the tendency is quite positive, there is not statistical evidence that participants feel that their behavior influences the system (Hypothesis h1.2, **q2**). The rates of participants who agreed and of the participants who disagreed that using the tools influenced the themes of new rooms are likely equals (**q3**). The first explanation of this result is the rather limited duration of the exploration. Ten minutes is probably not long enough for people to perceive that the museum is progressively populated by objects that correspond to their centers of interest. Unfortunately, this duration was chosen after some participants declined to participate in the experiment for time reasons. In fact, it is not surprising that the participants did not clearly perceive the activity of the system. On the one hand, the pheromone's spreading takes time and allows the proposition of quite various concepts. On the other hand, one of the goals of our proposition is to promote discovery. Thus, the system can be perceived as resistant to the user in some ways. Nevertheless, answers to question **q3** indicates that the tools are not well understood and that they were ineffectively handled. This result is confirmed by the answers to the open-ended questions. Some participants hoped to immediately find objects that corresponded to their use of the tools. They believed that these tools were like an entry in a search engine whereas in fact, the tools are designed to indicate preferences to the system, not to ask precise questions. However, participants strongly agreed that the system allowed the discovery of novelties in line with their centers of interest even if there was no initial evidence of this interest (Hypothesis h1.4, question **q4**, Figure 22) an encouraging result. They also agreed in the open questions that the propositions made by the system were very interesting for them. Of course, we would have had to run another experiment with a system that proposes priority objects that are associated with irrelevant concepts, to make a comparison. In our opinion, the fact that the system evolves with the user's center of interest (which we named co-evolutive exploration) makes it difficult for participants to analyze their experience.

Concerning Hypothesis H2, the analysis of the traces shows that the 3D virtual museum allows the consultation of more objects than does the 2D web interface ($p < 0.01$) However, the number of visited rooms is equal. This result suggests that the 3D presentation makes it possible to perceive the objects more quickly. The sizes of objects vary according to the displacement of the users. They objects can appear larger than in the 2D interfaces; when the user approaches a specific object, he also approaches also to objects that are semantically close to it. The perspective changes continually, and the dynamic of the visual flux can improve the perception by focusing attention. As considered in the enactive field of cognitive science, representations are based on sensory motor invariants, and the displacement of the user in the 3D virtual museum favors these invariants. Answers to question **q5** confirm that participants felt that the virtual museum was more effective than the 2D web interface in promoting discovery. The answers to the open-ended questions confirm this finding: *the 3D is more attractive, it affords moving towards this or that object. When I see an open door, it makes me go take a look.* Participants also confirmed that the 3D museum was better adapted to determine the semantic proximity of objects (question **q6**). Answers to question **q7** and the statistical test reveal that almost 70% of the participants found that the 3D presentation provided more guidance for exploration than did the 2D presentation.

Participants did not consider the 2D web page to be superior in term of efficiency (question **q8**). The participants' perception can be explained by the fact that some participants were lost in the museum and were more comfortable with a 2D web interface whereas others explored the information in the virtual museum easily and quickly.

Finally the virtual 3D museum was largely preferred for the exploration of information (question **q9**). One interesting point is that we did not find any links between the appreciation of the 3D virtual museum and user age or familiarity with video games. This point is important because people who might use this type of interface are not necessarily young or video gamers.

9 Limitations

Our study has some limitations. Concerning the evaluation, a first problem is the time during which the participants experimented the system (10 minutes for Exp.1 and 2x5 minutes for Exp.2). The second one is that the questionnaire was rather short without redundant questions. Indeed, it would have been better to have longer sessions and to offer more comprehensive questionnaires as the IEQ (Immersion Experience Quality) (**jennett2008measuring**) or the UES (User Engagement Scale) (**o2018practical**). These limitations are mainly due to organizational constraints. The cultural heritage days last only two days and visitors are present rather in the afternoon. So, even if we installed six workstations, we had few time to make these experimentations and to accumulate enough data. We could choose another place and others days but some pre-tests (not presented in this paper) showed us that it is preferable to make these experimentations with people who value cultural heritage. Regarding this recommendation, we have to mention that never a participant asked us to stop the experimentation and that some participants asked us to have much time (requests that we couldn't meet to respect the experimental protocol). Furthermore, one of the objective of this work is to help people to understand a context or a situation by grasping the links that exist between the data and that constitute the context that sheds light on the information (see section 2 and 4). From this perspective, our evaluation can't confirm this purpose. It only addresses its prerequirement. Indeed, following constructivism and enactive field, it is crucial that the system co-evolves with the human and our experiment confirm this point. But it is not a confirmation that people better understand a complex thing like the principles or functioning of a civilization (in the case of cultural heritage). It is very difficult to address such a definitive evaluation. It needs some long term studies as well as a protocol that insure the measurement of the notion of understanding. Generally, psychologists evaluate the skills (**AGGARWAL2006128**) or memory (**DBLP:journals/ijhci/HoareauQBG17**). But how to evaluate *under-*

standing, considering that each person could have her own interpretation, her own center of interest and point of view about a situation. This crucial point remains an open question.

Our questionnaires, even if they were proposed after discussions with psychologists of our lab, are not formally validated. We needed short questionnaires (for time reason) to evaluate the feeling of adaptation, i.e. the fact that users felt that the system was adapting to them. We didn't find such a questionnaire in the literature and the time to elaborate an external or ecological validation of a questionnaire is out of our reach. We limited recurrent questions to simplify the task of participants. So, an internal validation is also not possible. Consequently, our results must be considered with prudence in regard of this limitation even if we think that these first results provide an indication that our system co-evolves with the user and that 3D performs better than 2D on many aspects.

Another limitation is the calibration of the model. Currently, we defined the values of the variables empirically. We made some tests (not presented here) and it is not warranty that the size of the semantic structure has no impact on the capability of the system to follow or guide correctly the user. This size could also have an impact on the computation time of the relevance of each concepts. The main part of the work was done with the same ontology and the same database. We showed that the system can be used with other ontologies and other databases but we didn't study the model behavior in details. In particular the relation between the size of the semantic graphs, the rate of evaporation as well as the augmentation rate ($\lambda(n)$) must be studied.

Another difficulty is the use of annotated data according to an ontology. It needs a lot of time and is faced to the problem of the definition of a consensual ontology. However, our approach is compatible with folksonomies and could be used for collaborative authoring of database. This perspective can avoid the pre-annotation step and is more compatible with the notion of co-construction at the basis of our work.

To finish, we observed that, even if the tutorial explained that the interactive tools are not dedicated to find a precise object (in this case, our approach is a nonsense) many users had the tendency to use it for such a purpose. We have to work on a mean to cause users to not consider that the system is a research engine but an *understanding engine*.

10 Conclusion and future work

This paper presents a co-evolutive principle of data exploration, its formalization and its evaluation. The motivation of this work is the improvement of the understanding of complex problems or situations in general. Such an understanding is not accessible by investigating different specific information but by grasping the different links that exist within it. To this end, we followed a constructivist and enactivist point of view: the behavior of the user transforms his perception of his environment, which changes the future behavior of the user. To address this purpose, we associated 1) graphical adaptable representations of information, 2) the user's interaction analysis and 3) semantic links between data elements. We have formalized the real-time self-evolution and adaptation of the environment. We created two versions: one that situates the user within the information and one that place him outside this information. We performed two types of evaluations in the context of cultural heritage. The task was not so ambitious as understanding a complex problem but, rather, it was only to appreciate a huge collection of cultural heritage objects. The first experiment confirmed that our algorithm is able to construct progressively an environment that is adapted to the user's centers of interest. The second experiment confirmed that immersing the user in the information is more appreciated by the participants and simultaneously allows the discovery of more information. Of course there remains a great deal of work to address the final goal. First, we began the construction of a full immersive version to more fully achieve the embodiment promoted by enactivism. We must also show that it is possible to apply our model in very different contexts. In fact, we have recently tested it on a database of scientific publications without any notable problems. The only requirement is to have a database and ontologies of its data. Another important improvement that our results suggest is the possibility of parameterizing the model based on many usage traces. For example, it is possible to better establish the thresholds of the supposed relevance of concepts from a statistical analysis of the anwsers to question **q1**. A more complex challenge is the evaluation of the understanding of a complex problem. Indeed, one weakness of our evaluations was the limited time alloted to the participants in the experiments. In the future, we must find a way to conduct an evaluation of the understanding of a well-known complex problem on the long term.

11 Data

The two next tables provide the description of the collected data during Exp.1 (table 3) and Exp.2 (table 4) .

C_1	C_2	C_3	C_4	Q1	Q2	Q3	Q4	R	I	T	VR	O
F	49	2	3	0	0	1	0	15	36	2	9	25
M	24	4	5	1	1	1	1	5	54	31	10	9
F	24	2	4	1	1	1	0	8	26	0	3	21
F	24	2	5	1	1	0	0	14	40	0	7	24
M	68	3	4	1	1	1	0	5	19	0	3	13
M	14	5	2	1	1	1	0	12	40	4	7	28
M	13	5	3	1	0	1	0	11	30	0	9	12
M	64	2	4	0	0	0	0	6	40	5	4	28
F	65	1	4	1	0	1	0	4	29	4	1	21
M	35	3	5	1	1	1	0	19	41	1	16	24
M	53	1	3	1	1	1	0	20	41	3	14	24
M	57	1	2	1	1	1	0	10	43	4	9	28
F	60	1	3	1	0	1	0	4	30	1	3	23
M	15	1	3	0	1	1	1	4	44	8	5	28
F	16	2	3	1	1	1	1	9	75	2	7	40
F	38	1	4	1	1	1	0	10	30	0	9	21
F	31	2	4	1	1	0	1	10	54	10	6	25
M	41	1	4	0	0	1	0	10	26	4	5	15
F	64	1	4	0	0	1	0	10	24	0	6	18
M	65	1	3	1	0	0	1	9	44	3	9	20
F	37	2	4	1	1	1	1	15	68	0	10	31
F	13	4	4	1	1	1	1	11	74	12	15	28
F	37	1	4	0	0	1	0	8	35	1	4	23
M	29	5	3	0	0	1	0	7	22	1	2	17
M	64	1	5	0	0	0	0	10	42	2	8	32
F	62	2	5	1	0	0	0	12	56	0	11	31
F	58	1	4	0	1	1	0	13	27	2	9	14
M	74	2	4	0	0	1	0	10	33	0	10	16
F	62	2	5	0	0	1	0	7	23	3	2	14
M	29	2	2	1	0	1	0	7	33	2	4	21
F	33	2	4	0	1	1	0	8	31	3	9	18
M	41	5	4	1	1	1	0	15	54	2	20	18
F	12	3	3	0	1	1	0	15	34	6	8	19
M	26	1	4	0	0	1	0	6	47	4	8	32
M	12	4	5	1	1	1	0	9	48	3	6	34
M	45	3	3	0	1	0	0	11	54	0	6	37
F	13	2	2	1	1	0	1	8	44	1	6	25
F	71	1	5	1	0	1	0	8	33	0	3	23
F	50	1	3	0	0	1	0	10	53	6	7	27
F	53	1	1	0	0	1	0	8	27	3	6	13
F	25	1	4	1	0	1	1	11	33	0	6	27
F	64	1	3	1	0	1	0	9	42	0	8	27
F	53	2	4	1	1	1	0	13	54	0	10	41
M	50	5	2	1	1	1	1	13	55	13	8	32
M	42	5	5	1	1	0	0	17	90	14	13	66

Table 3 Each line corresponds to a participant for Exp.1. Column C_1 is the genre of the participant, C_2 is her age, C_3 her familiarity with video game, C_3 her level of interest for cultural heritage. $Q1$ to $Q4$ is her answer to corresponding questions, R is the number of rooms that were created during the experimentation, I is the number of interactions performed by the participant, T is the number of use of tools (map, timeline and keywords), VR the number of visisted rooms (it is not the same as the number of created rooms because participants rarely visited each room. O is the number of consulted objects.

C	G	A	VG	CH	Q1	Q2	Q3	Q4	Q5
3D/2D	M	41	1	4	3	3	3	4	2
3D/2D	F	31	2	4	3	2	1	3	2
3D/2D	F	65	2	3	4	2	1	3	2
3D/2D	F	37	1	5	4	3	3	1	3
3D/2D	M	29	5	4	4	3	4	1	3
3D/2D	F	33	2	4	4	3	4	1	3
3D/2D	F	53	2	4	2	3	3	1	3
2D/3D	F	55	1	4	4	3	4	1	3
2D/3D	F	24	2	2	3	3	1	1	3
2D/3D	F	31	1	3	4	3	3	3	3
2D/3D	M	39	3	4	4	3	1	3	3
2D/3D	M	25	4	4	3	3	3	1	3
2D/3D	M	18	4	2	3	3	1	4	3
2D/3D	M	38	2	5	4	3	3	0	3
2D/3D	M	63	3	5	3	3	3	3	3
3D/2D	M	63	1	5	4	3	4	1	3
2D/3D	M	75	1	4	2	3	4	1	3
2D/3D	F	70	1	3	4	3	3	3	3
2D/3D	F	62	1	5	3	2	4	3	3
3D/2D	F	46	2	5	3	3	4	1	3
3D/2D	F	61	1	5	4	3	3	0	3
3D/2D	M	55	2	5	3	3	3	1	3
3D/2D	F	30	4	5	4	3	4	1	3
2D/3D	M	43	2	4	4	3	3	3	3
2D/3D	F	48	1	3	3	3	4	1	3
3D/2D	F	41	1	5	3	2	1	3	2
3D/2D	M	30	5	3	4	3	4	0	3
3D/2D	M	29	2	4	3	2	3	0	3
2D/3D	M	17	5	4	4	3	1	3	3
2D/3D	M	61	4	5	2	3	1	3	2
3D/2D	F	43	1	4	2	2	0	3	2

Table 4 Each line corresponds to a participant for Exp.2. Column C is the order of the conditions (2D then 3D or 3D then 2D), G is the genre of the participant, A is her age, VG her familiarity with video games, CH her level of interest for cultural heritage. $Q1$ to $Q5$ is her answer to corresponding questions (see section 7.2)

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