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Visualization experience and related process modeling

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ABSTRACT

The visualization process is a transformation of information content into knowledge via a visual representation. *Visualization experience*, proposed herein, reflects human sensations arising during the visualization process. It provides a basis in which to objectively measure and evaluate human participation in the visualization process; and thereby provides methods of control. Visualization experience modeling allows leveraging on the natural environment to augment understanding, therefore improve decision making. The application emphasis in this paper is on the theoretical development of visualization experience in the visualization process as applied to Ambient Assisted Living and Clinical Decision Support Systems.

1. Introduction

The visualization process is a transformation of information content into knowledge via a visual representation. It involves visualization systems that transform content into pictures termed visualizations and humans who transform these visualizations into knowledge. Humans have roles of users and thinkers. As users, humans can alternate visualizations by interacting with the systems whereas as thinkers, humans cognitively formulate knowledge based on the visualizations.

The broad term, *visualization experience*, is introduced in this paper to reflect human sensations arising during the visualization process and representing a degree of cohesiveness, knowledge formulation, and satisfaction in the visualization environment. Visualization experience is natural and inherently preexisting in human interactions with visualization systems. However, without precise modeling of this, the potential to harness human experiences during the visualization is limited. An important goal of the visualization process is to maximize the degree of knowledge that humans as thinkers can obtain from visualizations. This can be achieved by enabling the visualization systems to generate visualizations that in turn promote and facilitate maximal knowledge formulation. The visualization experience provides a definitive basis in which to objectively measure and evaluate the cohesiveness of the visualization environment for humans as users and thinkers; and thereby provides methods of control over the visualization process. An "excellent visualization experience" implies no need of control as the evaluations would indicate high knowledge formulation, whereas a "poor visualization experience" provokes interaction since the evaluations indicate possible improvement opportunities. Although various visualization processes, systems, and human-centered models have been proposed in the past, the extent of the cohesiveness coupled with human satisfaction and knowledge formulation as implied in the definition of visualization experience seems holistically lacking in such previous works. The development of such a precise model allows leveraging on the natural environment to augment understanding; and hence, lead to expected better decision making.

The focus in this paper addresses the development of a visualization experience model. A visualization process is defined which forms the basis for the objective parts of visualization experience, namely, measurement, evaluation and control. There are two main components in the

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processing modeling: information streams and visualization stages. Information streams connect systems and humans in terms of information flow. Visualization stages are defined as transformations of the information streams during the visualization process. Visualization experience is measured via visualization metrics that reflect the qualities of information flow and user involvement in the system–user interaction. These metrics in turn can be used to affect the visualization process in form of suggested methods of control. Such a model can be applied to various types of visualization systems that serve a diverse end-user community. The application emphasis in this paper is on the theoretical development of visualization experience in the visualization process as applied to healthcare systems, and in particular, to Ambient Assisted Living (AAL) and Clinical Decision Support Systems (CDSS).

The end-users of healthcare systems are varied, from domain specialists who use such visualizations as a means of investigation of certain phenomena in their area of expertise to patients who typically are more interested in their well-being. Such phenomena might range from statistical patterns in health records to real-time patients' activity. Consider an example of CDSS which are expected to provide insightful suggestions to medical professionals: in such cases as when they interact with the system via displays, they are involved in the visualization process. Therefore, the quality of their performance may well depend on the quality of visualizations. Yet, a survey on CDSS architecture and deployment evaluation between 2008 and 2012 shows that a user interface (therefore, the visualization process) is not considered as an important component of the CDSS in the majority of cases ([1–14]). The present paper employs the visualization experience in process modeling to prototype an interface for AAL systems, such as [15,16], that include CDSS as a component (from a visualization point-of-view).

The rest of the paper is organized as follows. Section 2 briefly discusses development of the visualization models in terms of human involvement in the visualization process. Furthermore, it provides several examples of work related to the application of this paper. Section 3 models the visualization process. It is divided into several subsections, namely, overview (3.1), information streams (3.2), and visualization stages (3.3). This section provides theoretical models necessary to define visualization experience. Section 4 introduces the main contribution of this paper, namely, visualization experience. Section 5 introduces the application system of this research that illustrates the theory. The last section concludes the paper and reveals future research plans.

2. Related work

The early visualization process models [17,18] leave very little flexibility to the human: to obtain and manipulate visualization results users had to have a total control over all of the visualization steps which also implied an in-depth knowledge of the problem domain [19]. Recently, there is a visible evidence of the importance of human perception, cognition, and interaction incorporated in the visualization process [20–23]. Also, there are number of works connecting visualization science with related disciplines through techniques [24] and frameworks [21,25]. Nguyen et al.'s Faithfulness model [26] extends the van Wijk model [20], placing more emphasis on the role of data in the visualization process and less emphasis on the human role.

The visualization pipeline in this paper is similar to the one in Chen and Jaenicke's paper [21], but focused less on the theoretical aspects and more on the visualization mechanics. Chen and Jaenicke compare communication and visualization systems from the perspective of information theory and the stages of visualization are described as stages of signal transmission affected by errors. The pipeline in the present paper is focused on transformation of abstract data to visual information in order to facilitate human knowledge. On the system side, a multi-layered interface organization is proposed as a way to simultaneously visualize information of different complexity targeted at various user groups. The importance of it is discussed in [27]. The emphasis on multiple visual layers has led to incorporation of parallel pipelines into the visualization process model. An example of a similar technique is found in [28].

User feedback, as modeled in this paper, enables manual or automated control of the visualization process via adjustment of visualization parameters and functions. The methods of manual control can vary from direct manipulation [29], to more complex system–user relationships when cognition is recognized as a property of interaction [25]. Automated control can be performed via automated mapping [30], 2D layout [31], 3D modeling [32], and virtual camera control [33–35].

Work related to the application side of this research is focused on the design and usability considerations of the CDSS interfaces. Yang et al. propose several usability metrics for CDSS systems [36], namely, learnability, efficiency, effectiveness, error handling, and user satisfaction. Different from the metrics described in the present paper, these five measure usability post-factum. There is no adjustment during the interaction involved. Frize et al. suggest criteria for successful CDSS deployment [37]. Somewhat related to the present research are user-friendliness, simplicity and effectiveness of visualizations together with the requirement of demanding the least amount of physician time possible. All of these are qualities of an “excellent visualization experience”.

Other application-related work is healthcare applications of avatars and data visualization in 3D environments. In [38], the authors use virtual personal assistants to communicate to Alzheimer's disease people. The work has been validated with a focus group and results show that an interface like that is intuitive and easy to use. In [39], the authors use personal assistants to help users to cope with special disease related exercises. Personal assistants guide users and help them to perform tasks. In [40], the authors visualize a smart living environment in the Smart Condo project. The visualization shows the user's position via an avatar placed in virtual 3D representation of the condo. Also, it partially involves sensory data visualization. In [41], sensory data is mapped to a 3D model of environment, with humans as well represented as animated 3D models. The work uses realistic representation of a wireless network's environment, visualization of a network and its state, and visual representation of semantic information as opposed to raw sensory data. These works support technological development of the present application by providing an evidence of usefulness of such technologies in healthcare applications.

3. Visualization process

3.1. Overview

This section describes the visualization process in a general system composed of two major components: an information generator and a visualization component. The process begins with raw data and completes with the knowledge obtained by humans from a single visualization or a sequence of visualizations. There is a feedback loop that preserves quality visualization experience for humans. The process includes data transformation, interaction, and measuring the visualization experience.

Let S define an abstract system that exchanges information with the environment. Let $S.I$ define an information generator of S that gathers, stores, processes, and generates data using various algorithms and techniques. $S.I$ produces the *content*. Let $S.V$ define a visualization subsystem that transforms abstract data into visual information. $S.V$ produces the *presentation*. The output of S is expressed as following:

$$S \mapsto content \times presentation. \quad (1)$$

The visualization process is a transformation of content into knowledge by creating an appropriate presentation (visual representation). The visualization process here has five data transformation stages and one interaction stage.

The data transformation stages that form $S.V$ are *filtering*, *mapping*, *layout*, *layer fusion*, and *rendering*. Those stages are described in detail in Section 3.3. The interaction between S and users facilitates the visualization experience that is described in detail in Section 4. Table 1 summarizes frequently used notation.

Table 1
Nomenclature.

S	Information system;
$S.I$	Information generator of S;
$S.V$	Visualization subsystem of S;
Information streams	
I_i^{dom}	i-th information stream of domain *dom* in the system, where *dom* is abstract (A), visual (V), graphical (G), and intermediate (O);
T	Lifetime of a stream;
D	Delivery rate of a stream;
P	Human processing rate;
Visualization stages	
F	Filtering;
M	Mapping;
L	Layout;
$>$	Layer fusion;
R	Rendering;
Visualization experience	
α	*Smoothness* of interaction;
β	*Availability* of relevant information;
γ	Correctness of *interpretation*;
ζ	*Adaptability* to change operation modes;
δ	Visualization metrics threshold;
σ	Threshold of communication state;

3.2. Information streams

The information streams define the communication between S and users, both abstractly and at the application level.

Let I denote a stream of information

$$I = (i_1, i_2, \ldots, i_n), \quad (2)$$

where i_i is a chunk of information delivered at t_i, and $t_{i+1} \geq t_i$. The *lifetime* T of a stream is the period of time between delivery of the first and the last chunks of information in a stream: $T = t_n - t_1$. Streams are delivered at a certain *delivery rate*, D, that is the number of information chunks delivered per unit time: $D = \Delta i_d / \Delta t$. The information *processing rate*, P, is a number of information chunks processed per unit time: $P = \Delta i_p / \Delta t$. P is limited by the human abilities to process information.

Information streams may vary the domain of their contents throughout the visualization process. There are four types of information streams considered here.

1. I^A: an abstract information stream (containing data values in domain A). It can be raw data obtained via sensors, system-processed, and system-generated data. $i_i^A = (value, time, type, semantics)$.
2. I^V: a visual information stream (containing visual descriptions of data values in domain V). These streams are the result of the mapping, layout, and layer fusion functions. $i_i^V = ((\Psi, \Lambda), semantics)$, where Ψ is a set of mapping parameters which may be $\Psi = (mapping\_type, geometry, color)$, and Λ is a set of layout parameters which may be $\Lambda = (X, Y, Z, view, scale, order, alpha\_channel)$.
3. I^G: a graphical information stream (containing rendered visual information streams in domain G). These streams are the output of a visual interface. $i_i^G = (X, Y, color\_space)$.
4. I^O: an intermediate information stream (containing physical transmission signals in domain O). These streams deliver information from the interface to users and from users to input devices such as haptic or sensory.

For any stream I_n there is a substream I_m, such that $I_m \subseteq I_n$. Both streams must be of the same domain.

3.3. Visualization stages

The visualization process has five stages, namely, filtering (F), visual mapping (M), layout (L), layer fusion ($>$), and rendering (R). Fig. 1 shows the visualization stages and information transformations during the visualization process. Each stage is a family of functions that process parallel pipelines. Input for each stage includes data and metadata. While data are primary arguments for the functions,

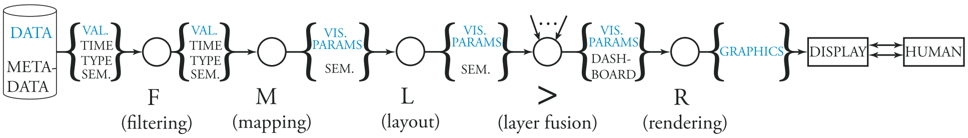

Fig. 1. The visualization pipeline.

metadata support them with domain knowledge that is used to automate visual mapping and layout.

Filtering stage. A filter $F(I_n)$ on a stream I_n is a substream I_m with the following properties:

1. If $I_j, I_k \in I_m$, then $I_j \bigcap I_k \in I_m$;
2. If $I_j \in I_m$ and $I_j \subseteq I_k \subseteq I_n$, then $I_k \in I_m$.

Visual mapping stage. The *mapping function* $M(I_n^A) = I_n^V$ transforms abstract streams to visual streams $M : A \mapsto V$ by setting values of Ψ.

Layout stage. The *layout function* $L(I_n^V) = I_m^V$ selects and sets appropriate parameters from Λ based on *semantics* (domain knowledge), $L : V \mapsto V$. For 2D graphics these parameters include (X,Y) position of a visual element. For 3D graphics these include $(X,Y,Z,view)$, where *view* is a virtual camera $\omega_n \in \Omega$ that belongs to a set of virtual cameras in a scene.

Layer fusion stage. A function that fuses multiple layouts into an output view, based on Λ is the *layer fusion function* $> \ : V \mapsto V$.

Rendering stage. *Rendering function* R transforms Ψ and Λ into output graphics, $R : V \mapsto G$.

Following the rendering stage, there is an interaction stage that partially modeled in this paper via the visualization experience.

4. Visualization experience

Visualization experience reflects human sensations arising during the visualization process and representing a degree of cohesiveness, knowledge formulation, and satisfaction in the visualization environment. Visualization experience is natural and inherently preexisting in the user and thinker interactions with visualization systems. It is related to a more general term *user experience*. As the authors of [42] admit, it is hard to define the user experience due to the complexity and fuzziness of the involved concepts. Here, the visualization experience is modeled using fuzzy logic to incorporate qualitative descriptions of it that are natural to humans.

The visualization experience is obtained during an interaction with S. Typical users are unaware (and do not need to be aware) of the $S.I$ and the $S.V$ components of S. For them, S is its graphical user interface. Therefore, design choices of the interface can affect the visualization experience in a positive or a negative way. A discussion on it can be found in Section 5.

The metrics of the visualization experience defined here (originally inspired by [43]) are *smoothness*, *availability*, and *correctness*.

1. *Smoothness* of interaction (α) measures a human's comfortability of visual interaction with the system at a particular time. For each human, there is a range of comfortable processing (P) and delivery (D) rates during the interaction. Thus, any given state of interaction can be measured in these terms and potentially optimized for better visualization experience. Comfortable processing range (P_{min}, P_{max}) depends on abilities of a person to cognitively process information. If variable D is within that range, there is a smooth interaction (*smooth* membership function). Otherwise, there are two kinds of non-smooth (*fast* and *slow*) interaction (see Fig. 2). The horizontal axis in Fig. 2 is D measured in chunks per second with four *thresholds of smoothness* $(\delta_1 - \delta_4)$ that are values of P, also measured in chunks per second. Values lower than δ_1 belong to non-smooth slow interaction. In this case, delivery rate is much lower than minimal comfortable processing rate $(D \ggg P_{min})$, therefore users have to wait for a considerably long time between information updates. An example is a weather forecast display that updates few times per hour. Values in the interval (δ_1, δ_2) belong to an edge case $(D \approx P_{min})$ with the degrees of membership lower than one that may be described using linguistic variables (e.g. *quite slow*). An example is the stopping, buffering, resumption and again stopping of on-line video streamed at a low bandwidth. Values in the interval (δ_2, δ_3) belong to the category of smooth interaction: $D \in (P_{min}, P_{max})$. It leads to a comfortable smooth information processing without delays or skipping of information. Values in the interval (δ_3, δ_4) belong to a second edge case $(D > P_{max})$ that may be described using linguistic variables (e.g. *a little fast*). An example is watching a video on 2X speed. Values greater than δ_4 belong to non-smooth fast interaction $(D \ggg P_{max})$. An example is listening to someone speaking in an unknown (implies that $P \to 0$) foreign language. δ-values are obtained experimentally for each human. α is computed using the following rules:

$$\alpha(D) = \begin{cases} 0, & D < \delta_1 \vee D > \delta_4, \\ 1, & \delta_2 < D < \delta_3, \\ \dfrac{D - \delta_1}{\delta_2 - \delta_1}, & \delta_1 < D < \delta_2, \\ \dfrac{\delta_4 - D}{\delta_4 - \delta_3}, & \delta_3 < D < \delta_4. \end{cases} \quad (3)$$

2. *Availability* β measures relevancy and quantity of the information available to a human during the task accomplishment. For each chunk of information i_i there is an expected reaction r_i^e that is set by $S.I$ and stored as metadata; $r \in (null, \Upsilon)$, where *null* is no reaction and Υ is an action set defined for input capabilities of a particular interface. For each stream I_j there is an expected reaction set $R_j^e = (r_1^e, r_2^e, \ldots r_n^e)$. Construct the subsequent

partition set Z in the following way:

```
j←1
r_1^e ∈ Z_1
for all other elements r^e ∈ R^e do
    if r_i^e = r_{i-1}^e then
        j = j
    else
        j = j + 1
    end if
    r_i^e ∈ Z_j
end for
```

The set Z captures the variant order of change to expected reactions with each subset Z_j containing a continuous sequence of same expected reactions. Let $R_i^u=(|Z_1|,|Z_2|,\ldots|Z_n|)$ contain cardinality (a number of elements) of each set Z. For example, a set $R_1^e=(null, null, null, \upsilon_1, \upsilon_1, \upsilon_2)$ will contain three sets Z, namely $Z_1=(null,null,null)$, $Z_2=(\upsilon_1,\upsilon_1)$, $Z_3=(\upsilon_2)$; therefore, a set $R_1^u=(3,2,1)$. Let R_0^u denote a unique reaction set of the main input stream I_0 and R_1^u denote a unique reaction set of the main output stream I_1. If a subset of R_0^u does not exist in the output, then it is represented as $Z=0$ in R_1^u. For example, $R_0^u=(4,3,1,1)$, whereas $R_1^u=(4,2,0,1)$. To compute β the ratio R^β is estimated first by the following expression:

$$R^\beta=\begin{cases}\dfrac{1}{m}\sum\limits_{i=1}^{m}\dfrac{Z_{1_i}}{Z_{0_i}}, & m>0,\\ 0, & m=0,\end{cases} \tag{4}$$

where m is a length of R_0^u. A membership function for β is selected based on the sensitivity of information: more sensitive information requires higher ratio to be considered available. There are two *thresholds of availability* (δ_5, δ_6) that are values of R^β. A possible example (see Fig. 3) is defined here:

$$\beta(R)=\begin{cases}0, & R^\beta<\delta_5,\\ \dfrac{R^\beta-\delta_5}{\delta_6-\delta_5}, & \delta_5<R^\beta<\delta_6,\\ 1, & \delta_6<R^\beta.\end{cases} \tag{5}$$

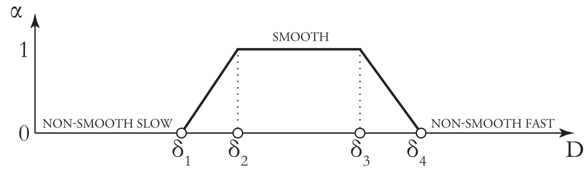

Fig. 2. α-Values and corresponding membership functions.

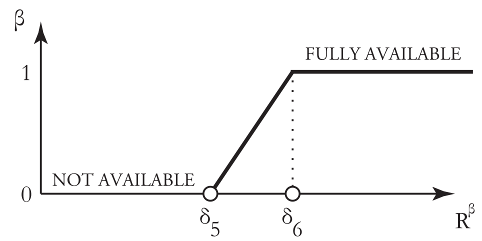

Fig. 3. β-Values and corresponding membership functions. δ denote availability thresholds.

The degrees of membership can be assigned to linguistic variables of *not available, partially available, fully available*, etc. Consider the example of an interaction between patients and medical professionals via telemedicine. Patients, located in a remote area, communicate with a medical professional located in a city. Availability is influenced by a filter, such as physical characteristics of a video camera in this example. The amount of information displayed on a screen for the medical professional is constrained by geometry and type of a camera lens on the patients' side (e.g. standard lens vs. wide-angle lens vs. fish-eye lens). When focused on a certain feature, it might fail to capture other important ones due to the lens constraints, which is *partial* information availability.

3. *Correctness of interpretation* of the perceived information is denoted by γ. Here, it is defined as follows. In addition to an expected reaction r_i^e, for each chunk of information output i_i there is an actual reaction r_i^a. Therefore, for each output stream I_i there is an actual reaction set R_i^a. γ is estimated by a domain specific function $R^\gamma=f(R^a,R^e)\mapsto[0,1]$ which considers the correspondence of actual to expected reactions in a given domain. A primitive example of such a function is the ratio of cardinalities of the actual and expected sets: $R^\gamma=|R^a|/|R^e|$. Similar to β, a membership function for γ depends on the importance of information: reactions to critical alerts are more valuable. There are two *thresholds of correctness* (δ_7,δ_8) that are values of R^γ. A possible example (see Fig. 4) is defined here:

$$\gamma(R)=\begin{cases}0, & R^\gamma<\delta_7,\\ \dfrac{R^\gamma-\delta_7}{\delta_8-\delta_7}, & \delta_7<R^\gamma<\delta_8,\\ 1, & \delta_8<R^\gamma.\end{cases} \tag{6}$$

Possible linguistic variables are *incorrect, partially correct*, and *correct* interpretation. Consider the previous example again. In conditions of partial information availability, the correct interpretation will lead to further exploration by changing, for example, a position or a zoom level of the camera. Incorrect interpretation, on the contrary, might not lead to additional exploration, but to incorrect decision making.

The experience function $E(\alpha,\beta,\gamma)\mapsto(c^-,c^0,c^+)$ is used to obtain the qualities of the communication in the process of interaction:

$$E=\begin{cases}c^-, & \alpha\wedge\beta\wedge\gamma<\sigma_1,\\ c^0, & \sigma_1<\alpha\wedge\beta\wedge\gamma<\sigma_2,\\ c^+, & \alpha\wedge\beta\wedge\gamma>\sigma_2,\end{cases} \tag{7}$$

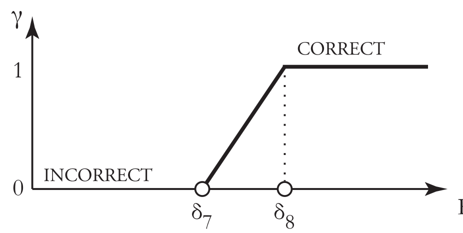

Fig. 4. γ-Values and corresponding membership functions. δ denote thresholds of correctness.

where c^-, c^0, and c^+ are, respectively, failed, discrete, and continuous communication. Visualization experience is described with the qualities of each metric and overall communication state. For example, visualization experience may be smooth, fully available, partially correct and with discrete communication. σ_1, σ_2 are *communication state thresholds*. σ_1 is a *threshold of communication failure* and σ_2 is a *threshold of communication continuity*. σ values for each human are first obtained via experimental measurement as a part of system deployment. σ_1 and σ_2 generate the *E*-curve (visualization experience function) at a particular moment of time. *E*-curves will vary throughout the day, therefore σ values could be updated based on user feedback. Eventually, a set of σ values representing the human potential for continuous communication with the system will be obtained.

The communication state provides a degree of quality control over the visualization process and enables users to make changes during the visualization process (feedback loops in Fig. 5). Different metrics are influenced by (and influence in feedback) different visualization stages. If a certain metric is low, then parameters of the corresponding stage of the visualization process should be altered. Some of the possible heuristics are given below:

1. The system's reaction to a low smoothness (α) value is to change the delivery rate (D). This can be achieved by altering mapping parameters such as speed of animation. In the case of a hardware problem (such as insufficient processing power or slow network connection), changing of rendering algorithm may increase the smoothness of output.
2. The availability (β) is a system-centered metric directly influenced by the quality of a filtering process. Low β typically means overfiltering. The expected system's reaction is changing the filter parameters.
3. The correctness of interpretation (γ) depends on such visualization parameters as color; relative size and position of visual objects on the screen; visual metaphors. These parameters are regulated by mapping, layout, and visual fusion functions.

Consider the following example. Let a sensor sample ambient temperature once every 2 s and assume that the temperature of 30 °C decreases one degree per second. When the temperature is 18 °C, a human switches off air

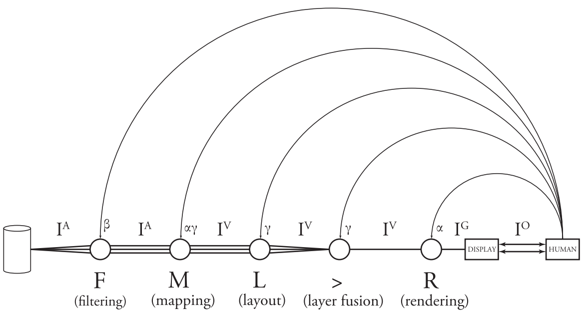

Fig. 5. The visualization process with feedback.

conditioning (AC) and the experiment stops. Then $I_0^A=(i_1, i_2, \ldots, i_7)$, where $i_1=(30, t_0, scalar, \text{"}location\text{"})$, $i_2=(28, t_1, scalar, \text{"}location\text{"})$, etc. Let this stream be visualized independently on two layers (2D and 3D) which are then fused together in the interface.

2D layer. Let F_j be a downsize filter, assume $F_j(I_0^A)=I_1^A=(i_2,i_3,i_4,i_5,i_6,i_7)$. Let M_j be a text visualization technique, thus $M_j(I_1^A)=I_1^V=(i_2,i_3,i_4,i_5,i_6,i_7)$, where $i_i=((text, font, color), \Lambda, \text{"}location\text{"})$. Let the text be lay out with an algorithm defined by L_j, thus $L_j(I_1^V)=I_3^V=(i_2,i_3,i_4,i_5,i_6,i_7)$, where $i_i=(\Psi, X, Y, \text{"}location\text{"})$.

3D layer. Let F_k be a downsize filter, assume $F_k(I_0^A)=I_2^A=(i_1,i_3,i_5,i_7)$. Let M_k be a glyph visualization technique, thus $M_k(I_2^A)=I_2^V=(i_1,i_3,i_5,i_7)$, where $i_i=(glyph\_type, geometry, color, \Lambda, \text{"}location\text{"})$. Let the glyphs be lay out with an algorithm defined by L_k, thus $L_k(I_2^V)=I_4^V=(i_1,i_3,i_5,i_7)$, where $i_i=(\Psi, X, Y, Z, camera, \text{"}location\text{"})$.

After the layout operation, the two layers are fused by $>$ that changes fusion parameters $(X, Y, Z, view, scale, order, alpha\_channel)$ and forms one output stream, thus $>(I_3^V, I_4^V)=I_5^V=(I_3^V, I_4^V)$.

Then the scene is rendered by R in RGB color space, thus $R(I_5^V)=I_5^G=(i_1, i_2, \ldots, i_n)$, where $i_i=(X, Y, R, G, B)$. The interface displays the information as an output stream I_5^O, that is delivered at $D=6/12=0.5$ chunk/s (the fastest stream, 2D layer). Assume $\delta_1=0.1$, $\delta_2=0.3$, $\delta_3=0.6$, $\delta_4=0.8$. $\delta_2<D<\delta_3 \Rightarrow \alpha=1.0$, which means a smooth interaction. The only expected reaction is to turn off the AC when it's slightly cold in the room (18 °C), therefore $R_0^e=(null, null, null, null, null, null, off)$, where *off* means switch of the AC. An expected reaction set for I_5^O is $R_5^e=(null, null, null, null, null, off)$. Unique reaction input and output sets $R_0^u=(6,1)$ and $R_5^u=(5,1)$. $\beta(I_5^O)=1/2(5/6+1/1)=0.92$, that is fully available (assume $\delta_5=0.1$ and $\delta_6=0.9$). In this example, the person actually switches off the AC at 18 °C. The actual reaction set $R^a=(null, null, null, null, null, off)$ γ is computed as the ratio of set cardinalities: $\gamma=|R^a|/|R^e|=6/6=1.0$, that is fully correct (assume $\delta_7=0.1$ and $\delta_8=0.9$). The experience function is described as smooth, highly available, and fully correct. Assume $\sigma_1=0.25$ and $\sigma_2=0.75$. $E=1.0\wedge 1.0\wedge 0.92=0.92 \Rightarrow E \mapsto c^+$, which is continuous communication.

Now consider that the filter is changed to pass one chunk per 10 s. Therefore, the output stream will be updated once per 10 s, that is 30°, 20°, 10°, etc. The second value (20) is still above 18, but the third one (10) is far below. Therefore, the user would not be able to switch the AC off on time. $D=\frac{3}{20}=0.15$ (chunk/s) α has changed accordingly: $\delta_1<D<\delta_2 \Rightarrow \alpha=(0.15-0.1)/(0.3-0.1)=0.25$ which can be described as *quite slow*. The expected reaction is to turn off air conditioning at 18. When it does not happen, there is a new expected reaction to turn off air conditioning at 17, then 16, etc. R_0^e contains 12 *null* elements followed by 9 *off* elements, therefore $R_0^u=(12,9)$. R_1^e contains 2 *null* elements followed by 1 *off* element, therefore $R_1^u=(2,1)$. $\beta(I_5^O)=\frac{1}{2}\left(\frac{2}{12}+\frac{1}{9}\right)=0.2$, that is partially available. R^a contains 20 *null* elements followed by 1 *off* element. Eventually, the user reacts after a screen update showing 10 °C. Therefore, $\gamma=\frac{3}{11}=0.27$, that is highly incorrect. Visualization experience is described as quite slow, partially available, highly incorrect.

$E = 0.25 \wedge 0.2 \wedge 0.27 = 0.2 \Rightarrow E \mapsto c^-$, the communication is failed.

The example does not explain how σ values are set, as it is meant to illustrate the system side of the visualization process. Changes in values of δ and σ are to be modeled together with the user interaction, which is not in the scope of the present paper.

5. Application

5.1. Discussion

The example application of this research is a visual interface that connects humans to intelligent systems ([14,15]) that integrate multiple technologies such as CDSS, ubiquitous computing, cloud computing for advanced data processing and knowledge acquisition in an Ambient Assisted Living (AAL) environment. Initially, these systems do not provide any interface suitable for the interaction with the human in AAL. Such an interface should be convenient enough for patients (α,γ sensitive) and functional enough for medical professionals (β sensitive). It should support various levels of information representation from highly metaphoric for non-professional users (low γ threshold) to very detailed and technically precise for professionals (high γ threshold). It should provide easy and efficient ways of communication between the system and all involved users (therefore $E \mapsto c^+$). This section describes how the theoretical model introduced above results in a multimodal visual interface (MMI) suitable for AAL.

The MMI (schematically represented in Fig. 6) is designed to be the primary form of communication between users and S. The target users of the MMI are patients and direct caregivers such as nurses or caregiver volunteers. The MMI is designed to provide interactive user experience in certain physical spaces such as hospital wards or smart homes. To shorten the learning curve, the MMI is envisioned to have natural input methods (such as voice and gestures), and a high-fidelity 3D graphical output. It realistically models the environment and the users themselves in 3D. It uses human-like virtual personal assistant (PA) to stimulate interactions between the users and S. Finally, it serves as a source of relevant context information provided by $S.I$ and visualized by $S.V$. These tasks are split between three visual layers that form the MMI: the 3D-model of the environment (Scene), the avatar–personal assistant (A–PA), and the heads-up-display (HUD).

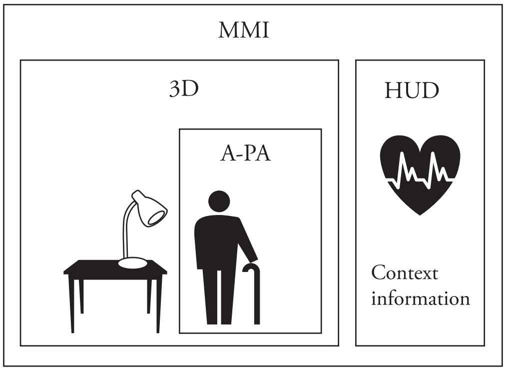

Fig. 6. Schematic view of MMI.

The Scene realistically represents the environment and is used as a canvas for visualization. It enables humans to relate visual output with the real environment which increases the correctness of interpretation (γ) of the visualized information. The objects in the Scene form a hierarchy that helps to easily maintain the large amounts, treating them independently, or applying similar visualization techniques to semantically related objects. There are two types of objects: active and passive. Active objects have sensors attached to them, therefore their changes in the environment are reflected in the Scene. Passive objects normally do not change often and do not have sensors, therefore are static in the Scene.

The A–PA layer is used to visualize a patient's appearance and their measurable status, as well as animate their actions. It is divided into two sub-layers, namely, A and PA. The A sub-layer contains the avatar—"virtual self" a representation of a person in the virtual world. The main purpose of A is to visually represent a person's appearance, location, actions, and status. It is achieved due to realistic 3D model, animation, and application of visualization techniques. A is always visible, tracking patient's movements. The PA sub-layer contains the virtual personal assistant that provides services, similar to the ones by a real personal care assistant. Examples are helping people with their daily living activities and rehabilitation, natural communication. PA is only visible during active communication to a user. Both avatar and personal assistant have their own virtual cameras that follow them. These cameras provide various views of A and PA such as a front-head view.

The HUD layer contains the context information represented as text and graphics. It provides semantic descriptions of a current situation and patient's measurable status. The layer provides context in the dashboard view of the interface, as focus is on the dominant Scene or A–PA layers.

5.2. The visualization model of MMI

The visualization model of the MMI (Fig. 7) is an instance the visualization process described in Section 3. $S.I$ (represented by the application systems) provides six data categories for $S.V$ to visualize on three different visual layers ($S.V$ therefore has three visualization pipelines). The following are the five stages of the visualization process.

1. In the filtering stage, data are obtained, filtered, and split between visualization pipelines. $S.I$ provides both data obtained directly from users and from the algorithmic processing of other data. The input stream is expressed as $I_0 = \bigcup_{m=1}^{6} I_m$, where I_m is a stream of one of the following data categories: unstructured *text*, *multimedia*, *sensory* data (the user data); *knowledge* derived from text, *context* information, semantic

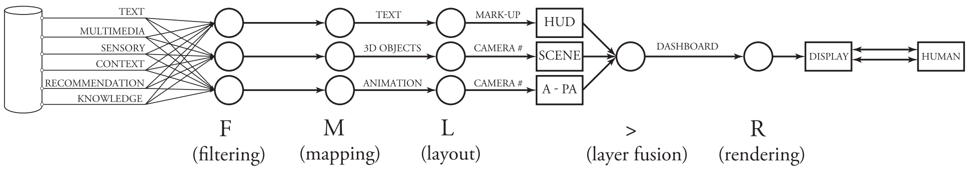

Fig. 7. The visualization process.

recommendation (the system processed data). The data are distributed between the three layers as follows:

- Scene: sensory, context, recommendation;
- A–PA: sensory, context, recommendation;
- HUD: text, multimedia, sensory, knowledge, context, recommendation.

The HUD is fed by all types of data, as it provides context to humans. Limited data scope of the other two layers is due to their 3D nature: there is no need to map text and multimedia in 3D, as there is the HUD layer designed specifically for such types of data. The stream equation for the filtering stage is $I_n^A = F_n(I_0)$, where $n = 1,2,3$.

2. In the mapping stage, data based on their type are transformed from abstract to visual by several mapping functions (which are not difficult to build). The transformations include
   - Scene: sensory↦objects at certain position of certain color and size; alternate color and size of objects;
   - A–PA: sensory↦position of A and PA; alternate color and size of body elements of A and PA;
   - HUD: sensory↦parameters of visualization object or text; text, knowledge, recommendation↦font, size, color.

   The stream equation for the mapping stage is $I_n^V = M_n(I_n^A)$, where $n = 1,2,3$.
3. In the layout stage, visual objects are placed together in a virtual canvas, or positioned in the point of view of a virtual camera.
   - Scene: select $\omega_n \in \Omega$;
   - A–PA: toggle head-camera;
   - HUD: layout I_n^V with a mark-up algorithm.

   The stream equation for the layout stage is $I_{n+3}^V = L_n(I_n^V)$, where $n = 1,2,3$.
4. In the layer fusion stage, all three layers form a dashboard: $I_7^V = >_7(I_{n+3}^V)$, where $n = 1,2,3$. The fusion algorithm places one of the layers in the focus of user's attention by centering and making it the largest in the dashboard. The other layers are aligned to the sides of the screen and provide the context.
5. In the rendering stage, the dashboard is converted to an appropriate color space by a rendering algorithm (Fig. 8). The stream equation for the rendering stage is $I_7^G = R_7(I_7^V)$.

Following the rendering stage is the interaction stage. The top picture in Fig. 8 shows the avatar in the camera view as can be seen by a caregiver. There are several information streams. Among them, the avatar (the A sub-layer) that is updated with the speed of patient's movements. What is actually considered as a chunk of information depends on users. For example, when a medical professional observes a patient recovering from a musculoskeletal trauma, they are interested in the quality of the patient's movements, therefore there are as many chunks of information as movements. In another example, caregivers might be interested in observing the patient's activities. In this case, the patient's actions (such as walking, changing of posture, etc.) are considered as chunks. Other streams in the picture are seen in the HUD layer. These include the status, the activity list, and the warnings. Slow rate of delivery definitely leads to discrete communication which is acceptable as HUD is not a dominant layer, therefore accessed relatively rarely.

The more complex example can be seen in the bottom left picture of Fig. 8. It shows the personal assistant giving the warning of taking a medicine. The HUD displays warnings information and a camera view embedded by the layer fusion algorithm. The personal assistant is pointing at the medicine, and a virtual red cone is incorporated on top showing the position of the medicine and emphasizing its importance. Important information streams are the PA sub-layer, the red cone, the camera view, the status, the activity list, and the warnings. The PA and the red cone are definitely the dominant streams for a patient (Alfred). For caregivers, though, a dominant stream is likely to be the camera view, as it shows Alfred's reaction to the warning. Following are the estimated metrics categories:

1. $\alpha \in$ *smooth* for both Alfred and the caregiver for all respective dominant layers;
2. $\beta \in$ *fully available* for both Alfred and the caregiver, as all important information is available on the screen and nothing important is filtered out;
3. $\gamma \in$ *correct*, as the information is overloaded (the red cone and PA are pointing at the medicine, the HUD displays the warning) and it is expected that the patient will react accordingly.

Estimated communication state is continuous ($E \mapsto c^+$), as the modeled scenario is relatively simple.

The possibility of failed communication can be seen in the bottom right picture of Fig. 8. It shows a view of a living room with avatar performing physical exercise guided by the personal assistant. The A and PA head-camera views are shown in the top left corner to illustrate how accurate Alfred follows the personal assistant. Consider the following situation: instead of focusing on the PA view (which should be the dominant stream), Alfred is

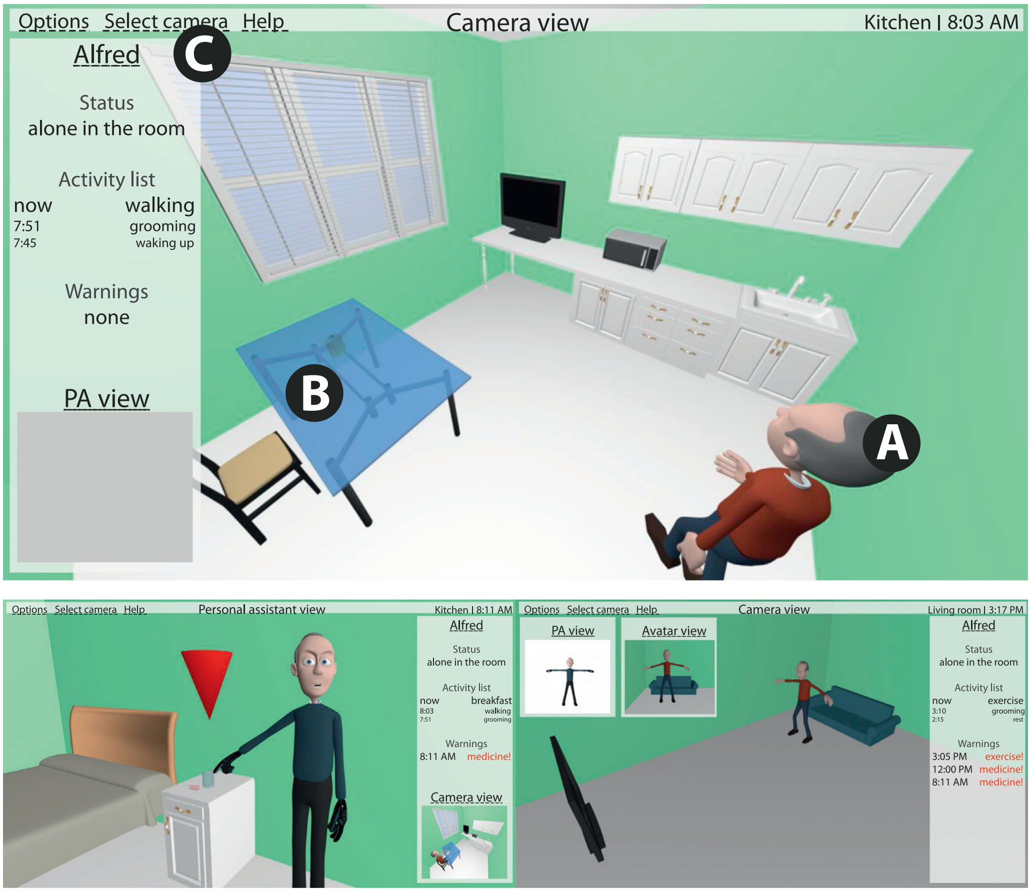

Fig. 8. The visual prototype of the interface. A denotes the A–PA layer, B denotes the Scene layer, C denotes the HUD layer. The top picture shows the avatar in the camera view. The bottom left picture shows the personal assistant in the PA view. The bottom right picture shows the avatar in the camera view and both the A and the PA views in HUD. Modeled and rendered in Autodesk® Maya® 2010 and edited in Adobe® Illustrator® CS5 by the author.

focusing on the Avatar view (observing his own movements). It leads to a failed interaction ($P \to 0 \Rightarrow \alpha = 0$) and to subsequent failed communication with the PA. Overall interaction with S is smooth, as Alfred is focusing on the Avatar view, therefore α is estimated to be high. There is a miscommunication with S, due to inability of Alfred to concentrate on the correct stream. The possible response from S is a removal of the Avatar view and making the PA a dominant stream by changing the interface view from camera to PA (all performed at the layer fusion stage). It will force Alfred to concentrate on the correct stream which will lead to continuous communication.

6. Conclusion

The paper is focused on the theoretical development of visualization experience in the visualization process as applied to healthcare systems. There are two main components in the processing modeling: information streams and visualization stages. Information streams connect systems and humans in terms of information flow. Visualization stages are defined as transformations of the information streams during the visualization process. The process in this paper is modeled to have five visualization stages and support for multiple pipelines that result in a multi-layer output. Visualization experience is measured via visualization metrics that reflect the qualities of information flow and user involvement in the system–user interaction. The metrics are smoothness of interaction, availability of information, and correctness of interpretation. These metrics produce the experience function E, that evaluates the communication state. The communication state provides a degree of quality control over the visualization process and enables humans to make changes during the visualization pipeline so as to obtain better (as measured by E) visualizations in the future.

The theoretical model developed in this paper is applied to an AAL/CDSS healthcare system to produce a user interface prototype for smart environments. The interface combines several visual layers, namely Scene, A–PA, and HUD, to display multiple types of information targeted at patients and medical professionals. Avatar and virtual personal assistant provide natural ways of communication with the system. Examples illustrating measurement and evaluation of visualization experience, and subsequent control of the visualization process are given.

Development of an interactive application requires an integration platform (such as 3D engine) and several visualization environments or programming languages such as Maya [44], AVS/Express [45], and Processing [46].

Furthermore, it requires a close collaboration between SC^3 [15] and CDSS [14] teams of the Ubiquitous Computing Laboratory of Kyung Hee University and medical professionals. The issues related to collaboration and realistic deployment of these projects are under consideration, thus, we do not have access to realistic data as yet. This paper, however, provides essential theoretical basis for future applications. Without a doubt, a prototype visually similar to Fig. 8 can be produced in an ad-hoc way. Such an approach, though, without methodological theoretical development, could lead to an unusable interface.

Serving as an entry point to the area of the visualization experience, this paper opens several research questions for further investigation. For example, the development of the three metrics, their contribution to the experience function, choice of the initial values of certain parameters, user and thinker specific parts of the visualization experience, and more. The theoretical contribution of this paper forms a basis for critical analysis of visualizations from various application domains. This analysis is first based on imperically measuring the proposed visualization metrics, and second considering the combination of such metrics in light of visualization experience.

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Models used in the visual prototype of the interface are obtained from Sweet Home 3D project [47] and distributed under GNU license, the avatar/personal assistant model is by Rodri Torres [48] and available for non-commercial use. Icons used in Fig. 6 are from The Noun Project [49], available in the public domain or under Creative Common License. We thank the authors for the availability of these models.

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