A three-dimensional mirror augmented by medical imaging: Questioning self-portraying at the limit of intimacy

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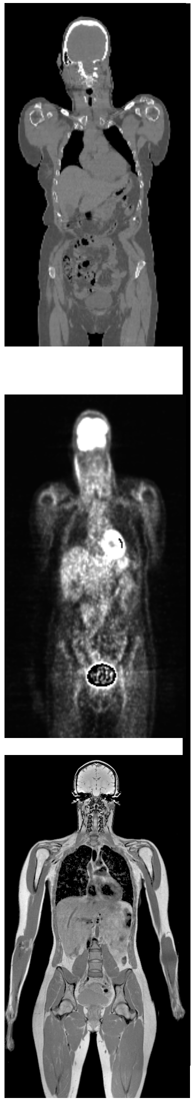

Figure 1: Central coronal slices extracted from acquisitions on three women by X-ray Computed Tomography, Positron Emission Tomography, and Magnetic Resonance Imaging.

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Abstract
With the rapid developments of medical imaging, our personal inner body can be unveiled as never before. Medical images are usually considered as ordinary objects and their potential intimate value is never really considered. In this paper, we present an exploratory installation which anticipates prospective issues when medical and self-images interfere with each other. *Primary Intimacy of being* acts as a digital mirror reflecting the users' bodies with three-dimensional avatars, which are computed in real time from three medical imaging modalities (Fig. 1). A first evaluation reveals individual differences between users with respect to their personal privacy concerns while interacting with the installation. Thereafter, these issues may be probed in the scope of self-portraying.

Author Keywords
Medical imaging; embodiment; intimacy; augmented mirror; volumetric rendering.

ACM Classification Keywords
H.5.1 **[Information interfaces and presentation (e.g., HCI)]**: Multimedia Information Systems.

Introduction
At the end of 1895, when Wilhelm Röntgen imaged for the first time the interior of a human body *in vivo*, the

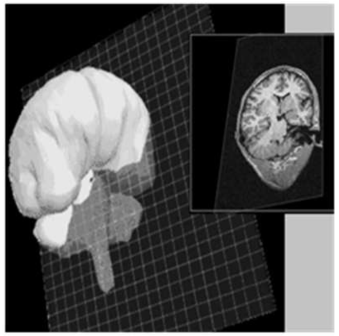

Figure 2: Moveable cutting plane technique from a brain dataset acquired with MRI [13]

Figure 3: Real-time visualization of 3D hyper-realistic anatomical models from [15]

mass media feared that this amounted to a new form of nudity and the dissolution of moral standards [1]. Some people even started selling X-ray-proof clothes for the sake of women's modesty. For decades, radiography had then revealed the tissue density of a body pierced by X-rays followed by developments in other modalities. So far, radiologists have kept performing their diagnosis using 2D images. With the acquisition of more complex multimodal and multiparameter datasets of the inner body, the field of medical volume visualization has undergone significant developments and the door has been opened to real time interactive applications [2] [3]. Associated with tangible interaction or augmented-reality technologies, these developments may provide powerful tools for clinicians to efficiently explore the images of the patient's anatomical and functional body [4] [5]. Going from 2D to 3D, from static to dynamic views, the everyday practitioner often keeps considering the outcomes of the inner visualization of the body as an ordinary subject of study, namely a separate object to study. Early wonders described in [1] are far from our current concerns. However, medical imaging presents the human body in a way we never could experiment ourselves before [6]. As recent years have seen the growth of theories emphasizing the role of the body in shaping the mind [7], one might ask whether such images of our inner self could influence not only our cultural representation of the body [8] but also the way we perceive ourselves, our boundaries, and the world around us [9]. In other words, what status the inner body has with respect to the self? Are those parts intimate? Thereof, are medical images obscene and is it legitimate to unveil them? How would it affect our self-perception, overall?

In this paper, we present the design, the first implementation, and an evaluation of an interactive exploratory installation, entitled *Primary Intimacy of being*, which challenges the prospective questions we have raised above. *Primary Intimacy of being* is a 3D mirror augmented by medical imaging. The participants face a large screen, which *reflects* participants' 3D avatars cut by a virtual 2D plane as if they were probed in real time by X-ray Computed Tomography (X-ray CT), Positron Emission Tomography (PET), or Magnetic Resonance Imaging (MRI). Using an embodied interaction paradigm, *Primary Intimacy of being* brings closer the medical image and the participants' body, blurring the line between inanimate object and intimate self-body representation.

Related works

In this section, we present how whole-body 3D datasets can be acquired by X-ray CT, PET, and MRI; how such 3D datasets may generally be visualized, and how self-mirrors or virtual images influence one's self-perception. Finally the pivotal role of the intimate value of inner images is discussed.

Medical data acquisition

Today, data are acquired faster, with much better temporal and spatial resolutions, in an interwoven integration of modalities and parameters [3]. Three medical modalities allow for whole-body acquisition: X-ray CT, PET and MRI (Fig. 1). X-ray CT is mainly a morphological imaging modality based on the absorption of X-rays passing through the body according to the density of the traversed tissues which delineates the bones and allows for processing 3D volumes [10]. PET is a functional imaging modality that aims at detecting injected radiolabelled molecules, and

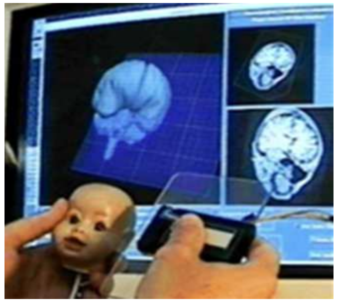

Figure 4: Three-dimensional props to control the cutting plane location: [13]

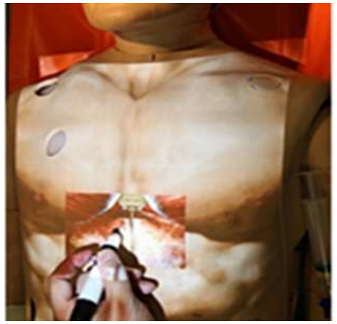

Figure 5: BodyExplorerAR: User tracking and augmented reality application on a mannequin [5]

following the related organismal metabolism [11]. Finally, MRI is a morphological and functional imaging modality based on the magnetic moment of the nuclear spin mainly of hydrogen. It is suitable for differentiating soft tissues [12].

Real-time visualization of volumetric data

The 3D and 4D data structures acquired and processed by any medical imaging modality cannot be used as such by clinicians. Rendering these volumetric datasets is a critical step for optimal visualization and human comprehension [2]. The outcome must be easily readable by the practitioners while preserving the original data information. The most commonly used approaches to visualize medical images are 1) the extraction of a plane as a 2D slice; 2) the extraction of surfaces from volumetric data by isosurface rendering; and 3) the visualization of density by volumetric rendering. The first approach is often combined with others. 1) A moveable 2D cutting plane technique can be used to explore the volumetric data with the help of a prop as shown in Fig. 2 [13], [14]. 2) Isosurfaces may provide a more global view of specific parametric fields (e.g. density, velocity, temperature, etc.) than cutting planes for 3D parametric maps. However, isosurfaces are suitable for continuous fields but fail for tracking highly heterogeneous data. 3) Maximum intensity projection (MIP) is an additional but less common approach for volumetric rendering. This technique is efficient for sparse data like PET or MRI angiography but it is computationally very expensive. The combination of late developments in imaging acquisition and volume rendering makes possible the production of hyper realistic anatomical models [3] such as in Fig. 3 ([15]).

Interactive visualization of volumetric data

After the rendering, one the of key challenge lies on how to control the visualization. Mouse or/and keyboard are standard interfaces for 3D handling of volumetric data. Hinckley *et al*. argued that a more intuitive manipulation technique could provide a better understanding of the volumetric data structure [13]. Researchers in Human Computer Interaction (HCI) have developed a wide variety of interaction metaphors and tangible paradigms. Passive interface props were the first 3D interfaces to support continuous clipping interaction in 3D space (Fig. 4). Some recent works have included a gesture-controlled 3D anatomy model application [16] or a body explorer with user tracking and augmented reality on a mannequin (Fig. 5), [5]. The possibilities for interactive medical imaging visualization are wide over the coming years and will rapidly be available to the common run of mankind. The resulting ubiquity of realistic images of our inner body stresses the need to acknowledge their intimate value and their influence on our self-perception.

Avatar bodies, self-image, and self-perception

Human self-perception is highly malleable as experienced with avatars. Avatars are digital body representations controlled by the user. From the first developments of cyberspaces, issues were raised about the ambiguous phenomena of body ownership [17]. With the modern developments of graphic rendering and motion tracking, these avatars are coming closer to human doppelgangers questioning the limit of our self [18]. These forms of embodiment have been shown to influence our self-perception as with the Proteus effect [19] (e.g. users express more dominance if acting through a tall avatar [20]). The degree of control fosters this type of effect: The more the user embodies

Figure 6: Mirracle: Augmented-reality magic mirror system for Anatomy Education [24].

Figure 7: Augmented reality application for improved perception of 3D medical imaging data in-situ [25].

the avatar, the more the avatar influences the self-perception [21]. Old as the Greek mythological character Narcissus, standing in front of a reflecting medium is a fundamental self-perception-building experience. As ordinary as it may seem, the mirror experience is an alienating self-experience: our embodied self may perceive the reflected body as an external object, in a third person perspective [22]. For Western people, self-observation through a mirror increases interoceptive sensitivity [23].

Whether these self-images are qualified as real or virtual, they shape our identity and our behaviors. All these works show a tight coupling between what we perceive of our body and how we act through it. Recent applications such as AnatOnMe [24], Mirracle (Fig. 6, [25]), or the application in [26] (Fig. 7) map inner images onto the participant's body, thus enhancing their embodiment. So far, the purpose of these applications is never personal. They address planning therapy, predictive simulation, diagnosis, learning, education, or patient-doctor communication. They do not raise questions about their influence over our self-perception and, by consequence, our behaviors. How images of the body interior, once embodied, are perceived is a primary question.

Inner Images and Intimacy

Inner images of living bodies have initially feared people as they were suggesting extreme nudity [1]. This association of body interior and personal privacy is characteristic of the Western culture, for which the inner self lies deep in the body. Etymologically, *Intimacy* comes from *Intimus* which is the superlative degree of interior in Latin. Intimacy is thus somehow spatial, with the body seen as the container. Since the antiquity, the interior has been reified and it can be discovered through introspection, by "looking inward" [27]. Considering this background, it seems understandable that imaging one's body can be sensed as a violation of one's intimacy. Van Dilck reports a study where 10% of the population refused to show the outcomes of their scans for teaching purposes [8]. Nowadays, people are more used to imaging capabilities but discovering these images may still affect them in an intimate way.

Intimacy vs Privacy

The issues raised above have to be differentiated from privacy concerns. Privacy mostly refers to the possibility to keep unveiled information from the masses and its clear definition is debated by law academics [28]. As conceptualized in psychology, intimacy refers to an interpersonal process in close relationship, which partly consists in self-disclosure [29]. "We form relationships with differing degrees of intimacy and self-revelation" [28]. The intimate value of an object or a body part is therefore related to the proximity of the people to whom we are able and willing to unveil it. In this work, we are interested in this second view as it relates more directly to the personal experience.

The exploratory installation *Primary Intimacy of being* we describe in the next section aims at questioning the impact of the embodiment of the images of one's inner body. First, the technical challenges behind such rich real time visualization are detailed. Then, a preliminary evaluation of *Primary Intimacy of being* is introduced. It focuses on the perception of these inner images: "do people embody these inner images?" and "do they consider them as intimate parts?" are the two main

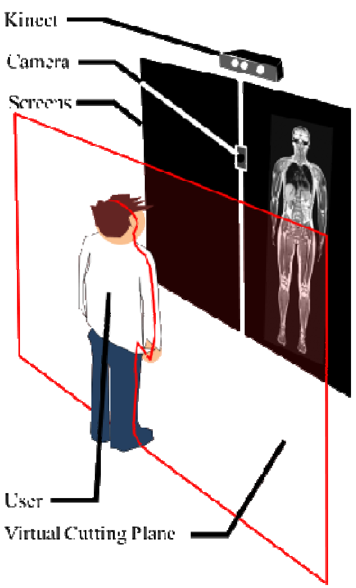

Figure 8: Illustration of the installation

research questions raised here. This is a first step before going further into the question of self-perception and self-portraying.

System description

The implementation of the installation *Primary Intimacy of being* relied on whole-body data acquisition for the selected three medical imaging modalities, 3D data rendering, 3D avatar animation and motion tracking. To our knowledge, this is the first system enabling this full body illusion based on real anatomical data.

Data acquisition with X-ray CT, PET, and MRI
For the three imaging modalities, data were acquired for a male and a female in two subsequent series: one for the upper body and one for the lower body. These two parts were then merged using a dedicated script on Matlab® (The Mathworks, Natick, MA, USA). X-ray CT and PET were performed as part of a clinical exam on two patients, female aged 68 years and male aged 48 years, on a Biograph 6 (Siemens Healthcare, Munich, Germany). The total acquisition time was 26 min with a spatial resolution close to 1 mm^3 for X-ray CT. The spatial resolution for PET data was 3 mm^3. MRI acquisitions were performed on two healthy volunteers, female aged 26 years and male aged 44 years, at 1.5 T (Achieva®, Philips Healthcare, The Netherlands). A gradient echo sequence was implemented with a 1.6 mm isotropic spatial resolution and a total acquisition time of 180 min. It is possible to achieve a mirror like illusion with someone else medical images as most people inner body remains unknown. People could feel they face their inner body as they do not know it and because it moves as they do.

3D real-time animation and visualization

Animating such high resolution 3D data requires the use of a high-end graphic processing unit (GPU) performing both skeleton-based animation and 3D rendering using OpenGL/GLSL acceleration (Khronos Group, Beaverton Or. USA).
Volumetric structure from medical data - As GPUs are designed to process triangles, we designed a complex structure composed of isospheres (diameter 1.5 cm, each composed of 32 triangles) based on the matrix data. One million spheres were generated and located at semi-random location provided that the corresponding matrix data value was higher than a threshold. Adjusting this threshold enabled us to control the shape of the geometrical rendering structure. Following this approach, the mesh was set dense enough so it could be clipped along any surface and still presented a fully filled image of the corresponding slice in the data. The volumetric data was stored in a (1024×1024×512) 3D matrix.
Volumetric structure of skeletons - Skeletons were placed onto the resulting 3D mesh and automatically rigged to it using a dedicated algorithm. They were manually corrected using a 3D brush tool.
Animation of the volumetric structures - The animation was performed using per vertex GPU deformation (Vertex Shader), enabling real-time animation of 64 million vertices at 30 fps. Deformation was applied using quaternion-based rotations of the underlying skeleton generated by the motion capture system (see next section). Rotations and joints were smoothed using Spherical linear interpolation (SLERP). Depth perception was enhanced by a gradient base coloration which made the body brighter or darker depending on its position on the depth axis. The use of a glass free stereoscopic screen would have clearly been a great

Figure 9: One Primary Intimacy of being with two people interacting with

improvement, but in a context of a museum, no suitable technologies were available to us.

User tracking
Motion tracking of multiple users – For the installation, users had to be effectively and non-intrusively tracked in order to simulate the mirror effect. We chose to use a Kinect® sensor (Microsoft, Redmond, Washington) with the FAAST middleware [30]. Within this framework, the skeletons were defined by 24 joints (head, shoulder, elbow, wrist, waist, knee, ankle etc.).
User gender tracking – To match the avatar gender to the user, we integrated a gender recognition software (Shore [31] [32]) with an added camera (Logitech® HD Webcam C525). The matching between the detected genders, with the webcam, and the detected skeletons, was done by projecting the 3D reference frame of the Kinect®, located at the top of the installation, onto the 2D frame of the camera (see Fig. 8).
Installation setup and first implementations
Fig. 8 shows the basic configuration of one mirror augmented by medical imaging. It comprised two 65" Philips monitors; a Kinect® sensor; a webcam; a HP Z800 workstation (Hewlett-Packard, Palo Alto, California) with an Quadro 4000 graphic card (nVidia, Santa Clara, California), and a dual Intel Xeon processor at 2.40 GHz (Intel, Santa Clara, California). Thanks to the GPU based approach and the Kinect low latency, the system was very reactive. Lag was almost unnoticeable and only fast motions made the lag somehow appear to the user. This low latency is very important to achieve a mirror like perception.

Evaluation

This section presents an exploratory evaluation of the user experience while interacting with the *Primary Intimacy of being*. It aimed at probing the way individuals perceive the embodied inner images in a controlled and private setup. More specifically, it evaluated if people embody the virtual inner body and feel intimacy issues in front of the system.

Participants and protocol
Thirty volunteers (14 females, 16 males) of age (33.1 ± 10.1) years (mean ± standard deviation) participated in the study. First, each participant was personally introduced to the principle of the installation: "In the screen you will be facing, you will see a human silhouette you can control by your movements. If you go toward the screen, you will go through a cutting plane which reveals the inside of the silhouette". Then, each participant was asked to stand in front of the installation and to freely interact with the system during 3 min. The participant was left alone. Finally, just after having completed the task, participants were asked to fill a self-report questionnaire. The questionnaire dealt with three different dimensions: intimacy (Intim) and embodiment (Embod) which correspond to our two main questions; and depth perception (D-Perc) for controlling what could be a confounding variable (being able to see the depth could enhance the embodiment experience). Embodiment was decomposed in the three subscales defined by Longo *et al.*: self-identification (S-Ide), location (Locat), and agency (Agenc) [33]. For each subscale, three items were proposed, each one associated with a ten-point Likert scale ranging from -5 (total disagreement) to +5 (total agreement) (Tab. 1). The way participants explore their body with the installation is probably tightly coupled with their experience. To evaluate this coupling, the participant's movements during the interaction were recorded with the Kinect® of

		S-Id	Loca	Agen
Embo	r	**.833**	**.900**	**.928**
	p	**.000**	**.000**	**.000**
S-Id	r	1	**.557**	**.719**
	p		**.001**	**.000**
Loca	r		1	**.776**
	p			**.000**

Table 2: Pearson correlations between the embodiment subscales

		D-Per	Intim
Embo	r	.283	**.369**
	p	.130	**.045**
S-Id	r	-.069	**.492**
	p	.719	**.006**
Loca	r	**.457**	.178
	p	**.011**	.346
Agen	r	.303	.360
	p	.103	.051
D-Per	r	1	.064
	p		.736

Table 3: Pearson correlations between the embodiment subscales and the depth perception and intimacy scales

the installation. The movement data were lost for two participants due to temporary malfunction. Two global variables related to the participant's movements were computed: the total quantity of motion (QoM) and the ratio of the quantity of motion on the z axis (depth axis orthogonal to the screen) by half of the quantity of motion on the xy plane (parallel to the screen) (QZ/XY). The absolute position of 5 joints (head, hands, and feet) was used. Data was low pass filtered with a 2nd order Butterworth filter at 7 Hz and normalized to the participant's height [34].

Results

Tab. 1 shows the descriptive statistics of the different scales. Subscales of *Embodiment* show acceptable to good internal consistencies (α ranges between 0.62 and 0.82). The overall *Embodiment* scale, which comprises the first nine items, shows excellent internal consistency (α = 0.88). *Intimacy* shows good internal consistency (α = 0.73) but *Depth perception* shows really poor internal consistency (α = 0.37). For this scale, excluding the 10th item increases α to 0.48, which is still weak. For the whole population, participants positively reported to *embodiment* subscales and *depth perception*. The mean values are between 1.41 and 2.51, which correspond to "slight agreement" and "agreement". Participants negatively reported to the *Intimacy* scale ("slight disagreement"). The high standard deviation of *Intimacy* suggests strong individual differences. Fig. 10 shows the distribution of our population on the *Intimacy* score. This distribution is not normal (Shapiro Wilk test: p=0.001) but almost linear along the score range. Tab. 2 shows Pearson correlations between the embodiment subscales. Strong and significant positive correlations appear between them, which confirms the good internal

Table 1: Descriptive statistics for the 3 scales and 3 subscales used for self-report, n=30

Scale	α	Mean	SD	N°	Items
Embod	0.88	2.06	1.88		
S-Ide	0.73	2.51	1.95	1	I had the impression of looking at my own body in the screen
				2	I had the impression that the body in the screen looked like my own body
				3	I had the impression that the body in the screen was mine
Locat	0.82	1.41	2.56	4	I had the impression that my body was at the location of the body in the screen.
				5	I had the impression of projecting myself in the body in the screen
				6	I had the impression of being at the body location in the screen
Agenc	0.62	2.27	1.86	7	I had the impression of controlling the body in the screen
				8	I had the impression of moving through the body in the screen
				9	I had the impression of being able to do the movements I wished with the body in the screen
D-Perc	0.37	1.68	2.35	10	I had the impression of seeing the inside of the body in the screen
(without	0.48			11	I had the impression of seeing the body in the screen along its depth
n°10)				12	I had the impression of perceiving the body in the screen as a volume
Intim	0.73	-1.43	3.21	13	I felt embarrassed and/or some modesty in front of the screen
				14	I had the impression of being naked in front of the screen
				15	I would not put myself in front of this screen with other people if they were not relatives

		QoM	QZ/QXY
Embo	r	-.176	.194
	p	.371	.323
S-Id	r	-.334	.118
	p	.082	.548
Loca	r	-.006	.311
	p	.974	.108
Agen	r	-.177	.034
	p	.368	.864
D-Per	r	-.282	.095
	p	.146	.632
Intim		**-.454**	-.146
		.015	.459
QoM		1	-.066
			.738

Table 4: Pearson correlations between all the subscales and the two global motion-related quantities QoM and Qz/QXY.

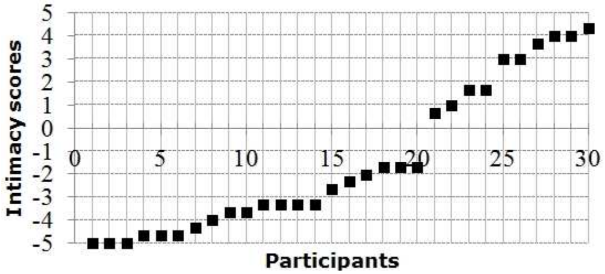

Figure 10: Intimacy scores sorted in increasing order

consistency of the *Embodiment* scale. Tab. 3 shows Pearson correlations between the embodiment subscales and the depth perception and intimacy scales. *Embodiment* significantly and positively correlates with *Intimacy*. The *Self-Identification* subscale, which significantly and positively correlates with *Intimacy,* appears to be the only dimension of embodiment responsible for the association between *Embodiment* and *Intimacy*. The *Location* subscale significantly and positively correlates with *Depth perception*. Tab. 4 shows Pearson correlations between the two global motion-related quantities and the self-report scales. The *Quantity of Motion* appears to correlate negatively and significantly to *Intimacy*.

Discussion

For the population who experienced *Primary Intimacy of being*, the installation elicited embodiment in its three subscales, with a negative level of Intimacy. This suggests that participants effectively made the body in the mirror their own without feeling any intimacy issue. However, looking at the score distribution along the Intimacy scale unveils strong individual differences: about one third of the population reported having intimacy issues in front of the installation. What and why these differences exist is an interesting pending question. The positive correlation between the Intimacy and the Self-Identification scales provides a first hint to guide the analysis further: the ability to make an external artifact part of one's self is a mediating variable. The negative and significant correlation of the Quantity of Movement with Intimacy confirms the embodied nature of this feeling: it suggests that people who experience intimacy issues moved less during the interaction which might be interpreted as a sustained attention while in front of the mirror. As noted by one reviewer, another possibility for this result is the influence of the general participant shyness. In this experiment, depth perception was independent from these phenomena. Overall, these results outline the need to study the link between medical imaging and self-portraying in a differential way. Understanding the role and covariates of these individual differences could be a first approach to uncover underlying processes associated with intimacy issues.

Conclusion

Medical imaging is on the way to personalized medicine. With progresses in acquisition, real time rendering and interaction techniques, interactive medical imaging applications are becoming realistic and accessible to the masses. This ubiquity enables numbers of potential medical developments but it also questions the impact of these images on self-portraying. In this paper, we have presented a mirror augmented by medical imaging, the *Primary Intimacy of being,* which aims at probing the prospective issues raised by such developments. This exploratory installation invites people to interact with 3D avatars and to explore inside their body as X-ray CT, PET, or MRI may probe them. The system developed here relies on the GPU to specifically render in real time heavy volumetric datasets such that users, *reflected* in the mirror, can cut through the interior of the avatar body as if it were their own. While this application has great potential for anatomy education and doctor-to-patient communication, our focus in this paper was on intimacy issues raised by such a system. We proposed a preliminary evaluation of the system to acknowledge how people feel while interacting with the system. If most participants reported to embody the inner images in the mirror, it was not systematically associated with intimacy issues: large individual differences appeared in the way the installation provoked modesty reactions. Going deeper in the understanding of this plurality of experiences will be the next step of our investigations, going along with questions about self-perception. As realistic as it may look, several limitations of our installation have probably impaired the inner images embodiment. The most important cause of illusion-breaking in front of the mirror was the mismatch between the virtual agent and the participant's morphologies, other than height and gender. A proper estimation of the participant's size and corpulence with a matched 3D avatar body should be involved in creating a better self-body illusion. The user’s experience could also be improved by making use of the biomechanical information X-ray CT or MRI data simply provides here over the whole-body to determine local transformations according to the tissue properties. In addition, physiological signals related to the cardiac and respiratory cycles could be advantageously exploited to provide biofeedback and to increase the embodiment experience. These two key points are exciting technical challenges that can bring closer the external inner image and the personal self. The ubiquity *Primary Intimacy of being* carries might be part of future developments in clinical practice. It is already now a platform that questions the impact of medical images on self-portraying. Future technical developments will go along with deeper perceptual and behavioral analyses. As the presented study implicitly shows, understanding this experience requires interdisciplinary skills and we believe that the Human Computer Interaction community could take over the topic in an insightful way.

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