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Avatar-Centered Feedback: Dynamic Avatar Alterations Can Induce Avoidance Behaviors to Virtual Dangers

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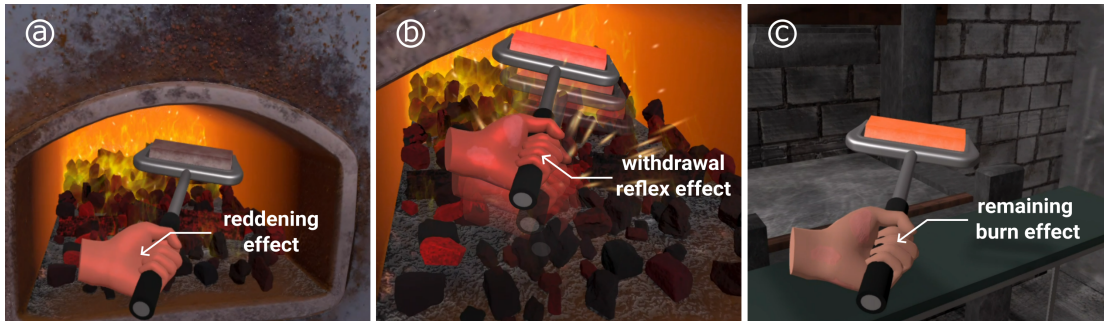


Figure 1: Snapshots of our experiment studying the impact of *avatar-centered feedback* of a virtual fire on avoidance behaviors’ induction. In (a), the avatar’s hand stays relatively distant from the virtual fire, leading it to slightly redden as a form of avatar-centered feedback. In (b), as the user deepens the virtual hand inside the fire, it strongly reddens and burns appear. The avatar movements are also altered, simulating withdrawal reflexes in reaction to adjacent sparks bursting. In (c), as the user moves away from the virtual fire to proceed to the next task, the reddening diminishes, but the burns persist.

ABSTRACT

One singularity of VR is its capacity to generate a strong sensation of being present in a dangerous environment, without risking the physical consequences. However, this absence of consequences when interacting with virtual dangers might also limit the induction of realistic responses, such as avoidance behaviors, which are a key factor of various VR applications (e.g., training, journalism, or exposure therapies). To address this limitation, we propose *avatar-centered feedback*, a novel, device-free approach, consisting of dynamically altering the avatar’s appearance and movements to offer coherent feedback from interactions with the virtual environment, including dangers. To begin with, we present a design space clarifying the range of potential implementations for this approach. Then, we tested this approach in a metallurgy scenario, where participants’ virtual hands would redden and display burns as they got closer to a virtual fire (appearance alteration), and simulate short withdrawal reflexes movements when a spark burst next to them (movement alteration). Our results show that in comparison to a control group, participants receiving avatar-centered feedback demonstrated significantly more avoidance behaviors to the virtual fire. Interestingly, we also found that experiencing avatar-centered feedback of fire significantly increased avoidance behaviors toward a following danger of different nature (a circular saw). These results suggest that avatar-centered feedback can also impact the general perception of the avatar vulnerability to the virtual environment.

Index Terms: Virtual Reality, Embodiment, Perception

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1 INTRODUCTION

Many actions that would be dangerous in the real world (e.g., bringing one’s hand inside a fire), can be experienced in VR without any physical consequences. Moreover, the strong sensory immersion also permits users to feel present around the danger [52, 53] and, to some extent, to perceive and respond realistically to it (e.g., in terms of behaviors[49], emotions [6], or physiological responses [57]). Various VR applications benefit from this specificity, which improves user engagement [6], knowledge retention [30], skill transfer [44], or emotional readiness [39]. This is relevant for a wide range of VR applications such as VR training [34], immersive journalism [12], exposure therapy [16], or behavioral research [37].

However, VR experiences differ from real-world experiences in many aspects, inducing perception and responses to virtual dangers that are generally only partly realistic [57, 1, 35]. Hence, finding new techniques contributing to stronger realistic responses to virtual dangers can benefit the aforementioned applications. This challenge was outlined by Spanlang et al. as follows: “*One way to think about the goal of presence research is that to be successful it should be able to discover what would be necessary to make people actually and physically run away from a virtual fire*” [57].

In this paper, we place our focus on the induction of realistic responses to virtual *physical* dangers, i.e., virtual elements whose real counterparts can have a direct negative impact on user’s body. Such elements will be referred to as “virtual dangers” for simplicity.

One element playing a key role in the induction of realistic responses to virtual dangers is the *avatar*, the user’s virtual body [55]. Indeed, users embodying an avatar tend to adopt more realistic reactions to virtual dangers [56]. This effect increases with a stronger *sense of embodiment* [20], which can be induced by increasing the realism and the anthropomorphism of the avatar appearance [62, 1, 35, 27], or the sensory coherence [2, 29].

Yet, realistic responses to virtual dangers are mostly induced *a priori*, i.e., the sensation that “a virtual danger is real” and that “I have a physical presence in the virtual environment” induces a sensation that “I *could* be injured”. However, this sensation is generally not confirmed *a posteriori*, as users usually do not experience any consequences of performing an *injurious interaction* (the avatar interacting with a virtual danger in a way that would have harmed it in the real world). This absence of consequence, negating the sensation that the virtual danger might be real (and ergo dangerous), could decrease the induction of future realistic responses. This assumption is in line with common models of presence in VR, which state that virtual elements not reacting to users’ actions tends to reduce the perception that VR events are actually occurring, a phenomenon also referred to as *plausibility* [52, 53].

Haptic feedback is a common approach to provide *a posteriori* feedback on an interaction with a virtual element [4, 60]. However, their utilization involves numerous drawbacks, such as the device specificities to a limited range and types of generated haptic sensations, cumbersomeness, expansiveness, or additional environmental cost [5]. Hence, there is a need to conceptualize device-free approaches to provide feedback of virtual dangers.

For this reason, we introduce the concept of *avatar-centered feedback*, a device-free, and flexible approach that can, among others, be utilized to present consequences of injurious interactions. Specifically, we define this concept as: “a dynamic alteration of the avatar’s appearance or movement, in response to its interaction in the virtual environment”. Examples of avatar-based feedback are scarce, but we can notably mention solutions altering fingers’ color to provide feedback on virtual contacts [40], enlarging fingertips as they come into contact with an object, providing contact force feedback [33], or altering movements control-display ratio to simulate virtual forces, such as weight [46], or forces fields [42].

In order to explore the potential of avatar-centered feedback of virtual dangers, we conducted an experiment measuring their impacts on users’ behaviors and perceptions in regard to virtual dangers (illustrated in Figure 1). First, this experiment aimed at measuring the impact of avatar-centered feedback of a virtual danger, on realistic responses toward it (**RQ1**). Furthermore, we were wondering whether experiencing avatar-centered feedback of a specific danger could impact at a more general scale, future avoidance behaviors to dangers of different natures (without them generating any avatar-centered feedback) (**RQ2**).

The main contributions of this paper are: (i) the presentation of a design space describing the range of possible implementations of avatar-based feedback, and (ii) a user study involving 42 participants, providing insights into the usability of avatar-centered feedback for inducing realistic responses to virtual dangers.

2 RELATED WORK

In this section, we review previous works that guided this research. Specifically, we start by organizing factors known to contribute to the induction of realistic responses to virtual dangers. Then, we gather insights from previous applications, informing about the feasibility and factors to consider for implementing avatar-centered feedback of virtual dangers.

2.1 Factors Provoking Realistic Responses

Generally, realistic responses in VR largely depend on the sense of *presence* [52, 53], the sensation of “*being there*” [18, 50, 51]. Slater divided presence into two dimensions: “*Place Illusion*” (the sensation of being in the virtual place) and “*Plausibility*” (the sensation that events perceived in VR are actually occurring). While *Place Illusion* mostly relies on objective qualities of the VR system (e.g., tracking system, or display accurately adapting to head movements), *plausibility* is more complex and has to be designed

deliberately [53]. Slater proposed three contributing factors to *plausibility*: (i) reactivity of the environment to participant’s actions, (ii) contingent references by elements of the environment to the participant, and (iii) credibility of expectation, i.e., the environment is constructed based on evidence of what is supposed to happen in real life where this is relevant [53]. When plausible environments are designed, they can induce realistic responses to virtual dangers. For example, users might experience a threat sensation in response to a virtual crowd looking directly at them [3], or heart rate acceleration in responses to physical props providing plausible haptic feedback of their actions in a high altitude environment [32, 49].

However, in most VR applications, injurious interactions with virtual dangers do not lead to any consequences, resulting in the absence of factors (i) and (iii) in the aforementioned model of *plausibility*, in turn weakening the realism of responses to following attendance to the danger. The effect of repetitive presentations to virtual dangers was tested in the past, without revealing a decrease of physiological nor behavioral responses [13]. However, considering the abruptness of the danger (a crusher suddenly descending onto the avatar’s hand, five times), these results might also be due to a ceiling effect, which led authors to hypothesize that the results could be different with more repetitions. We can also imagine a danger that would be less abrupt (i.e., a virtual fire) could lead to different results. Reversely, Berton et al. reported that the absence of feedback from interactions with a virtual crowd could diminish future avoidance behaviors [4], suggesting that realistic responses diminish as consequences of an interaction are not perceived.

In the real world, the potential consequences of physical dangers that lead us to react to them concern the pain they could provoke (which is, obviously, not ethically desirable to replicate), but also the impact they could have on one’s body. In VR, while the avatar is only a virtual representation, it might still be perceived by its user as their own body, and provoke comparable reactions. Indeed, while the consequences of injurious interactions rarely impact the avatar, the mere presentation of the avatar can increase realistic responses to it [56]. This can be attributed to a sensation *a priori*, that one could be physically harmed in the virtual environment). This bodily connection felt toward the avatar is usually referred to as the *sense of embodiment* [20, 58], and was originally demonstrated in VR by the *virtual hand illusion* (VHI) [54, 48]. It can notably be amplified by increasing the similarity between the real and virtual appearance [1, 26, 11], or from a stronger sensory coherence [38, 48, 8]. Beyond embodiment, the perception of avatar’s characteristics, which can notably be modulated by its appearance [7], might also impact responses to virtual dangers [10, 28]. For example, as compared to a human-looking avatar, it was reported that embodying a tough-looking alien reduced avoidance behaviors to cannon shots [10], while a strong robot could induce a stronger sense of security in high altitude [28]. Considering that embodying an avatar increases realistic responses to virtual dangers *a priori*, we can imagine that modifying it dynamically in consequences of injurious interactions (similarly to what happens in the real world) might in turn strengthen them *a posteriori*. In Section 1, we referred to this approach as a form of “avatar-centered feedback”. Formally, this approach distinguishes itself from previous embodiment research and from the VHI principle, usually based on minimizing mismatches between the real body and the avatar, by voluntarily inducing such body mismatches to instead better match the avatar to its interaction with the virtual environment.

Considering that this approach remains largely unexplored, in the next section we review previous research that could offer insights into important factors to consider for its utilization.

2.2 Insights On Avatar-Centered Feedback

An avatar is characterized by its appearance and its movements. Hence, we consider these two aspects as potential sources of avatar-

centered feedback of virtual dangers.

Alteration of the avatar appearance. Embodying an avatar which appearance differs from the user’s appearance (a *dissimilar avatar* [9]), can impact physiological [24, 31, 61], emotional [28, 23], and behavioral [10] responses, or different aspects of the user’s perception [61, 28, 36, 33]. Regarding danger perception, a burning avatar can, for example, generate real burn sensations [61] and engender changes in the body temperature [24]. As mentioned above, a tough-looking avatar can also alter the fear of height [28] and avoidance behaviors [10] in VR. Interestingly, embodying an injured-looking avatar has also been reported to increase pain sensitivity [36, 31] and to induce a sensation of unpleasantness [36, 23]. Promisingly, these results suggest that using an avatar injury as feedback of injurious interactions might lead to realistic responses, even though their impact on behavioral responses remains unclear. Furthermore, previous research also suggests that embodying injured avatars does not necessarily diminish the sense of embodiment [36, 23], which is essential to maintain the quality of the user experience [20]. However, contrary to the aforementioned results focusing on static avatar appearances, the impact of dynamic adaptations of the avatar appearance (i.e., appearance-based avatar-centered feedback), remains largely unexplored. Some of the few examples, concern the alteration of finger colors as feedback of virtual contact [40], or the enlargement of fingertips as a contact force feedback [33]. Hence, while avatar-centered feedback based on appearance seems promising for inducing realistic responses to virtual dangers, its real impact and feasibility remain largely unknown

Alteration of the avatar movements. Avatar-centered feedback based on movement alterations has often been utilized to provide feedback on forces exerted by a virtual element, e.g., a force field [42], or virtual objects’ weights [46]. Contact forces are also commonly simulated by blocking the avatar’s movement as it comes in contact with an object [41, 22]. Such techniques were generally reported to be enjoyed by users [41, 46], and to generate a strong sense of presence [46, 22]. These results are promising regarding the utilization of movement-based avatar-centered feedback of virtual dangers. Indeed, we can hope that when applied to virtual dangers, it will be similarly accepted, and generate high interaction realism and realistic responses. However, inducing a mismatch between real and virtual movements may also reduce the sense of agency [25], in turn reducing the sense of embodiment [20]. Furthermore, to the extent of our knowledge, movement alterations have mostly focused on simulating mechanical forces, and little is known about their applications to the simulation of bodily reactions, such as withdrawal reflexes.

3 DESIGN SPACE FOR AVATAR-CENTERED FEEDBACK

In this section, we provide a design space that aims at clarifying the range of possible implementations for avatar-center feedback, a concept that we defined as “a dynamic alteration of the avatar’s appearance or movement, in response to its interaction with the virtual environment”. Note that while the rest of this study focuses on its application to virtual dangers, conceptually, avatar-centered feedback can be used in response to any virtual element (e.g., wind, liquid, or virtual characters). The design of an avatar-centered feedback should answer several key questions which come as follows.

3.1 Trigger. What does the feedback respond to?

To begin with, we should define what is the feedback responding to. As already mentioned, while our study focuses on its application to virtual dangers, avatar-centered feedback can respond to any virtual element. The element can even be invisible (e.g., wind, temperature [43], or sound), and potentially only *exist* through the avatar-centered feedback. Furthermore, avatar-centered feedback is not limited to responding to elements that would impact the user’s body in the real world, for example, it can be used as an indirect,

abstract modality to convey other information (e.g., the fuzziness of a material or the contact point with a virtual object [40]).

3.2 Alteration. How is the feedback be rendered?

After defining the trigger, we need to define the avatar alteration that it will produce. Categories defining an alteration come as follows.

Localization. The portion of the avatar where the alteration is applied. It can either be (i) *global*, when applied to the entire body (typically, the entire avatar trembling from an earthquake), or (ii) *localized* (typically, a bruise appearing at a specific impact point).

Modality. Whether the alteration concerns the avatar’s (i) *appearance* (typically, a bite), or (ii) *movements* (typically, a numb limb).

Transformation (appearance alteration). If as for the modality we alter the avatar’s appearance, we need to define what will be altered precisely. Following a previous taxonomy of avatar dissimilarities [9], the alteration can either impact the avatar’s (i) *structure*, i.e., the kinematic chain (or “bone structure”) of the avatar (typically, a finger chopped off), (ii) *volume*, i.e., the shape around the structure (typically, a swollen hand), or (iii) *superficial aspect*, i.e., the visual aspect around the volume (typically, the skin paling).

Modification of the user’s movement (movement alteration): If as for the modality we decide to alter the movement of the avatar, we need to define this alteration, in relation to the original user’s movement. The alteration can either follow a (i) *control-display ratio*, if it consists of a movement gain (typically, the body slowing down), (ii) *noise*, if it is applied on top of the user’s movements (typically, shivers), or (iii) *overwrite*, if it completely replaces the user’s movements (typically, an immobilized finger).

3.3 Granularity. How adaptable is the feedback?

After defining the alteration, we need to define its granularity, i.e., the amount of intensity levels that might potentially be produced, depending on the interaction with the trigger virtual element. Especially, this amount of intensity levels can either be described as (i) *unique*, if only one level of intensity can be applied (typically, a bullet shot), (ii) *discrete*, if the alteration can be applied with several but discrete levels of intensity (typically, an impact mark intensifying at each new impact), or (iii) *continuous*, if the alteration can be applied with continuous levels of intensity (typically, shivering intensifying as the temperature decreases).

3.4 Temporality. When is the feedback rendered?

Finally, we should define how the alteration might evolve over time. Categories that define the alteration temporality come as follows.

Onset. The moment from which the alteration begins in relation to the trigger time. It can either be (i) *immediate*, if starting when the feedback is triggered (typically, hand movements slowing down as it enters a force field), or *delayed* (typically, the hand swelling sometime after it gets stung).

Persistence. The duration of the avatar’s alteration. It can either be (i) *temporary*, if the alteration has a predefined time of effect (typically, vibrations produced by a large gong ringing), (ii) *circumstantial*, if the alteration can disappear due to different factors linked to the virtual scenario (typically, shivers stopping as the user gets nearby a virtual fire), or *persistent*, if the alteration remains for the entire experience (typically, a knife cut).

In the next section, we describe a user study involving three types of avatar-centered feedback of a virtual fire: a reddening, a burn, and a withdrawal-reflex effect. Their description is provided in Section 4.4, and can be used as examples of potential implementations of our design space.

4 EXPERIMENT

We conducted an experiment to explore the impact of experiencing avatar-centered feedback of a virtual danger, on realistic responses

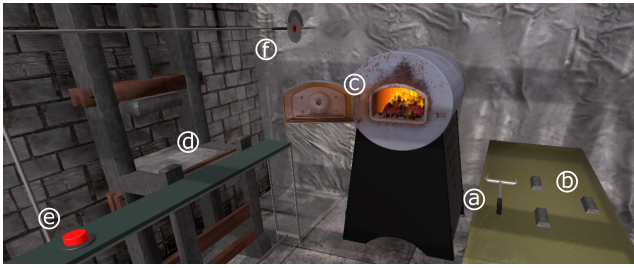


Figure 2: The virtual environment, including (a) the long tong, (b) metal ingots, (c) an industrial oven, (d) a press, (e) the activation-button, and (f) a circular saw.

toward it (RQ1), and toward virtual dangers of a different nature (RQ2). Specifically, we decided to explore the impact of avatar-centered feedback of fire. This choice was motivated by two main considerations. First, a fire consists of a “danger area” of increasing intensity (as we get closer to it), which gives participants the possibility to adopt a large range of safety levels, allowing us to measure avoidance behaviors on a continuous scale. Furthermore, the visual aspect of a virtual fire already conveys dangerousness [1] (as compared to a corrosive liquid for example) which reduces the impact of the avatar-centered feedback as a mere *informative* feedback about the existence of a danger, and put more emphasis on measuring how it impacts the perceived plausibility of the danger.

This experiment consisted of a VR metalworking scenario, including a *heating operation* consisting of bringing an ingot inside an oven’s fire with a metalsmith tong. Participants were equally split into two groups, one of them receiving avatar-centered feedback from the virtual fire (feedback group), described in Section 4.4. The other group did not experience any feedback (control group). The objective was to observe the impact of avatar-centered feedback of fire, by studying the safety distance kept from it during the process (RQ1). At the end of the experiment, participants encountered two additional dangers (that did not generate avatar-centered feedback), electric arcs and a circular saw. The objective was to observe the general impact of experiencing avatar-centered feedback of fire, on avoidance behaviors to other dangers (RQ2).

A between-subject design was chosen to avoid a potential order effect impacting behavioral changes (e.g., by reducing the surprise effect of additional dangers, or risking participants to transfer mechanically their behavioral patterns from one condition to another).

4.1 Participants

We recruited 42 participants (11 females, 30 males, 1 non-binary), aged between 23 and 35 years old ($M=25.5$, $SD=3.05$). 19.0% of them were left-handed, and 81% right-handed. 23.8% declared having no previous experience with VR, 40.5% declared using it less than once a month, and 35.7% more than once a month. Groups were balanced by gender as much as allowed by our sample.

4.2 Apparatus

Participants were immersed in VR using a Meta Quest 2 Head-Mounted Display (HMD), providing hand-tracking capabilities.

The virtual environment consisted of a factory, including an industrial oven (82 cm deep) with flames and sparks inside, a big industrial press, tables, a button, metal ingots, and a metal tong (see Figure 2). Fire and sparks’ sounds were also rendered. Participants’ avatar consisted of virtual hands aligned with the real hands’ movements. Considering that the rest of the body was not tracked, we preferred not to represent it to avoid introducing mismatches between the avatar and the virtual body. Furthermore, considering that different appearances (skin tone, gender) could bias the observation of appearance alterations, we only used a generic androgyn-

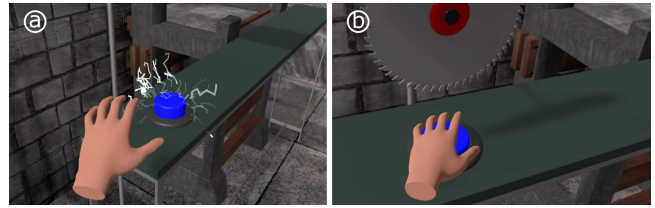


Figure 3: Additional dangers appearing at the end of the experiment: (a) electric arcs and (b) a circular saw.

nous white-skinned hand (the skin color was chosen to match the predominantly caucasian demographic in our sample).

4.3 Main task

The task consisted of six cycles of successive heating and press operations, illustrated in a video provided in supplementary material.

Heating operation. This task was meant to expose participants to the fire danger and to measure the impact of avatar-centered feedback from it on the safety distance users would maintain. Participants had to heat an ingot by bringing and maintaining it inside the oven (illustrated in Figure 1). The temperature would rise faster as it was brought deeper inside the oven (as a reference, the ingot would take 147 s to fully heat when maintained 25 cm into the fire, and 41 s when maintained 50 cm into the fire). The temperature of the ingot was communicated by its color, transitioning from grey to orange as it heated. A sound indicated when the ingot was warm enough to proceed to the next step. In order to observe participants’ behaviors with different levels of incentives to reach deeper into the oven, each of them performed the task several times with two different tong lengths. The fastest completion time among our participants was 28 s and the longest was 244 s.

Press operation. This task served as a distraction, creating a time frame where additional dangers could be presented without participants expecting them. It consisted of flattening the ingot by placing it under the press, releasing the tong, and actuating the press by pushing the activation button and holding it for 20 s while the press operated. Two additional dangers that would not generate any avatar-centered feedback were presented consecutively during the last repetition of the press operation, both illustrated in a video provided in supplementary material. The first danger, **electric arcs** (inspired from previous works [35]), would appear around the activation button (illustrated in Figure 3.a) along with electric sound, as participants placed the ingot under the press. The electric arcs would only disappear as the participant’s dominant hand would get close enough to the button (20 cm), which was meant to capture the moment participants would resign to risk approaching the danger while avoiding direct contact between the hand and the electric arcs. It is worth mentioning that in order to ensure that participants would not press the button without first looking at it as they got used to the task, the button would take 4.5 s after the ingot was placed to become interactable, which was indicated visually by its color changing from red (inactive) to blue (active). The second danger, a **circular saw** (inspired from previous works [21]), would start spinning and advance along rails toward the button (illustrated in Figure 3.b) along with actuation sounds, 3 s after the participant started pressing it. We were interested in whether participants would keep their hand on the button to continue the press actuation, or remove it to avoid getting in contact with the saw, and if so, how far they would move their hand away. The experiment stopped with the screen turning black slightly before the saw blade reached the button, preventing it from coming in contact with the avatar hand, in case the participant kept it on the button.

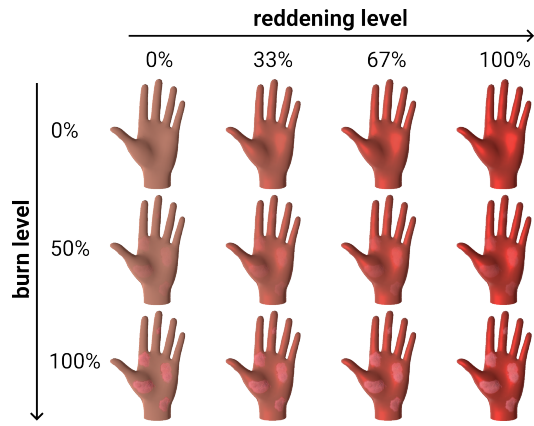


Figure 4: Different intensity levels of avatar’s hand appearance alteration (reddening and burn effects).

4.4 Avatar-Centered Feedback

Avatar-centered feedback of virtual fire was only presented to the feedback group. Given the variety of potential implementations (demonstrated in Section 3), and to focus on our main goal (i.e., assessing whether avatar-centered feedback can impact user behaviors and if they would negatively impact the sense of embodiment), we preferred to test an aggregation of diverse avatar-centered feedback, rather than evaluating different types individually. Specifically, we implemented a reddening, burn, and withdrawal reflex effect (illustrated in Figure 1). Their intensity, and variation depending on other factors (e.g., hand depth, exposition time) were tested in preliminary pilot studies to ensure that they would be visible without reaching their maximum value too quickly. These effects can be observed in a video provided in supplementary material for a better appreciation, and were designed as follows:

Reddening (temporary appearance alteration). The reddening effect consisted of the avatar’s hands’ color continuously reddening as they were brought deeper and longer inside the oven (the effect’s intensity converged toward a threshold value, which would get higher as the hand gets deeper). Reversely, when the hand was pulled further from the oven, the intensity would diminish (and converge toward the associated value, if still inside the oven). Different levels of reddening intensity are illustrated in Figure 4.

Burn (permanent appearance alteration). The burn effect consisted of burn textures becoming increasingly visible on the avatar’s hands as they were brought deeper and longer inside the oven (the intensity converged toward the same value as for the reddening effect, however, the increase speed was four times slower). Contrary to the reddening effect, the burn level was not reversible. Different levels of burn intensity are illustrated in Figure 4.

Withdrawal reflex (temporary movement alteration). This effect consisted of altering the avatar’s hands’ movements to simulate a withdrawal reflex independent of the participant’s hands’ movement (a quick up-down motion), in reaction to a spark bursting by the avatar’s hand. The closer the hands were to the spark burst, the greater the alteration’s amplitude (up to 15 cm). The simulated movements were always directed upward to preserve the hands’ depth inside the oven. Sparks were bursting around the oven’s front, at a frequency fluctuating randomly between 3 s and 9 s.

4.5 Protocol

The experiment followed a between-subject design with participants equally distributed between *Feedback* and *Control* groups, defining whether they received avatar-centered feedback of the virtual fire. Participants were unaware of this aspect of the experiment.

At the beginning of the experiment, participants signed a consent form, filled in a demographic form, and were briefed about the experiment process. No mention was made of the avatar-centered feedback. Furthermore, they were told that the only objective was to complete the tasks, without any particular requirement in terms of time, or interaction approach. Participants were not compensated economically for their participation.

The experiment consisted of repeating six times a heating operation followed by a press operation, described in Section 4.3. The first three tasks were performed with a *long* tong and the three last with a *short* one (respectively maintaining 47 cm and 35 cm between the avatar hand and the ingot). The order was not randomized, as we were interested in gradually increasing the incentive of bringing the hand deeper inside the fire (the opposite might have pushed users to accept high level of avatar-centered feedback intensity from the beginning of the experiment).

After completing the six repetitions (which ended with the introduction of *additional dangers*), participants were asked to remove the HMD, and fill in questionnaires about their subjective experience, elaborated in Section 4.6.2.

In total, the experiment took from 15 min to 30 min, including explanations and questionnaires. Note that the duration of the experiment mainly depended on how quickly participants would complete the heating operation, and hence, on how deep they tended to bring their hand inside the oven.

4.6 Measures

We measured the influence of avatar-centered feedback on the prevention behaviors as well as the perception of different virtual dangers, whether they were triggering avatar-centered feedback (i.e., the fire), or not (electric arcs, and circular saw). For each of them, we used behavioral and subjective data, respectively by the mean of movement measurements, and a questionnaire.

4.6.1 Behavioral Measures

Reaction to the virtual fire was assessed by measuring the time taken by participants to complete each heating operation. This time would be shorter as participants brought the ingot further inside the oven (and thus the avatar’s hand). To gain further insight into users’ behaviors, we also recorded the dominant hand’s position, as well as the reddening and burning effects’ intensity over time.

Reaction to electric arcs was assessed by measuring the time taken by participants before they resigned to press the button (starting from the appearance of the electric arc).

Reaction to the circular saw was observed by measuring the distance made between the button and participants’ dominant hand’s palm center, just before the saw’s blade reached the button.

4.6.2 Subjective Measures

Subjective data was collected from a questionnaire filled in at the end of the experiment, provided in supplementary material. Questions were related to: sense of ownership, sense of agency, place illusion, plausibility of the overall experience and of each particular danger (fire, electric arcs, and circular saw), as well as some questions related to the perception of risk regarding sparks and hands’ depth inside the oven. Participants’ general feedback was also collected. Questions related to the sense of embodiment were adapted from the virtual Embodiment Questionnaire [47], which allowed us to extract separately the sense of ownership and agency. However, we did not ask to participants questions related to the perception of body change, considering that the avatar’s proportions were aligned to the participants. Questions relative to place illusions and plausibility (together referred to as presence), were adapted from a previous study by Steed et al. [59]. Plausibility questions were repeated to refer to the overall experience, and each specific danger (fire,

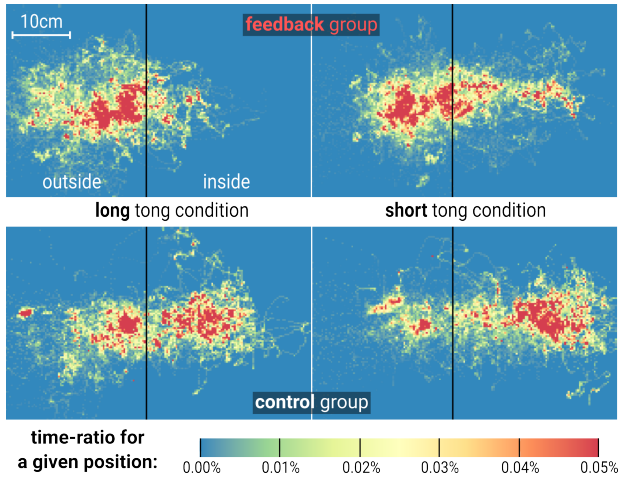


Figure 5: Heatmaps summarizing the participants’ dominant-hand position over time (top view) during the heating task. Data is normalized by heating operation and participant, and grouped by feedback and tong-length conditions. The vertical black line represents the virtual plane of the oven’s door, the left side being the outside. We can appreciate that overall participants in the control group kept their hand longer inside the oven compared to the feedback group.

electric arcs, and the circular saw). To gain further insight into participants’ specific risk perception when a spark busted, and when they brought their hand deeper into the oven, we added two questions for each of these risks, related to the perception that (i) they could actually burn themselves, and that (ii) their real body was being altered by it. All questions were answered on a 7-points Likert scale (1 = strongly disagree; 7 = strongly agree).

4.7 Hypotheses

We had two main hypotheses, respectively based on the research questions RQ1 and RQ2, developed in Section 1: **(H1)** the feedback group will demonstrate more avoidance behaviors and a higher perception of danger toward the fire, and **(H2)** the feedback group will demonstrate more avoidance behaviors and a higher perception of danger to the electric arc and the circular saw. Specifically, we expect the differences in avoidance behaviors to be observable from behavioral measurements, and the perception from the associated dangers’ plausibility questionnaires.

5 RESULTS

We conducted a post-hoc power analysis (G*power) for each of the conducted statistical tests. Given the obtained effect sizes, we achieved power levels higher than 0.8 for each of them.

5.1 Objective Measures

Figure 6 provides a summary of the objective measurements from which we detail in the statistical analysis in the following.

Reaction to virtual fire. We performed a 2-way ANOVA, with one between-subject factor (feedback vs control groups) and one within-subject factor (long vs short tong condition). Considering that heating duration data was positively skewed, it was normalized using an inverse transformation. Results showed a main effects of the feedback group ($F_{1,40} = 19.40; p < .001; \eta_p^2 = 0.327$), with longer time completion in the feedback group, and tong length ($F_{1,40} = 12.05; p < .001; \eta_p^2 = 0.231$), with longer time completion with the short tong. To gain further insights, we provide in Figure 5, a heatmap of participants’ dominant hand positions for each group and tong size. The interaction effect was non-significant ($F_{1,40} = 3.37; p = 0.078; \eta_p^2 = 0.074$), but since it was close to significance, we performed pairwise tests

to test whether the tong condition had an impact within each group. Pairwise tests with Bonferroni correction, showed that participants only took significantly more time to complete the task with different tong lengths in the feedback group ($p < 0.05$). This effect can be appreciated on Figure 6.

To further inform on the intensity of avatar-centered feedback experienced by the participants of the feedback group, we also provide in Figure 6, the burn intensity at the end of the third and sixth heating operation (respectively the last iteration carried with the long and short tongs), as well as the average and maximum reddening levels, aggregated by tong length conditions. The length of the tong significantly increased the maximum ($t_{20} = -4.22; p < 0.001$) and the average ($t_{20} = -4.65; p < 0.001$) reddening for the small condition. The final burn intensity, as it was accumulated during the experiment and did not increase linearly, is reported for highlighting the final state of the avatar-centered feedback.

Reaction to electric arcs. Group comparisons were performed using either t-tests or Wilcoxon rank-sum test, depending on the assumption on data normality. The normality assumption was tested using the Shapiro-Wilk test (with data assumed to be normal for p-values greater than 0.05). Measures of the time taken to press the button in the presence of the electric arcs did not show significant differences ($W = 209; p = 0.78$). The median time taken by the feedback group to press the button was 10.3 s (IQR 7.6-18.7), against 12.0 s (IQR 7.3-17.6) in the control group.

Reaction to the circular saw. A similar analysis was performed to that for the electric arcs. Measures of the distance between the dominant hand and the button, as the circular saw reaches the button, showed significant differences ($t_{40} = -2.52; p < 0.05$). Distance toward the saw was significantly greater for the feedback group ($M = 44.6cm; SD = 23.5$) compared to the control group ($M = 28.8cm; SD = 24.8$).

5.2 Subjective Measures

Questionnaire scores were aggregated for each participant given the following questions’ groups: ownership, agency, place illusion, situation’s plausibility, fire’s plausibility, electric arcs’ plausibility, circular saw’s plausibility, perceived risk related to the hand depth in the oven, and perceived risks of the sparks. Results are reported in Table 1. A similar analysis was performed to that for the reaction to electric arcs. None of the categories showed significant score differences between the feedback and control groups.

6 DISCUSSION

6.1 Impact of Avatar-Centered Feedback on Behavioral Changes toward a Corresponding Danger

The study’s main objective was to assess if avatar-centered feedback of a virtual danger could induce realistic behavior toward it (RQ1). Our results reveal that avatar-centered feedback of a virtual fire induced significantly longer time-completion of a heating operation, due to participants maintaining more distance to the fire. This aligns with H1 and demonstrates the potential of avatar-centered feedback to induce realistic behaviors toward virtual dangers.

While we did not collect data permitting to compare individual contributions of each feedback type (reddening, burn and withdrawal reflex effects), the observation of participants’ behaviors along with informal follow-up discussions, suggest a stronger impact of the reddening effect on users’ behaviors. This might be attributed to the higher responsiveness to virtual fire offered by this feedback, whose responses were directly related to the distance with fire (as opposed to the withdrawal movement) and relatively quick to arise (as compared to the burning effect). However, four participants also mentioned that they started to be more careful about their distance from the virtual fire, as they realized during the pressing operation that the burns were permanent and would not naturally heal. Regarding the impact of the withdrawal reflex movement, most participants believed it had a lower influence on

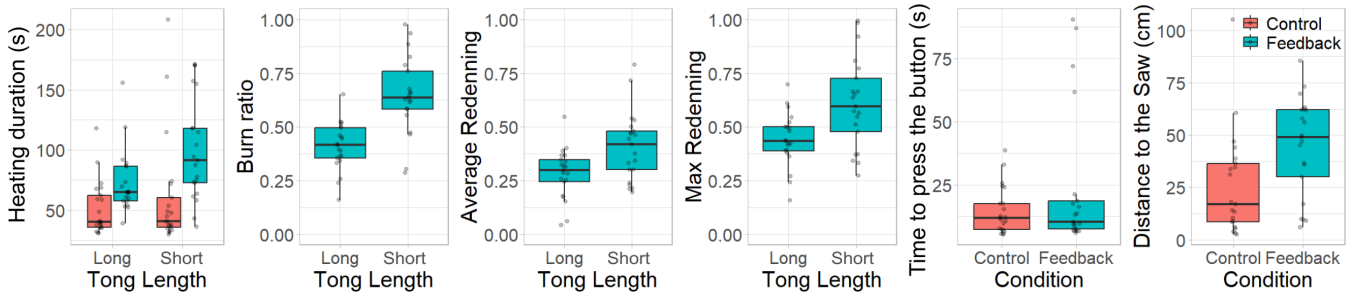


Figure 6: Results to the objective measures of reaction to fire (heating time, final burn effect, average reddening effect, maximum reddening effect), electric arcs (time to press the button), and circular saw (final distance to the button). Results are split by groups, and tong length for the heating operation). Box plots show the interquartile range (IQR), whisker plots the 1.5 IQR, and grey dots the individual values.

Group	Ownership	Agency	PI	Psi Sit.	Psi Fire	Psi Elec.	Psi Saw	Depth	Spark
<i>Feedback</i>	5.3 (5.75-6.5)	6.3 (5.75-6.5)	4.8 (4.4-5.0)	3.7 (2.8-4.2)	3.2 (2.2-4.0)	4.4 (3.4-4.8)	4.2 (3.2-5.4)	2.5 (2.0-4.0)	2.0 (1.5-3.0)
<i>Control</i>	5.3 (4.7-5.7)	6.3 (5.75-6.5)	4.6 (4.0-4.8)	3.3 (3.2-4.5)	2.8 (1.8-3.4)	4.0 (3.4-5.6)	4.2 (3.2-6.0)	2.0 (1.0-3.0)	2.0 (1.0-3.5)

Table 1: Questionnaire scores (median, followed by 1st and 3rd quartiles) for feedback and control groups, aggregated by Ownership, Agency, Place Illusion, Plausibility of the situation, Plausibility of fire, Plausibility of electric arcs, Plausibility of the circular saw, perceived risk related to hand depth in the oven, and perceived risk of sparks. No significant results between groups, for each of the aggregated score.

their behavior. Furthermore, some participants also mentioned that they sometimes misinterpreted it as tracking issues. Such potential misinterpretation of a movement alteration into tracking issues (especially when it is subtle) should probably be a parameter to keep in mind for future implementations of avatar-based feedback.

Furthermore, based on observations and informal discussions, we identified three different interaction profile categories of participants in the feedback group, which specificities might be important to consider and design for in future applications: (i) participants maintaining the avatar’s hand relatively far from the fire throughout the entire experiment (i.e., participants for whom the desire to avoid injurious interactions was much stronger than the willingness to finish the task quickly), (ii) participants who gradually brought their hand further inside the oven, exposing the avatar to stronger feedback, especially as the tong got shorter (i.e., participants for which the willingness to finish the task quickly gradually took over the desire to avoid injurious interactions), and (iii) participants who maintained for some time their hand relatively far from the fire, until they suddenly drastically change their behaviors by bringing their hand substantially deeper inside the oven (i.e., participants who completely gave up on the desire to avoid injurious interactions when the willingness to finish quickly the task took over it, rather than maintaining it partially).

Regarding the control group, most participants adopted identical strategies (which can be observed in Figure 6 from the lower cross-participants duration variability), and to mainly focus on maintaining a specific ingot depth regardless of the tong length, rather than a specific distance between the hand and the fire (which can be observed from the smaller differences of heating operation duration in the control group, between tong length conditions).

6.2 Impact of Avatar-Centered Feedback on Subjective Perception of Corresponding Danger

Surprisingly, subjective questionnaire scores of fire plausibility (as well as presence scores which are theoretically linked to it [52]), did not reveal a significant impact of avatar-centered feedback which does not support H1 nor align with reported behavioral changes.

One explanation could lie in the between-subjects design of this study, which was preferred to avoid strong order effects on behaviors measures. Indeed, when it comes to subjective measures, between-subject designs are often unable to detect small to medium

effect sizes, due to participants not using previous answers as a reference to respond to others (resulting in more inconsistency) [45].

Another explanation might be that participants in the feedback group, while they kept their hands significantly further away from the oven than the control group, still brought them relatively deep inside it when incited to do so by the shorter tong (see Figure 5). This behavior naturally exposed the avatar to strong avatar-centered feedback, which might have accentuated the mismatch with the real hand and potentially reduced the perceived plausibility. This assumption aligns with some participants of the feedback groups declaring in follow-up discussions, that they decided to bring their hands further inside the oven to finish the task, while in reality, they would probably have simply given up on the task.

Finally, we cannot exclude that avatar-centered feedback might have been unconsciously perceived as an implicit rule, leading participants to behave realistically as an effort to conform to it, without perceiving a sense of plausibility to the virtual fire.

6.3 Impact of Avatar-Centered Feedback on Different Following Dangers

The second objective of this study was to assess if experiencing avatar-centered feedback of a specific danger, could engender realistic responses to following dangers of different natures (RQ2). Interestingly, objective measures regarding the behavioral response to additional dangers, after experiencing avatar-based feedback of virtual fire, partially supported this hypothesis. Indeed, participants in the feedback group kept significantly more space between their hands and the approaching virtual saw. However, no significant difference was found regarding the behavioral response to the electric arcs, nor on scores of plausibility questionnaires to both electric arcs and the circular saw (the absence of significant differences on the questionnaire results might be attributed to the between-subject design of the study [45], as discussed in Section 6.2).

Still, behavioral differences regarding the circular saw suggest that avatar-centered feedback might not only alter the perception of a specific danger, but also the general perception that the avatar is vulnerable to the environment. Such alteration of a potential *sense of vulnerability* might also be responsible for previous results reporting that participants who embodied tough-looking alien

or robot avatars, demonstrated less avoidance behaviors [10] and a stronger sense of security in high altitude [28].

While this effect deserves further investigation to be better understood (e.g., considering its strength, or generalization), it might bring new theoretical perspectives on realistic response inductions, and at a larger scale on embodiment theories. From a practical perspective, it might also contribute to simplifying the design of VR experiences that require realistic responses to virtual dangers.

6.4 Impact of Avatar-Centered Feedback on the Sense of Embodiment

Finally, it is important to notice that participants presented with avatar-centered feedback, despite the alteration in the avatar's appearance and movements, did not experience a reduction of sense of ownership and agency. These results are consistent with previous works reporting these sensations can be preserved even with altered avatar's appearance [9] and movements [14, 19]. Moreover, they are valuable to the understanding of avatar-centered feedback's usability, as they show that such feedback can be utilized and convey significant results on users' behaviors, without negatively impacting other subjective qualities of the experience. Furthermore, realistic reaction to a virtual danger is commonly utilized as an objective measure of embodiment [38, 1]. With this metric, such avatar alteration matching with the environment's interaction even increases the sense of embodiment. Focusing on the sense of agency, it would be interesting to further investigate the impact of movement-based avatar-centered feedback, especially, we can wonder whether the movement alterations might be partly self-attributed [14, 19], or mimicked [17], as it was previously reported in different contexts.

7 LIMITATIONS AND FUTURE WORKS

7.1 Generalization to a Larger Demographic

Considering that our sample was mainly composed of relatively young male participants, our results should be replicated with different demographic groups in order to ensure that they do not include social biases. Furthermore, our experiment used only one hand appearance, a relatively androgynous white-skinned hand, to avoid perception biases over appearance alterations. It is important for future research to ensure that similar results can be obtained with diverse appearances (which might require adapting the appearance alteration) in order to avoid demographic discrimination. Finally, it would also be interesting to study the impact of individual psychological differences (e.g., personality traits, or pyrophobia).

7.2 Generalization to Other Feedback of Virtual Danger

Avatar-centered feedback entails a wide range of potential implementations. While this paper demonstrates its potential, more research should follow to investigate its generalization to other categories of avatar-centered feedback (e.g., arm swelling as it gets stung, shoulder getting numb after bumping into an object, or skin paling to simulate sickness), and the effect of isolated feedback types on users' perceptions and behaviors (including feedback that we studied in aggregation), or its applications to other body parts. Furthermore, it would be interesting to measure its impact on a danger that does not consist of an "area of danger" (e.g., a hammer), as it might leave less opportunity for the user to dynamically observe and adapt to the feedback. There is also a need to investigate the distinct impact of movements and appearance alteration feedback.

Furthermore, similar to how vibration is often used as a generic tactile feedback to render various sensations, it would be interesting to investigate the usability of a "generic" avatar-centered feedback of virtual danger, i.e., an abstract feedback that does not realistically reproduce the impact of a given danger (e.g., vibrating or blinking hands). Such generic feedback could be used, for example, to provide feedback from a danger that does not involve a direct or immediate impact on the body in the real world (e.g., a radioactive area),

or in order to avoid multiple time-consuming implementations for VR scenarios involving numerous types of dangers.

In this study, we explored behavioral changes to measure realistic responses to virtual dangers. Future research might employ other measures of realistic responses to virtual dangers (e.g., physiological responses [57, 2]) to extend the understanding of avatar-centered feedback's impact, on the induction of realistic responses to virtual dangers. It might also be interesting to study how avatar-centered feedback compares to other feedback modalities (e.g., haptic, audio), and the potential benefit of combining them.

7.3 Generalization to Other Types Interactions

While this study demonstrates the benefits of using avatar-centered feedback of virtual dangers, in the future, we hope that this concept will be extended to simulate a wider range of virtual sensations. For example, we can imagine avatar-based feedback being utilized to dynamically simulate fatigue (e.g., with slow-down movements, or sweat), excitement after drinking a coffee (e.g., with artificially jerky movements, or pulsing veins), wetness (e.g., with skin reflection, and control-display ratio movements alteration simulating a sliding effect when touching virtual objects) but also unrealistic interactions, such as an intangible body passing through an object (e.g., with a flickering avatar effect). Furthermore, while *social touch* simulations often involve haptic feedback [15], we can also imagine avatar-centered feedback inducing such sensation, for example by displaying a blushing skin, a body vibration simulating a "purring" effect, or even some abstract feedback with positive connotations, such as a sparkling effect.

7.4 Carry over effects

This study revealed the impacts of avatar-centered feedback of a virtual danger, on the perception of this danger, and the following dangers of different natures. Now, it would be interesting to study how much these effects can be carried over and their limiting factors. For example, we can wonder if the realistic behaviors toward the danger we provide feedback of would remain over time, or as we stop providing feedback of it, i.e., can the user re-learn that the danger is not dangerous? It is also unclear whether the impact on dangers of different natures (vulnerability) would fade over time, and if it could disappear as the user experiences later interactions invalidating it (e.g., the avatar hand passing through the virtual saw without any avatar-centered feedback). We can even wonder if the impacts can be carried over in between VR sessions. Answering these questions would benefit the design of future applications aiming at leveraging avatar-centered feedback to induce realistic responses to virtual dangers.

8 CONCLUSION

In order to provide solutions to induce realistic behaviors toward virtual dangers, we developed and assessed the concept of *avatar-centered feedback*, a dynamic alteration of the avatar's appearance or movement, in response to its interaction with the virtual environment. First, as an effort to characterize this novel concept, we provide a design space describing its range of possible implementations (which are not restricted to responses to virtual dangers). Then, in a user study, we tested the impact of avatar-centered feedback of a virtual fire, on realistic responses toward virtual dangers. Our results show that experiencing avatar-centered feedback of fire, could not only impact avoidance behaviors toward it, but also toward following virtual dangers of different natures. This suggests that this flexible, device-free approach could be applied and benefit numerous types of VR applications involving virtual dangers, such as training, immersive journalism, or exposure therapy. Potential extensions of this concept to other types of feedback (e.g., simulation of fatigue, excitement, or social touch) are also discussed.

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