Toward dynamic pain expressions in avatars: Perceived realism and pain level of different action unit orders

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Abstract

The facial expression of pain can be decomposed in three sets of Action Units (AUs), the smallest discriminating facial movements: Brow lowering (B), Nose wrinkling + Upper lip raising (N), and Orbit tightening + Eyelid closure (O). This study compared the perception of realism and pain level from different onset orders of AUs in avatars. Seven videos of facial expressions of pain were created with four different avatars (2 women): six sequential onsets combining the three sets of AUs and one synchronized onset. 45 healthy adults (22 women; aged 23.6 ± 5.2 years) rated the realism of facial movements, and the level of intensity and unpleasantness of perceived pain. A more realistic expression was associated with the onset of *O* before or at the same time as *N*, a more intense expression was associated when *B* occurred last, and a higher level of unpleasantness was associated with the onset of *N* before *B*. Therefore, the sequence *ONB* yielded the highest ratings on both measures of realism and pain levels. These findings describe the perceived content of different orders of facial movements that could contribute to the creation of realistic pain-expressing virtual agents designed to study human-computer interactions.

Keywords

Dynamic facial expressions, Pain of others, Virtual agents, Action Units, Perception, Behavioral realism

Highlights

- Fine facial movements can affect the perception of virtual facial expressions
- Perceived realism and pain level change according to the order of pain AUs
- Avatars' gender affects the perceived realism and pain level of the order of AUs
- A specific combination of AU yields the highest ratings on realism and pain level
- AUs order should be considered in the creation of virtual humanoid

1. Introduction

With the latest advances of CGI (computer-generated imagery) technologies, it is possible to create photorealistic avatars, i.e. CG humans, that deceit our eyes. Despite this technological progress, observing and interacting with avatars can still elicit an eerie feeling, particularly when they perform subtle natural movements. This process by which the realism of the physical behavior of a virtual agent contributes to its overall realism is called behavioral realism (Groom et al., 2009), and is related to the Uncanny Valley phenomenon (Mori, 1970). This sensitivity to subtle changes is especially prominent in facial movements (Tinwell, Grimshaw, & Williams, 2010). One of the reasons for this failure to reproduce realistic facial expressions may be the lack of knowledge about the time course of facial movements and the affective content perceived from those movements.

Meanwhile, the capability of avatars to express emotions and pain elicits a lot of interest in the study of social cognition through human-computer interactions (Bombari, Schmid Mast, Canadas, & Bachmann, 2015; Wykowska, Chaminade, & Cheng, 2016). Pain communication is especially relevant to study social interactions as pain has the dual adaptive functions to protect the organism from harm and to promote help-seeking behavior (Williams, 2002). Pain has thus the potential to trigger an affective reaction as well as an empathic response in an observer (Goubert et al., 2005). For this reason, most studies have used pain observation paradigms to study empathy (Lamm, Decety, & Singer, 2011).

Research on empathy for pain could benefit from development in human-computer interactions (e.g., Asada, 2015; McQuiggan & Lester, 2007; Paiva, Leite, Boukricha, & Wachsmuth, 2017; Rodrigues, Mascarenhas, Dias, & Paiva, 2015) because this social ability is dynamic in nature and because it needs to be studied in a more ecological context while maintaining a high level of experimental control (Jackson, Michon, Geslin, Carignan, & Beaudoin, 2015). Moreover, realistic pain facial expressions depicted by virtual agents have the potential to improve specific virtual training designed to optimize empathy in different populations (as in Dyer, Swartzlander, & Gugliucci, 2018; Herrera, Bailenson, Weisz, Ogle, & Zaki, 2018; Kral et al., 2018). Therefore, in order to create realistic interactive pain-expressing avatars to study social interactions and relevant responses in the context of pain, such as empathy, the timing of the facial expression of pain needs to be systematically investigated.

1.1. Facial expression of pain.

Because pain is a subjective state that cannot be measured directly, facial expressions provide an easy, accessible and non-invasive nonverbal proxy of other's pain (Prkachin, 2009). In order to decode and study facial expressions, the *Facial Action Coding System* (FACS; Ekman, & Friesen, 1987; Ekman, Friesen & Hager, 2002), a widely used standardized measure, was developed to provide psychometric rigor and great descriptive power (Cohn & Ekman, 2005). The FACS is an atheoretical codification system that decomposes facial expressions in terms of Action Units (AUs). AUs are the smallest visually discriminative movements on the face associated to a muscular contraction or relaxation (Cohn, Ambadar, & Ekman, 2007). Intensity ratings are attributed to each AU, from the muscle at rest (0 %) to the maximal contraction possible of the muscle (100 %).

A group of AUs has been frequently associated with the expression of pain across studies: AU 4 (brows lowering), AUs 6-7-43 (orbit tightening and eye lids closure) and AUs 9-10 (nose wrinkling and upper lip raising) (e.g. Craig, Prkachin, & Grunau, 2010; Kappesser & Williams, 2002; Prkachin, 1992; Prkachin & Solomon, 2009; Simon, Craig, Gosselin, Belin, & Rainville, 2008). These AUs have been described as the "basic signal of pain" because of the consistency of their appearance across different types of pain experience such as electric shock, cold immersion, pressure and muscle ischemia (Prkachin, 1992). They are also distinct from other facial expressions of negative emotions (Simon et al., 2008). A recent systematic review on the facial movements displayed during pain found the same three sets of pain-related AUs, but with the addition of the opening of the mouth (AUs 25-26-27) (Kunz, Meixner, & Lautenbacher, 2019). The presence of this last facial movement could, however, be related to preparatory movements in pain vocalizations at the end of the expression of pain and thus be associated with secondary reactions to pain rather than to directly pain-related movements (Prkachin & Solomon, 2009). Also, AU 4 and AUs 9-10 have been associated with the affective dimension of pain whereas AUs 6-7-

43 have been associated with the sensory dimension of pain (Kunz, Lautenbacher, Leblanc, & Rainville, 2012), suggesting that these three sets of pain-related AUs encode different dimensions of this experience. In terms of AUs, the composition of the prototypical pain expression is thus well known and has been established by a number of studies.

1.2. Observers' characteristics and bias influencing the decoding of facial expressions of pain.

The facial expression of pain is part of the social communication model of pain (Craig, 2015; Craig, 2009; Hadjistavropoulos et al., 2011). Beyond the production of facial expressions of pain, this framework also takes into consideration the decoding of the facial expression by an observer, often times a caretaker. Indeed, some characteristics and bias of the observer have been associated with changes in how the facial pain expression is perceived. According to several studies, women are faster and show more accuracy at identifying the emotional meaning from nonverbal cues like facial expressions (Babchuk, Hames, & Thompson, 1985; Hall, 1978; Hampson, Vananders, & Mullin, 2006; Rotter & Rotter, 1988; Thayer & Johnsen, 2000; Wingenbach, Ashwin, & Brosnan, 2018). This advantage for women could also be reflected in their greater sensitivity to nonverbal behavioral realism of virtual humans compared to men (Bailenson, Blascovich, Beall, & Loomis, 2003; Guadagno, Blascovich, Bailenson, & McCall, 2007). It is, however, interesting to note that pain in male facial expressions is generally perceived as more intense and is being detected more rapidly and more accurately than in female facial expressions (Coll, Budell, Rainville, Decety, & Jackson, 2012; Pronina & Rule, 2014; Riva, Sacchi, Montali, & Frigerio, 2011; Robinson & Wise, 2003; Simon, Craig, Miltner, & Rainville, 2006).

Other individual characteristics, such as pain catastrophizing and empathy, have been shown to modulate the perception of pain expressions. Catastrophizing about one's own pain is defined as: "an exaggerated negative mental set brought to bear during actual or anticipated painful experience" (Sullivan et al., 2001). A number of findings have indicated that observers' pain catastrophizing is associated with an amplification of attentional bias toward pain-related information such as pain expressions (Crombez, Eccleston, Baeyens, & Eelen, 1998; Crombez, Eccleston, Van Den Broeck, Van

Houdenhove, & Goubert, 2002; Crombez, Van Ryckeghem, Eccleston, & Van Damme, 2013; Heathcote et al., 2015; Van Damme, Crombez, & Eccleston, 2004). This implies that the manner in which observers experience pain (e.g., pain catastrophizing) could affect how they represent the pain of others. Empathy is defined as "the ability to share and understand the feelings of another without confusion between oneself and another" (Decety & Jackson, 2004; Decety & Lamm, 2006), and has been conceptualized into a multidimensional trait varying between individuals (Davis, 1980, 1983). Regarding facial expressions, one study found that high empathizers paid more attention when discriminating happy and angry facial expressions compared to low empathizers (Choi & Watanuki, 2014). Another study showed that the concordance of the observers' ratings with the pain of the participants when expressing suppressed, genuine or exaggerated facial expressions was associated with higher dispositional empathy (Ruben & Hall, 2013). Consequently, the results of these studies suggest that pain could be more or less perceived by an observer according to his or her level of dispositional (i.e., trait-like) empathy.

1.3. Dynamism of the facial expression of pain.

Research on facial expressions has focused on the study of intense facial expressions of emotions mainly through the use of static pictures. However, in a context of social interactions, humans are not in contact with still faces, but with dynamic faces that vary in intensity. In the past 20 years, a growing number of studies have addressed the contribution of dynamism in facial emotions recognition and have reported the observer's ability to detect fine changes in the time course of movements in facial expressions (e.g., Ambadar, Cohn, & Reed, 2009; Ambadar, Schooler, & Cohn, 2005; Cohn & Schmidt, 2004; Dobs et al., 2014; Edwards, 1998; Krumhuber, Kappas, & Manstead, 2013; Krumhuber & Kappas, 2005; Krumhuber, Manstead, & Kappas, 2007; Reinl & Bartels, 2015).

In comparison with studies on facial expressions of basic emotions, few studies have addressed the dynamism of the facial expression of pain. Indeed, only two studies tried to describe the time course observed in spontaneous facial expression of pain. Hill and Craig (2002) observed in patients suffering from lower back pain that, when they produced a fake facial expression of pain, AUs appeared in sequential order, whereas, when the facial expression of the pain was genuine, the AUs appeared more closely together in time. However, Prkachin and Mercer (1989) observed from videos of patients suffering from shoulder pain that the time course of pain expressions varied according to the intensity and duration of the pain experience. The cumulative sequence proposed of pain-related AU from this study, ranging from low to severe pain, was: (a) lowering of the eyebrows (AU 4) and beginning of the eye closure, (b) internal eyelid muscle narrowing (AU 7), external orbital muscle closure (AU 6), and total eye closure (AU 43), (c) upper lip lift (AU 10) and upper nasal fold (AU 9), and (d) opening of the mouth (AUs 25-26-27) and, in extreme cases, horizontal stretching of the lips (AU 12).

These results are relevant to two conceptions of the dynamism of facial expressions that are also supported by models of emotional facial expressions (Scherer & Ellgring, 2007). The first one is the *synchronized* onset of the AUs in a facial expression suggested by the basic emotions theory (Ekman, 1992). According to this theory, prototypical facial expressions of emotions are triggered entirely by the activation of affect programs. This implies that AUs recruited for a specific facial expression are activated synchronously and have a similar timing. The second conception is the *sequential* onset of AUs supported by the componential emotions theory (Ellsworth & Scherer, 2003). This theory conceptualizes emotions as an evaluative-type cognitive processing, where facial expressions reflect the appraisal process of emotions. Each new stage of the appraisal process is thought to result in the onset of new AUs in the expression. So, AUs contributing to the facial expression appear one after the other and are shifted over time. Accordingly, results on observational studies of pain expressions and actual theories on emotional facial expressions suggest two forms of dynamism in facial expressions of pain: the *synchronized* and the *sequential* onset of AUs which will be compared in the present study.

1.4. Synthesis of the facial expression of pain to study its dynamism.

Facial displays of emotions and pain using actors have been a well-proven strategy to study the affective content of facial expressions (Gosselin, Kirouac, & Dore, 1995). For instance, a study found that more pain was perceived when pain-related AUs were performed by actors synchronically compared to sequentially (Lee, 1985). However, as opposed to actors, the use of virtual characters to produce facial expressions has the advantage of allowing a precise control over the timing (in ms) and the intensity (in %) of each facial movement.

Avatars are graphical representations (2D or 3D) of the user's alter ego or of characters controlled by humans implemented in virtual reality. Some platforms that use avatars to display facial expressions (e.g., EEVEE, Jackson, Michon, Geslin, Carignan, & Beaudoin, 2015; FACSGen, Roesch et al., 2011), have been conceived to control the facial expression through parameters built from the FACS. With these new tools, different time courses of the pain expression can be compared experimentally.

1.5. The comparison of the two hypotheses of facial movements using avatars.

This synchronized and sequential hypotheses of the dynamism of facial expressions were first compared in emotion with two studies using avatars. The results of these studies showed that some sequential onsets of AUs did not differ significantly from the synchronized onset for several emotions, suggesting that the two types of dynamism have the same expressive value for target emotions (Krumhuber & Scherer, 2016; Wehrle, Kaiser, Schmidt, & Scherer, 2000).

When comparing these two hypotheses in the context of pain, one study using avatars showed that the sequential onset of AUs improved the discrimination between pain and disgust compared to the synchronized onset (Siebers, Engelbrecht, & Schmid, 2013). Moreover, in this study, the sequential onset of AUs in pain expressions was perceived as more natural, whereas the synchronized onset of AUs improved the accurate identification of pain in facial expressions. However, the creation of facial expressions was based on a platform of avatars that approximated the AUs rather than producing them based on the FACS. Because of its graphic limitations, this platform was not able to depict correctly the nose wrinkling (AU 9), an essential facial movement in the high-intensity prototypical pain expression, compromising the scope of outcomes of the study.

Therefore, in order to compare the content perceived from the sequential and synchronized hypotheses of dynamism in the facial expression of pain, a perceptual study was conducted using a platform of avatars based on the FACS (Jackson et al., 2015).

1.6. The present research.

The creation of realistic pain-expressing virtual agents is essential to the advancement in human-computer interactions, especially in the context of empathy. Therefore, the main objective of this study was to compare the realism and the perception of pain from different orders of AUs onset in the pain expression. For this purpose, the synchronized onset as well as the six possible sequences of the three main sets of AUs for pain were displayed on avatars and were assessed on their realism as well as the perceived pain intensity and unpleasantness. It was hypothesized that the sequence *Brow – Eyes – Mouth/Nose*, previously reported from a series of naturalistic video clips of patients suffering from intermediate pain intensity (Prkachin & Mercer, 1989), and the synchronized expression would stand out from other sequences of AUs on realism and levels of perceived pain.

A secondary objective was to examine the effect of the observer's sex and the target's gender on the realism and the level of perceived pain in dynamic facial pain expressions. It was hypothesized that more realism and pain would be perceived by women while more pain would be perceived from the male pain expressions. Another secondary objective was to explore the association between pain catastrophizing, self-reported empathy and ratings on both the realism and the level of perceived pain in dynamic facial pain expressions. It was hypothesized that positive associations would be found between the dispositional variables and both realism and pain ratings.

2. Method

2.1. Participants.

Forty-five healthy participants between the ages of 18 and 40 years, 22 women (M = 23.64, SD = 5.57 years old) and 23 men (M = 23.52, SD = 4.85 years old), were recruited through advertisements sent via *Université Laval*'s student and employee mailing lists. The sample of participants was representative of the

Université Laval's population (i.e., a majority of Caucasian students). Exclusion criteria consisted in reporting a neurological or psychiatric disorder, working with people suffering from a pain condition, working in the video game or 3D animation environments, or having previously participated in a study on pain expressions from our research laboratory. This study was approved by *Université Laval*'s Ethics Committee (#2017-003). Written consent was obtained from all participants and they received a 10$ CAD compensation for their participation.

2.2. Stimuli and measures.

2.2.1. Creation and animation of avatars.

The avatars used in this study originated from the EEVEE (Empathy-Enhancing Virtual Evolving Environment) platform (for more technical details about the design of the avatars, see Jackson, Michon, Geslin, Carignan, & Beaudoin, 2015). The creation and animation of the avatars were executed by a team of developers using the software Blender® (Blender Foundation), Photoshop® (Adobe Systems Incorporated) and Krita® (Stichting Krita Foundation). Animations of the avatars were created by blend shapes, preprogramed linear changes of the 3D model of the avatar represented by a mesh. Intensity value ranging from 0 % to 100 %, in 1 % increments, was attached to each blend shape, which determined the range of motion of the mesh in the 3D environment. A number of AUs were represented by specific blend shapes. Thus, each movement of a blend shape reproduced a specific facial movement as described in the FACS manual (Ekman, Friesen & Hager, 2002). The minimal (0 %) and maximal intensity (100 %) of AUs' blend shapes were also determined by the FACS manual.

Based on the male and female 3D models of EEVEE, two Caucasian male avatars (M1 and M2) and two Caucasian female avatars (F1 and F2) were created by changing the texture of the skin, the haircut and the color of the eyes (see Figure 1). For both female and male avatars, short haircuts were chosen to avoid covering the face of the avatars and to keep participants' attention on the face. Between avatars of the same gender, the structural characteristics of their face had the same proportions (e.g. eye level, nose size, etc.). The textures were produced from photos taken of two male and two female individuals. For each avatar, the same animation of blend shapes, thus the same AUs magnitude and timing, was applied with the software Blender®.

Figure 1. The physical appearance of the four avatars (two males and two females, respectively M1, M2, F1 and F2) used in the study, depicting a neutral expression.

***2.2.2. Making of the dynamic facial expressions of pain*.**

Specific sets of AUs, described as a "basic signal" of pain because of their consistency across different types of pain (Kunz & Lautenbacher, 2013; Prkachin, 1992; Prkachin & Solomon, 2009), were used to create the dynamic facial expressions of the avatars. These include: AU 4 (brows lowering), AUs 6-7-43 (orbit tightening and eye closure) and AUs 9-10 (nose wrinkling and the upper lip raising). All pain expressions were divided in three time periods: the onset (from a neutral facial expression, corresponding to the level of AUs at 0 %, to the maximal intensity of AUs), the apex (plateau of maximal intensity of AUs) and the offset (from maximal intensity of AUs back to a neutral facial expression). Seven dynamic facial expressions were produced: six possible sequences of cumulative onset of these AUs sets (Sequences 1 to 6) and one synchronized onset of the AUs (see Figure 2 for a detailed representation).

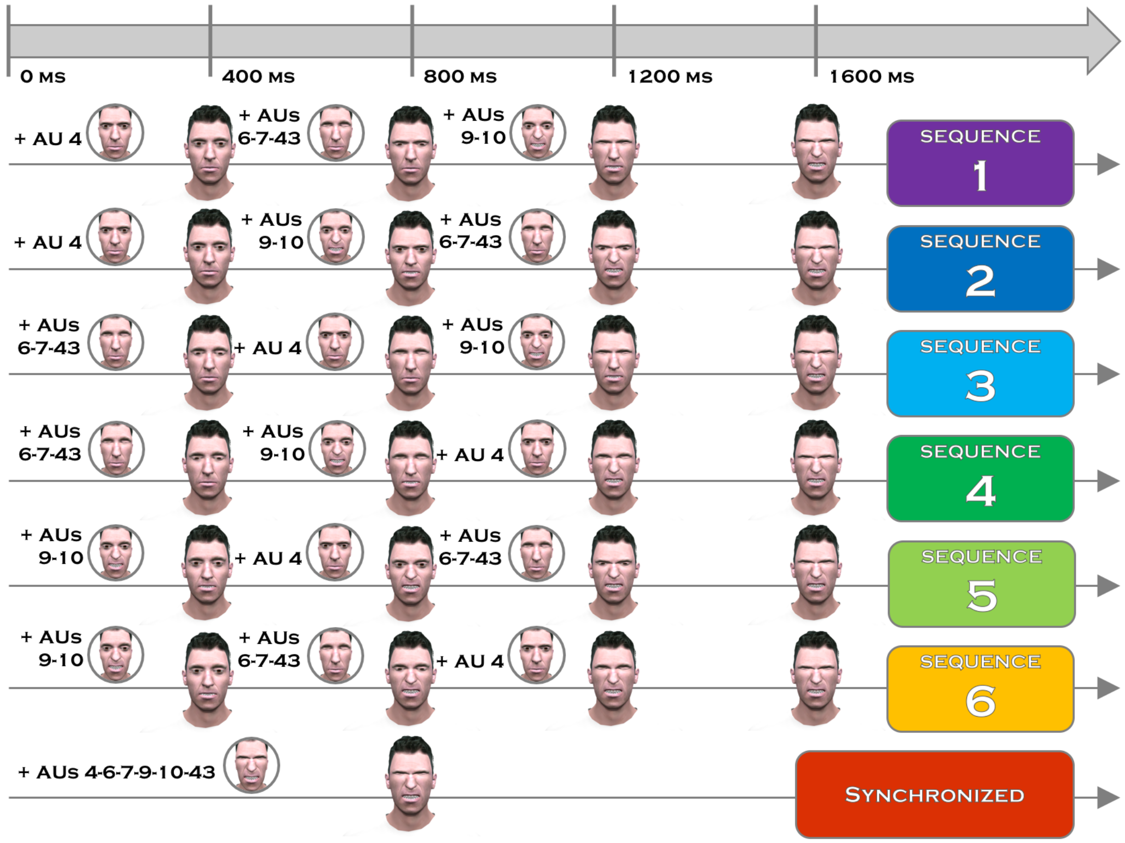


Figure 2. Description of the timing of the six sequential and the synchronized AUs onsets. The first six rows correspond to the six possible sequences of the three sets of pain AUs, numbered 1 to 6. The sequences started with the progressive apparition of the first set of AUs. 400 ms after the onset of the expression, the second set of AUs appeared and was added to the first set. After another 400 ms, the third set of AUs was added to the first and second sets and ended the onset part of the pain expression 1600 ms after the beginning of the expression. All sets of pain AUs reach their apex after 800 ms. Finally, the last row corresponds to the synchronized onset of the three sets of pain AUs. The pain AUs appeared with a progressive intensity and reached their apex after 800 ms.

To set the total duration of the facial expressions created, the UNBC-McMaster Shoulder Pain Expression Archive Database was used (Lucey, Cohn, Prkachin, Solomon, & Matthews, 2011). This database recorded the AUs of facial pain expressions of 129 patients suffering from shoulder pain while manipulating their affected limb. The mean duration of all facial pain expressions listed in this database corresponded to 2800 ms (84 frames at a rate of 29.97 frames per second when facial expressions were presented in the form of a video). The total duration of facial expressions was then divided according to the three temporal segments that compose facial expressions (Ekman, & Friesen, 1987; Ekman, Friesen & Hager, 2002): contraction of the facial muscles (onset), plateau of maximal intensity of the facial muscles (apex) and relaxation of the facial muscles (offset). Consequently, because the unfolding speed of each AU was shown to have more influence on the perception of facial expressions than the total duration of facial expressions (Kamachi et al., 2001), the duration of the onset and offset of AUs was set to 800 ms (24 frames), whereas the duration of the apex of the facial expressions was set to 400 ms (12 frames).

For the facial expressions with sequential onset of sets of AUs, the onset of the AUs was cumulative, meaning the next set of AUs was added to the previous ones, with some overlap between the sets (see Figure 3a). In light of the shifting time between the different sets, sequential facial expressions were composed of three different onsets, each lasting 800 ms (24 frames). To ensure cohesion and fluidity between the AUs, the onset of the second and third sets began at mid-point of the onset of the previous set of AUs, as seen in Krumhuber & Scherer, 2016. A first onset started at the beginning of the facial expression (at 0 ms or Frame #1 of the videos), a second onset at 400 ms (Frame #12) and a third onset at 800 ms (Frame #24). The duration of the facial expression's apex (when all AUs were at their maximum of intensity) was 400 ms (12 frames), but the duration of each AUs' apex depended on the time at which the AUs appeared (first apex: 1200 ms or 36 frames; second apex: 800 ms or 24 frames; third apex: 400 ms or 12 frames). The first apex of AUs started at 800 ms (Frame #24) after the beginning of the facial expression, the second apex started at 1200 ms (Frame #36) and the third apex started at 1600 ms (Frame #48). The offset of the facial expression was synchronized and lasted 800 ms (24 frames). For the offset, all AUs started at 2000 ms (Frame #60) after the beginning of the expression. The total duration of sequential facial expressions was 2800 ms (84 frames). Finally, by varying the order of the three AUs sets, the following six different AUs order can be extracted (see Figure 2).

As for the synchronized facial expression, all AUs had the same duration and started at the same time (see Figure 3b). Similar to sequential expressions, the duration of the AUs onset and the offset was 800 ms (24 frames) and the duration of the facial expression's apex was 400 ms (12 frames). All AUs started at the beginning of the facial expression (at 0 ms or Frame #1), the apex started at 800 ms (Frame

#24) and the offset started at 1200 ms (Frame #36). The total duration of the synchronized facial expression was 2000 ms (60 frames).

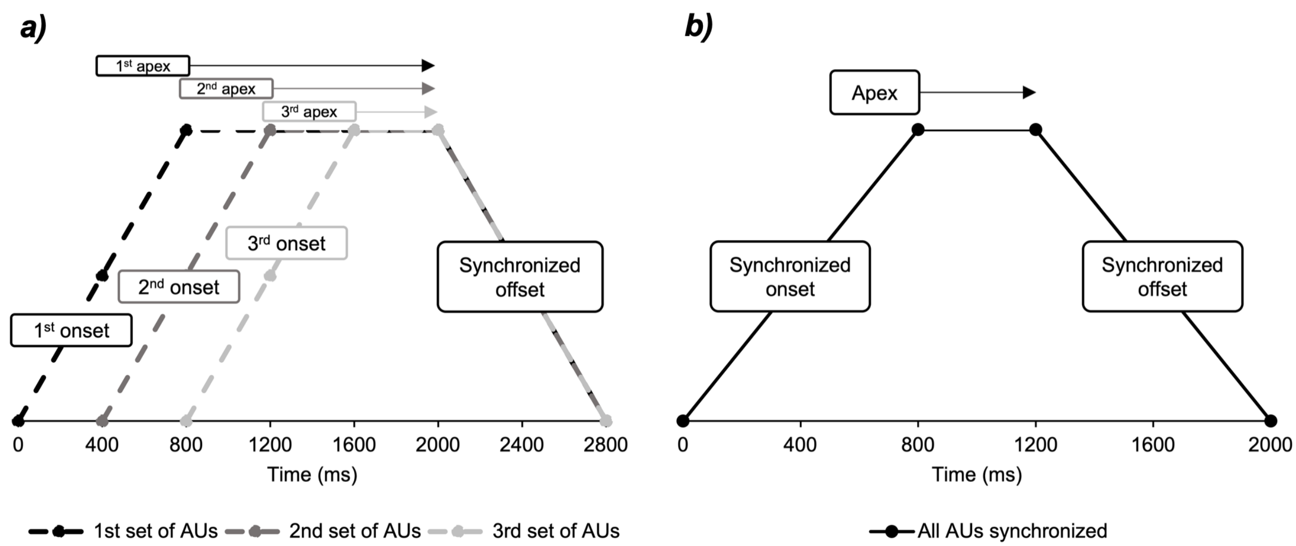


Figure 3. a) Timing of sequential sets of AUs onsets, apexes and offset. *b)* Timing of synchronized AUs onset, apex and offset.

For both sequential and synchronized expressions, pilot experiments were performed to determine the values of two parameters of the facial expression: the intensity and the temporal velocity of AUs. First, the maximal intensity of AUs was the same for all seven facial expressions. It corresponded to a blend shape intensity of 80 % for AU 4, AU 6 and AU 7 and of 100 % for AU 9 and AU 10. No percentage of intensity was associated with AU 43 because it consisted of a binary action, i.e. closing or opening of the eyes. In this case, the avatars' eyes were closed when AU 43 was triggered. The intensity of each facial action was set to create facial expressions of strong pain that were realistic, by avoiding any superposition of blend shapes associated with AUs, that would produce unnatural faces. Also, some ease-in and -out effects on the curve of the onset and offset of AUs were added to improve the smoothness of the facial actions in the pain expressions. The ease-in and -out curves of AUs 6, 7, 10 and 43 corresponded to a linear interpolation, while the ease-in and -out curves of AU 4 and AU 9 corresponded respectively to a quadratic and a cubic interpolation. These ease-in and -out effects on AUs were the same for all expressions and all models. With these intensities and ease-in and -out effects on AUs, the expressions of pain created appeared with less jerking and more homogeneous movements.

From these sequential and synchronized facial expressions, videos (at a rate of 29.97 fps) were created displaying front-facing avatars shown from the shoulders at the center of the computer screen. Behind the avatars, the background depicted a hospital room to create a medical context that helped to optimize the immersion in the task which was pain-related. The 28 resulting videos (7 orders of AUs onset [6 sequential and one synchronized] × 2 female avatars × 2 male avatars) constituted the stimuli of the computer task (see Supplementary material for videos of all facial expressions of M1).

***2.2.3. Realism and perception of pain measures*.**

The videos of sequential or synchronized facial expressions of pain were incorporated into a computer task to evaluate the realism of the facial movements along with the perceived pain intensity and unpleasantness expressed by the avatars. The computer task was created with the software PsychoPy v. 1.84.2 (Peirce, 2009).

The task consisted of evaluating the stimuli on three variables: the realism of the facial movements of the avatars, the level of pain intensity, and the level of unpleasantness of the pain. After each stimulus, a computerized visual analog scale (VAS) of 47 cm appeared on the center of the screen. The participants used a computer mouse to position the cursor (inverted triangle) on the VAS. The position of the cursor in pixels was converted in a % score to provide a value for each response. For the Realism block, the participants had to respond to this question: “How realistic are the facial movements performed by the avatar?” (all questions and labels are translated from the original French version). A VAS was presented beneath the question and was labeled “Not realistic at all” on the left and “Totally realistic” on the right. The question and the VAS were simultaneously presented for three seconds. For the Pain perception block, participants had to respond to two questions: “What is the intensity of the pain felt by the avatar?” and “What is the unpleasantness level of the pain felt by the avatar?”. The labels were “No pain” and “Extremely strong pain” for intensity, and “No pain” and “Extremely unpleasant pain” for unpleasantness. The two VASs for pain perception were presented simultaneously for 6 seconds. For half of the participants determined randomly, the pain intensity VAS was presented at the top of the screen and the pain unpleasantness VAS at the bottom of the screen, and inversely for the other half.

2.2.4. Questionnaires.

In order to quantify certain characteristics of the sample relevant to the decoding of facial pain expression and to the use of avatars, three questionnaires were administered to the participants.

Pain Catastrophizing Scale (PCS). The French version of the Pain Catastrophizing Scale (Sullivan, Bishop, & Pivik, 1995) was used to evaluate the different perspectives of pain catastrophizing. The PCS is a 13-item instrument in which participants are asked to indicate the degree to which they experienced certain thoughts or feelings when experiencing pain on a 5-point scale (“not at all” to “all the time”). A total score, obtained by summing up the answers to all 13 items, and three subscale scores assessing Rumination, Magnification and Helplessness are computed.

Interpersonal Reactivity Index (IRI). The French translation of the Interpersonal Reactivity Index (Achim, Ouellet, Roy, & Jackson, 2011; Davis, 1980, 1983) is a self-reported instrument assessing empathic abilities. The IRI is a 28-item instrument in which participants need to indicate to what extent each statement describes them most, on a 5-point Likert scale (“does not describe me well” to “describes me very well”). A total score is obtained by summing the answers to all 28 items, as well as four subscales of 7 items to assess Empathic Concern, Perspective Taking, Fantasy and Personal Distress.

3D animation movies and video games (3D+VG). To assess participants background of 3D animation movies and video games, we developed a questionnaire with open-ended questions and questions with Likert-type scales and checkboxes. The goal of adding this questionnaire was to get the participants’ insights concerning two frequent activities that would bring familiarity with avatars. They were asked, for example, to report how often and how many hours per week they played video games, how many 3D animation movies they watched in the last 2 months, etc.

2.3. Procedure.

Participants were seated approximately 60 cm from a Dell UltraSharp U2412MB monitor (24 inches screen diagonal size; 1920 x 1200 pixel resolution; 60 Hz refresh rate). Before the beginning of the computer task, standardized instructions were given to the participant. First, they were told that they would watch videos of facial expressions of pain of two female and two male avatars (also defined as virtual characters to the participants). They were asked to focus on the facial movements of the avatars and not on the form or the texture of the avatars' face. To accentuate the discrimination between the different AUs orders, a deceptive instruction was provided. Participants were told that some of the presented facial expressions were based on actual motion capture of patients with shoulder pain while others were artificially created. The debriefing included an explanation for this deception.

The computer task consisted of two test blocks (Realism and Pain perception, counterbalanced across participants), and before each block, one practice session (four trials corresponding to two sequences that were not used in the test blocks expressed by a male and a female avatar). Each test block lasted between 15 and 20 minutes with a short break between them. The instruction for the Realism block was to evaluate the realism of the avatars' facial movements, while the Pain perception block was to imagine the pain intensity and the pain unpleasantness expressed by the avatars. The pain intensity was defined as the strength of the pain felt, and the pain unpleasantness was defined as how the pain felt is perceived as unpleasant or uncomfortable. Examples were provided to distinguish between the intensity and the unpleasantness of pain.

All trials consisted of a fixation cross displayed for 2 seconds at the center of the screen followed by one of the stimuli (2 or 2.8 seconds depending on the condition, synchronized or sequential, respectively). The stimuli were randomly presented to each participant. The trial ended with the presentation of the VAS for 3 or 6 seconds depending on the block, Realism or Pain perception, respectively. See Figure 4 for an illustration of the design of the computer task.

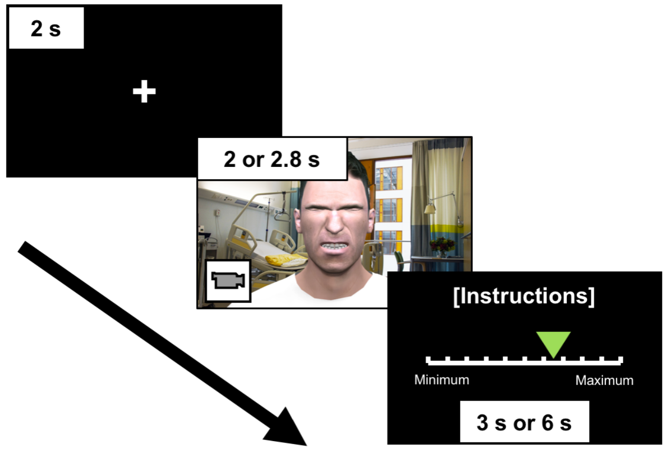


Figure 4. Design of the computer task. The task started with the fixation cross for 2 seconds, followed by the presentation of the stimulus for 2 or 2.8 seconds depending on the condition (synchronized or sequential, respectively). Finally, the VAS and the respective instructions appeared on the screen. In the Realism block, the VAS for realism was presented for 3 seconds, while, in the Pain perception block, the two VAS for pain intensity and pain unpleasantness were presented together for 6 seconds. One trial lasted between 7 and 10.8 seconds.

After the computer task, the three pen-and-paper questionnaires were administered (about 10 minutes). The participants were then debriefed about the rationale of the study and the deception inserted in the study. After taking their comments and answering their questions, participants received their monetary compensation. The testing lasted approximately one hour.

3. Analyses and results

3.1. Preprocessing and preliminary analyses.

The mean for each combination of the independent variables (7 orders of AUs onset × 2 gender of the avatars = 14 conditions) calculated from 8 measurement points (2 avatars per gender × 4 repetitions of the condition per avatar) was determined for each participant on all dependent variables (Realism, Intensity and Unpleasantness). Participants were considered outliers and were excluded from the analyses if one or more means for one condition was ± 3 SD of the mean of all samples for that condition. Consequently, data of three participants (three men) on pain Unpleasantness and Intensity measures were removed from subsequent analyses leading to a final sample of 42 participants (20 men) for these measures. Also, one male participant did not complete the 3D+VG questionnaire. Table 1 presents the socio-demographic information, mean responses on the task and mean scores or frequencies on questionnaires for all conditions.

Table 1

Socio-demographic information and mean responses or frequencies of the computer task and questionnaires for the whole sample and according to the sex of the participant

	All participants	**Participants' sex**	
		Men	**Women**
Sample	45	23	22
Age [18 – 40]	23.58 (5.15)	23.52 (4.85)	23.64 (5.57)
Computer Task			
Realism [0 – 100]	52.75 (10.78)	50.76 (10.77)	54.84 (10.63)
Intensity [0 – 100]	51.26[1] (7.86)	51.02[2] (4.57)	51.48 (10.09)
Unpleasantness [0 – 100]	55.03[1] (9.25)	52.31[2] (4.10)	57.50 (11.77)
PCS			
Rumination [0 – 16]	8.36 (3.71)	7.83 (3.85)	8.91 (3.56)
Magnification [0 – 12]	4.42 (1.94)	3.91 (1.86)	4.95 (1.91)
Helplessness [0 – 24]	7.00 (3.87)	6.39 (3.92)	7.64 (3.80)
Total [0 – 52]	19.78 (7.68)	18.13 (7.68)	21.50 (7.46)
IRI			
Perspective Taking [0 – 28]	20.07 (3.61)	20.17 (3.63)	19.95 (3.68)
Fantasy [0 – 28]	17.80 (4.55)	17.13 (4.34)	18.50 (4.75)
Empathic Concern [0 – 28]	19.18 (3.99)	18.78 (3.99)	19.59 (4.04)
Personal Distress [0 – 28]	10.18 (3.70)	9.17 (4.19)	11.23 (2.84)
Total [0 – 112]	67.22 (9.20)	65.26 (9.58)	69.27 (8.53)
3D+VG			
Do you consider yourself as a person who likes video games?			
Agree	17 (38 %)	14 (61 %)	3 (14 %)
Neither agree nor disagree	14 (31 %)	4 (17 %)	10 (45 %)
Disagree	14 (31 %)	5 (22 %)	9 (41 %)
Did you play video games at least once a week in the last 2 months?			
Yes	14 (31 %)	10 (43 %)	4 (18 %)
No	31 (69 %)	13 (57 %)	18 (82 %)
Do you consider yourself as a person who likes movies/animation series?			
Agree	37 (84[3] %)	18 (82[4] %)	19 (86 %)
Neither agree nor disagree	3 (7[3] %)	2 (9[4] %)	1 (5 %)
Disagree	4 (9[3] %)	2 (9[4] %)	2 (9 %)

Note. Numbers in brackets represent the range of the variable, and numbers in parentheses represent the standard deviation for the mean responses or the proportion in % of participants. PCS = Pain Catastrophizing Scale; IRI = Interpersonal Reactivity Index; 3D+VG = 3D animation movies and video games questionnaire.
[1] $N = 42$; [2] $N = 20$; [3] $N = 44$; [4] $N = 22$

Preliminary analyses were conducted to test the differences between same-gender avatars (F1 vs F2 and M1 vs M2) on the Realism, pain Intensity and pain Unpleasantness. To do so, two t-tests per measure were conducted. No significant difference was found between avatars F1 and F2 for Realism ($t(44) = -1.026$, $p = .311$, $\eta^2_p = .023$), pain Intensity ($t(44) = 1.149$, $p = .257$, $\eta^2_p = .029$) and pain Unpleasantness ($t(43) = 1.149$, $p = .257$, $\eta^2_p = .030$). Similarly, no significant difference was found between avatars M1 and M2 for Realism ($t(44) = 1.945$, $p = .058$, $\eta^2_p = .079$), pain Intensity ($t(43) = -.177$, $p = .860$, $\eta^2_p < .001$) and pain Unpleasantness ($t(43) = -1.329$, $p = .191$, $\eta^2_p = .039$). Therefore, to reduce the loss of degrees of freedom, subsequent analyses were performed on the gender of the avatar by pooling data of both female and male models.

To compare the realism and the pain perception within different orders of AUs onset when taking into account the sex of the observer and the gender of the avatar, a mixed-factorial design was used with the temporal order of AUs onset in pain expression (*AUs Order*; 7 levels: six sequential and one synchronized facial expressions) and the gender of the avatar (*Avatar Gender*; 2 levels: male and female) as within-subject factors and the sex of the participants (*Participant Sex*; 2 levels: men and women) as a between-subjects factor. The factor *Expression* and the interaction *Avatar Gender* × *AUs Order* was subjected to a Greenhouse-Geisser adjustment on degrees of freedom for non-sphericity of the variance-covariance matrix. When necessary, simple effects and post hoc comparisons were tested using Bonferroni-corrected levels of significance. All statistical analyses were performed with SPSS v. 25 (IBM Corp., Armonk, NY).

3.2. Mixed ANOVA on Realism.

A mixed ANOVA 7 (*AUs Order*) × 2 (*Avatar Gender*) × 2 (*Participant Sex*) on the dependent variable of Realism showed a significant main effect of *AUs Order* ($F(2.832, 121.768) = 23.405$, $p < .001$, $\eta^2_p = .352$). No statistically significant differences were found between male and female avatars ($F < 1$), nor between men and women ($F(1, 43) = 1.634$, $p = .208$, $\eta^2_p = .037$). The interaction *AUs Order* × *Avatar Gender* ($F(6, 258) = 5.638$, $p < .001$, $\eta^2_p = .116$) was significant. No other interactions were found significant ($p > .05$). Simple effects and post-hoc tests were conducted to decompose the statistically significant main effect and interaction.

A posteriori pairwise comparisons with Bonferroni adjustment for multiple comparisons ($\alpha_{\text{Post hoc}}$ = .05/21 = .002) were subsequently calculated for the effect of *AUs Order*. Of the 21 contrasts between temporal orders of AUs onset, 14 were statistically significant (see Figure 5). Thus, the dynamic facial expressions associated with the highest level of realism were Sequence 1 *Brows–Eyes–Nose/Mouth*, Sequence 3 *Eyes–Brows–Nose/Mouth*, Sequence 4 *Eyes–Nose/Mouth–Brows* and the Synchronized expression (dark gray in Figure 5), and those associated with the lowest level of realism were Sequence 2 *Brows–Nose/Mouth–Eyes*, Sequence 5 *Nose/Mouth–Brows–Eyes* and Sequence 6 *Nose/Mouth–Eyes–Brows* (white in Figure 5).

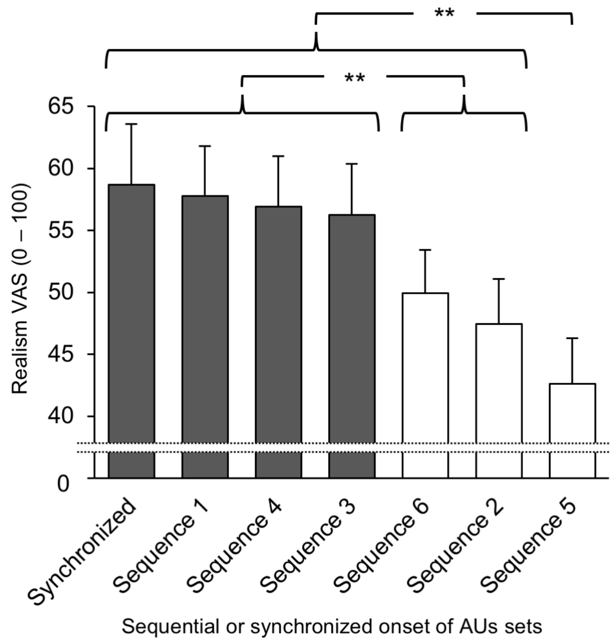
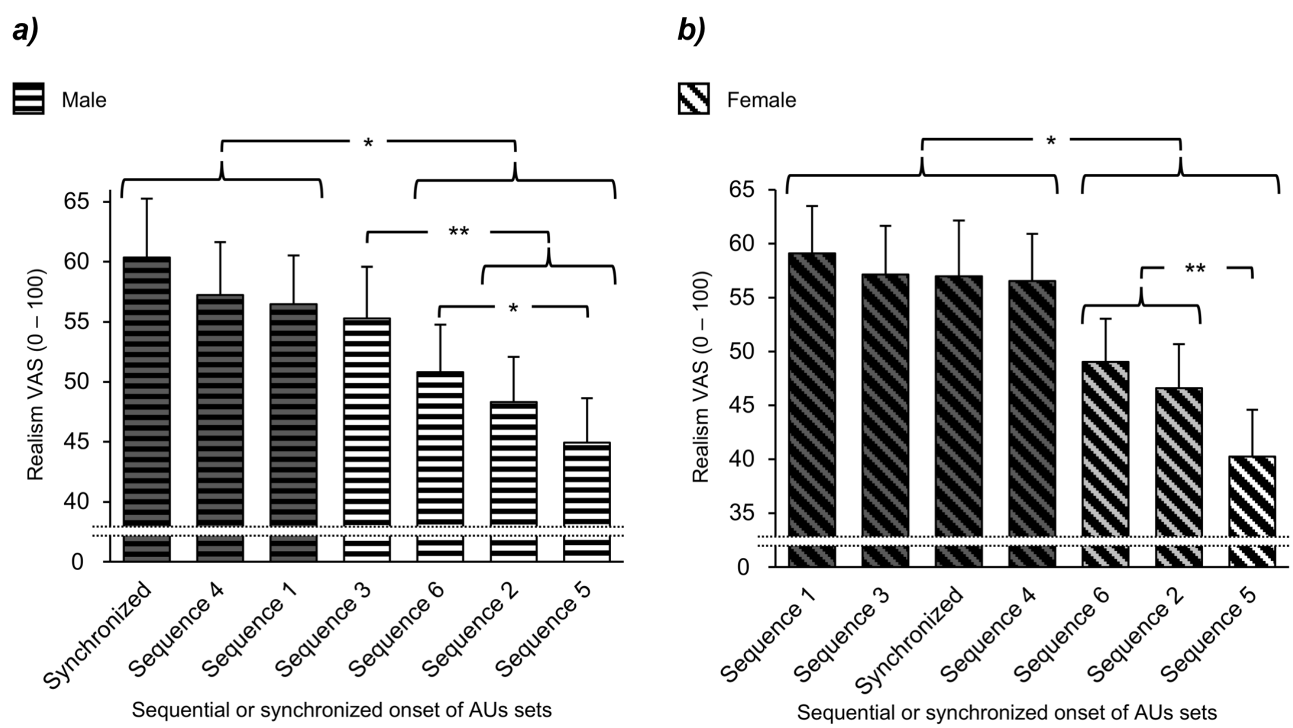


Figure 5. Effect of sequential or synchronized onset of AUs sets on the mean score of realism presented in decreasing order (n = 45). Error bars indicate a 95% confidence interval (CI). ** $p < .001$

To decompose the 2-way interaction between the *AUs Order* and *Avatar Gender*, nine simple effects were conducted with a Bonferroni adjustment ($\alpha_{\text{Simple effects}}$ = .15/9 = .017). Sequence 5 *Nose/Mouth–Brows–Eyes* and the Synchronized expression were perceived as more realistic when expressed by male avatars than female avatars (respectively, $F(1, 43) = 8.426$, $p = .006$, $\eta^2_p = .164$, and $F(1, 43) = 7.436$, $p = .009$, $\eta^2_p = .147$). Also, the effect of *AUs Order* of male ($F(6, 34) = 11.098$, $p < .001$, $\eta^2_p = .662$) and female ($F(6, 34) = 9.947$, $p < .001$, $\eta^2_p = .637$) avatars was statistically significant. Regarding male avatars (see Figure 6a), a group of higher realistic dynamic facial expressions (Synchronized, Sequence 4 *Eyes–Nose/Mouth–Brows*, Sequence 1 *Brows–Eyes–Nose/Mouth*; dark gray in Figure 6a) stood out from the other expressions, while the remaining expressions could be ranked from the highest to the lowest realism (white in Figure 6a): Sequence 3 *Eyes–Brows–Nose/Mouth*, Sequence 6 *Nose/Mouth–Eyes–Brows*, Sequence 2 *Brows–Nose/Mouth–Eyes* and Sequence 5 *Nose/Mouth–Brows–Eyes*. Regarding female avatars (see Figure 6b), three groups of dynamic facial expressions, from the highest to the lowest level of realism, could be distinguished: 1) Sequence 1 *Brows–Eyes–Nose/Mouth*, Sequence 3 *Eyes–Brows–Nose/Mouth*, Synchronized and Sequence 4 *Eyes–Nose/Mouth–Brows* (dark gray in Figure 6b); 2) Sequence 6 *Nose/Mouth–Eyes–Brows* and Sequence 2 *Brows–Nose/Mouth–Eyes*



(light gray in Figure 6b); 3) Sequence 5 *Nose/Mouth–Brows–Eyes* (white in Figure 6b).

Figure 6. a) Interaction effect of sequential or synchronized onset of AUs sets for male avatars on mean score of realism presented in decreasing order (n = 45). *b)* Interaction effect of sequential or synchronized onset of AUs sets for female avatars on mean score of realism presented in decreasing order (n = 45). Error bars indicate a 95% CI. * $p < .01$; ** $p < .001$

3.3. MANOVA on Intensity and Unpleasantness of pain.

A mixed MANOVA 7 (*AUs Order*) × 2 (*Avatar Gender*) × 2 (*Participant Sex*) on the combined dependent variables of pain Intensity and Unpleasantness revealed two statistically significant main effects: *AUs Order* (*Wilks'Λ* = .163, $F(12, 29) = 12.427$, $p < .001$, $\eta^2_p = .837$), and *Participant Sex* (*Wilks'Λ* = .850, $F(2, 39) = 3.443$, $p < .042$, $\eta^2_p = .150$) factors. No statistically significant difference was found between male and female avatars (*Avatar Gender* factor; $F < 1$). Furthermore, the interaction between the factors *Avatar Gender* and *AUs Order* was statistically significant (*Wilks'Λ* = .451, $F(12, 29) = 2.943$, $p = .009$, $\eta^2_p = .549$) while all other interactions were not (*ps* > .05). To assess the effect of the factors on each dependent variable, univariate *F*-tests on pain Intensity and Unpleasantness were computed. The familywise inflation of Type I error rate was controlled for by the Bonferroni adjustment ($\alpha_{\text{Univariate}} = .05/2 = .025$).

3.3.1. Pain Intensity.

A mixed ANOVA 7 (*AUs Order*) × 2 (*Avatar Gender*) × 2 (*Participant Sex*) on the dependent variable of pain Intensity showed a statistically significant main effect of *AUs Order* ($F(3.447, 137.885) = 10.742$, $p < .001$, $\eta^2_p = .212$). No statistically significant difference was found between male and female avatars ($F < 1$), nor between man and woman participants ($F < 1$). No interactions were found to be statistically significant (*ps* > .05).

A posteriori pairwise comparisons with Bonferroni adjustment for multiple comparisons ($\alpha_{\text{Post hoc}} = .025/21 = .001$) were subsequently calculated for the *AUs Order* effect. Of the 21 contrasts between temporal orders of AUs onset, 7 were statistically significant (see Figure 7). Thus, the dynamic facial expressions associated with the highest level of pain intensity were Sequence 4 *Eyes–Nose/Mouth–Brows* and Sequence 6 *Nose/Mouth–Eyes–Brows* (dark gray in Figure 7), those with a moderate level of intensity were Sequence 3 *Eyes–Brows–Nose/Mouth* and Sequence 5 *Nose/Mouth–Brows–Eyes* (light gray in Figure 7), and those with the lowest level of intensity were Sequence 1 *Brows–Eyes–Nose/Mouth*, Sequence 2 *Brows–Nose/Mouth–Eyes* and the Synchronized expression (white in Figure 7).

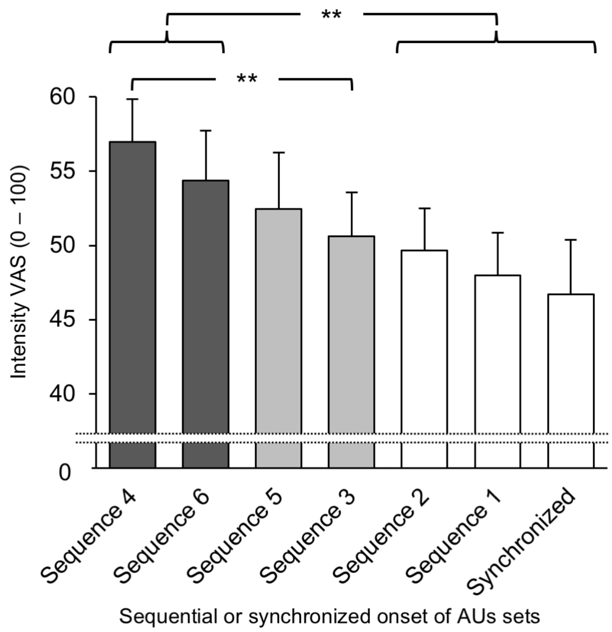
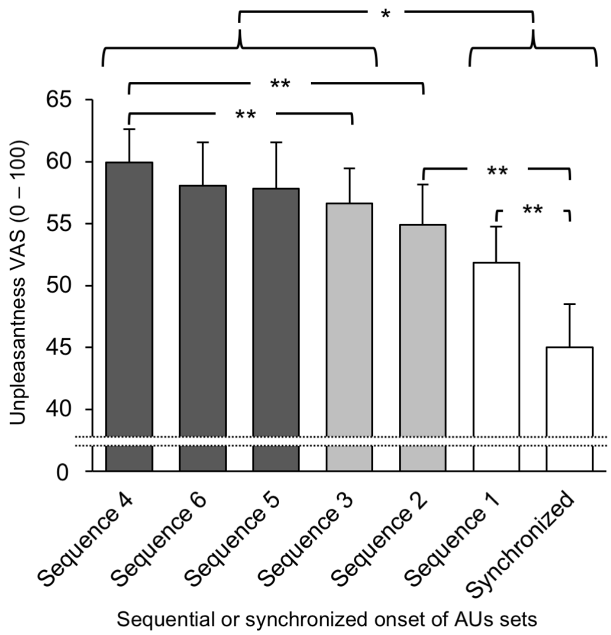


Figure 7. Effect of sequential or synchronized onset of AUs sets on the mean score of pain intensity presented in decreasing order (n = 42). Error bars indicate a 95% CI. ** $p < .001$

3.3.2. Pain Unpleasantness.

A mixed ANOVA 7 (*AUs Order*) × 2 (*Avatar Gender*) × 2 (*Participant Sex*) on the dependent variable of pain Unpleasantness showed one statistically significant main effect: the *AUs Order* factor (F(3.478, 139.106) = 33.070, $p < .001$, $\eta^2_p = .453$). No statistically significant difference was found between male and female avatars ($F < 1$), nor between man and woman participants (F(1, 40) = 3.487, $p = .069$, $\eta^2_p = .080$). The interaction between the factors *Avatar Gender* and *AUs Order* was statistically significant (F(6, 240) = 2.657, $p = .016$, $\eta^2_p = .062$) while all other interactions were not (*ps* > .05). Simple effects and post-hoc tests were conducted to decompose the statistically significant main effect and interaction.

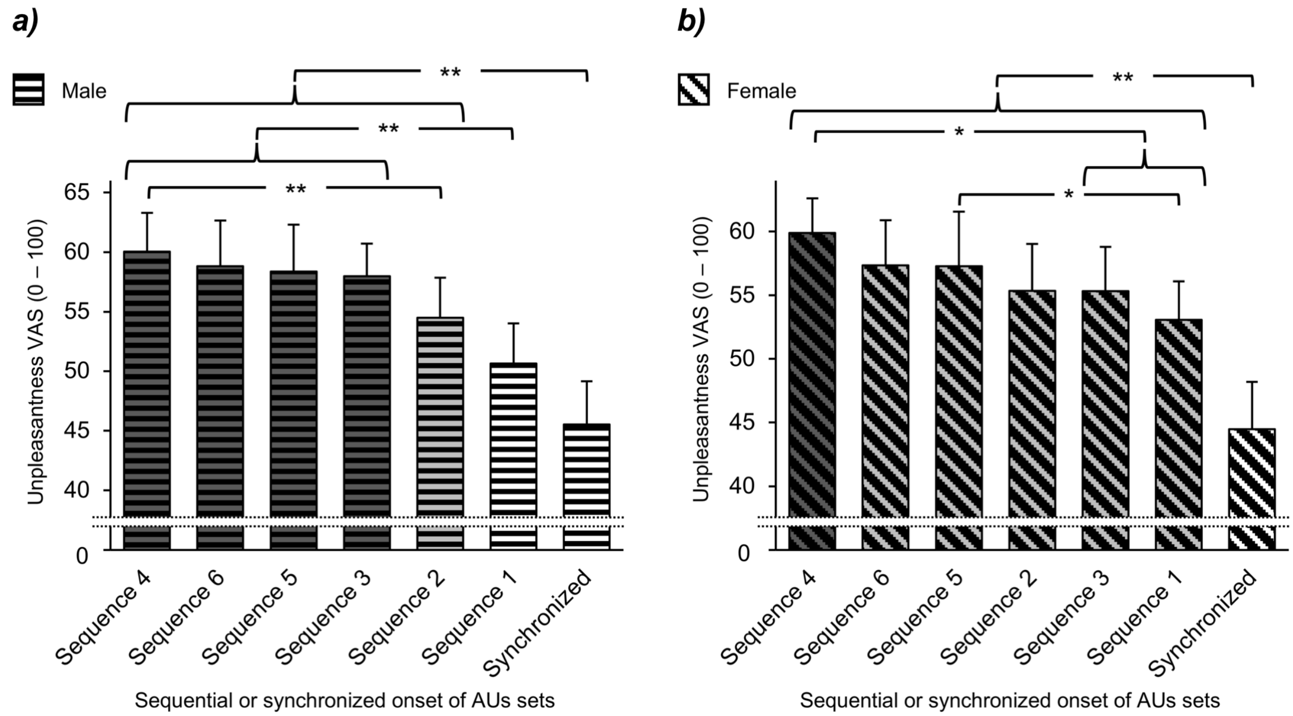
A posteriori pairwise comparisons with Bonferroni adjustment for multiple comparisons ($\alpha_{\text{Post hoc}}$ = .025/21 = .001) were subsequently calculated for the *AUs Order* effect. Of the 21 contrasts between temporal orders of AUs onset, 12 were statistically significant (see Figure 8). Thus, the dynamic facial expressions associated with the highest level of unpleasantness were Sequence 4 *Eyes–Nose/Mouth–Brows*, Sequence 5 *Nose/Mouth–Brows–Eyes* and Sequence 6 *Nose/Mouth–Eyes–Brows* (dark gray in Figure 8), those with a moderate level of unpleasantness were Sequence 2 *Brows–Nose/Mouth–Eyes* and Sequence 3 *Eyes–Brows–Nose/Mouth* (light gray in Figure 8), and those with the



lowest level of unpleasantness were Sequence 1 *Brows–Eyes–Nose/Mouth* and Synchronized expression (white in Figure 8).

Figure 8. Effect of sequential or synchronized onset of AUs sets on the mean score of pain unpleasantness in decreasing order (n = 42). Error bars indicate a 95% CI. * $p < .01$; ** $p < .001$

To decompose the 2-way interaction between the *Avatar Gender* and the *AUs Order*, nine simple effects were conducted with a Bonferroni adjustment ($\alpha_{\text{Simple effects}} = .075/9 = .008$). Of the nine simple effects, only the effect of the *AUs Order* on the male avatars ($F(6, 36) = 15.380$, $p < .001$) and on the female avatars ($F(6, 36) = 17.725$, $p < .001$) were statistically significant. Regarding male avatars (see Figure 9a), the dynamic facial expressions associated with the highest level of unpleasantness were Sequence 4 *Eyes–Nose/Mouth–Brows*, Sequence 6 *Nose/Mouth–Eyes–Brows*, Sequence 5 *Nose/Mouth–Brows–Eyes* and Sequence 3 *Eyes–Brows–Nose/Mouth* (dark gray in Figure 9a), the one with a moderate level of unpleasantness was Sequence 2 *Brows–Nose/Mouth–Eyes* (light gray in Figure 9a), and those with the lowest level of unpleasantness were Sequence 1 *Brows–Eyes–Nose/Mouth* and Synchronized expression (white in Figure 9a). Regarding female avatars (see Figure 9b), the dynamic facial expressions associated with the highest level of unpleasantness were Sequence 4 *Eyes–Nose/Mouth–Brows* (dark gray in Figure 9b), while the one with the lowest level of unpleasantness was the



Synchronized expression (white in Figure 9b). The remaining expressions, ranked from the highest to the lowest level of unpleasantness, formed three groups (light gray in Figure 9b): 1) Sequences 5 *Nose/Mouth–Brows–Eyes* and 6 *Nose/Mouth–Eyes–Brows*; 2) Sequences 2 *Brows–Nose/Mouth–Eyes* and 3 *Eyes–Brows–Nose/Mouth*; 3) Sequence 1 *Brows–Eyes–Nose/Mouth*.

Figure 9. a) Interaction effect of sequential or synchronized onset of AUs sets for male avatars on mean score of pain unpleasantness presented in decreasing order ($n = 42$). *b)* Interaction effect of sequential or synchronized onset of AUs sets for female avatars on mean score of pain unpleasantness presented in decreasing order ($n = 42$). Error bars indicate a 95% CI. * $p < .01$; ** $p < .001$

3.4. Correlations between PCS, IRI, Realism and Pain perception according to the sex of the participant.

To investigate the relationships between the mean responses on the computer task and the level of empathy and pain catastrophizing of participants, correlations between scores on the PCS and IRI questionnaires and on the realism, pain intensity and pain unpleasantness scales were calculated.

Regardless of the sex of participants, a strong and positive correlation between intensity and unpleasantness of perceived pain was statistically significant ($r = .736$, $p < .001$). No other correlations were statically significant.

As a posteriori analyses, the same relationships were investigated separately for each sex and differences between men and women were investigated using Fisher r-to-z transformation. For men, a strong and positive correlation between realism and perceived pain unpleasantness was statistically significant ($r = .508$, $p < .019$). However, the correlation found in men did not differ from the correlation found in women ($z = 1.218$, $p = .223$). For women, a strong positive correlation between intensity and unpleasantness of perceived pain ($r = .828$, $p < .001$) was statistically significant and differed from the association specific to men ($z = -2.599$, $p = .009$). Also, a moderate negative correlation between Personal Distress (IRI) and realism ($r = -.472$, $p = .027$) was statistically significant for women. However, the correlation found in women did not differ from the correlation found in men ($z = 1.022$, $p = .307$). Among women and men, no other correlations between scores on questionnaires and measures of realism or pain were statistically significant.

4. Discussion

In order to study social interactions with virtual reality and optimize empathy via virtual training, realistic dynamic pain facial expressions are needed. To this end, the primary aim of the study was to investigate the realism and the pain perception of different temporal unfolding in expressions of pain. It was found that the order of AUs onset in the pain expression affects the perception of realism as well as of intensity and unpleasantness of pain. Only one specific combination of AU yields the highest ratings on both realism and pain level: Sequence 4 *Eyes–Nose/Mouth–Brows*. These results are in line with previous literature on dynamism of facial expressions proposing an acute sensitivity of humans to detect fine changes in facial movements (Ambadar et al., 2009, 2005; Cohn & Schmidt, 2004; Dobs et al., 2014; Edwards, 1998; Krumhuber et al., 2013; Krumhuber & Kappas, 2005; Krumhuber et al., 2007). Therefore, because of its effect on the perception of observers, the order of AUs in the facial expression of pain should be not be underestimated in the creation of virtual agents.

4.1. Order of AUs in the facial expression of pain.

4.1.1. Level of realism of dynamic facial expressions of pain.

The results concerning the realism of expressions support the hypothesis that the Synchronized expression and Sequence 1 *Brows–Eyes–Nose/Mouth* are among the most realistic expressions. This finding is congruent with those obtained by studies on the perception of emotional expressions with avatars (Krumhuber & Scherer, 2016; Wehrle et al., 2000) that found a correspondence in the emotional content perceived of target emotions expressed synchronously or sequentially. Also, the fact that Sequence 1 *Brows–Eyes–Nose/Mouth* was among the most realistic expressions is in agreement with the observation of Prkachin & Mercer (1989) on the sequence of AUs expressed by patients suffering from shoulder pain. However, compared to the results of Siebers et al. (2013), no preference of realism for sequential expressions over synchronized expression was found in the current study. The poor representation of AU 9 (*Nose/Mouth* facial movement) in the study of Siebers et al. (2013) could have favored sequential expressions over synchronized expression by depicting, for example, a less intense and non-genuine pain (e.g., Hill & Craig, 2002). In contrast, the correct depiction of AU 9 could have provided the accurate high-intensity pain expression perceived as genuine to compare the realism of the two models on dynamism of facial expressions. Consequently, none of the two hypotheses from emotion theories prevails over the other concerning the perception of dynamic pain expressions with avatars. Therefore, at first glance, the same information on realism seems to be transmitted via synchronized or sequential onset of AUs in the pain expression.

However, other sequences than Sequence 1 *Brows–Eyes–Nose/Mouth* were categorized among the most realistic expressions. Indeed, all expressions for which the orbit tightening and eyelid closure appeared before or at the same time as the nose wrinkling and upper lip raising were perceived among the most realistic expressions. Therefore, the step-by-step transmission of facial signals (by AUs) over time seems to allow a successive categorization of the different affective signals by the observer. Accordingly, AUs 6 and 7 (orbit tightening) were previously associated with the sensory dimension of pain, while AUs 9 and 10 were linked to its affective dimension (Kunz, Lautenbacher, Leblanc, & Rainville, 2012). The results of the present study show a sequence that is perceived as realistic when the sensory information is presented before the affective information related to the pain. This can be explained by the concept of shared representations (e.g., Budell, Jackson, & Rainville, 2010; de Waal & Preston, 2017; Jackson, Meltzoff, & Decety, 2005; Kircher et al., 2013; Prochazkova & Kret, 2017; Ruben & Hall, 2013). This concept is described as the activation of the neural response related to first-hand experience of a certain state when an observer perceives the similar state in another individual. In other words, when participants observed the facial expression of pain of the avatars, their own neural representation of pain, associated with their first-hand experience of pain, would have been activated. When these same participants were asked to evaluate the realism of the pain expression of avatars, they found realistic an expression which matches the sequential model of pain (from the sensory to affective information), originating from their first-hand experience of pain. An EEG or MEG study could confirm or infirm this hypothesis by examining the neural correlates associated with the perception of realism of different dynamic facial pain expressions.

An alternate interpretation of the importance of the onset of the eyes before the nose wrinkling and the upper lip raising in the evaluation of realism would be that eye contact was used to distinguish between genuine and deceptive facial expressions of pain. Indeed, because of a deceitful instruction given before the computer task, participants thought that some facial expressions of the avatars were artificially created, and others were based on motion capture of patients with shoulder pain. To assess the human likeness of real and artificial humans, including avatars, a study showed that the fixation of the eyes area bore an essential role (Schwind & Jäger, 2015). In fact, the more a face was considered as human-like and realistic, the more time was spent fixing the area of the eyes. The inclusion of an eyetracking technique in future studies could thus provide information about the attentional deployment of observers during the evaluation of the realism of dynamic facial pain expressions.

4.1.2. Pain perception of dynamic facial expressions of pain.

A more intense expression was associated with the onset of the furrowing of the brows happening last, whereas a higher level of unpleasantness in pain expression was associated with the onset of the nose wrinkling and upper lip raising before the furrowing of the brows. Therefore, the results obtained on pain intensity and unpleasantness perceived in the dynamic facial expressions do not support the hypothesis that more pain will be perceived in the Synchronized expression and Sequence 1 *Brows–Eyes–Nose/Mouth*. In the case of the Synchronized expression, this result could be linked to the total duration that was shorter than for the sequences of AUs. However, considering that participants were also able to categorize the sequential expressions, the findings could rather suggest that humans have a bias toward affective information when pain is transmitted by others through facial expressions. Indeed, the pain intensity and unpleasantness were evaluated according to the order of the furrowing of the brows, as well as the nose wrinkling and upper lip raising, both are sets of facial movements associated with the affective dimension of pain (Kunz et al., 2012). This falls in line with results from Roy, Blais, Fiset, Rainville, & Gosselin (2015) who, with facial expressions of actors, investigated the visual information used by human observers to recognize pain. They found that the discrimination of the facial expression of pain from other emotions by human observers relies primarily on the information transmitted by wrinkles between the eyes (furrowing of the brows) and the mouth, while an “ideal observer” relies mostly on information of the eyes (inferior part of the *orbicularis*), part of the lips, mouth and nose. In the present study, the participants considered primarily the order of affective facial pain actions, i.e. brows, mouth and nose. Thus, similar conclusions to that of Roy and colleagues could be replicated, but with a perception task and dynamic stimuli of facial expressions produced with avatars. As proposed by Kunz (2015), this finding suggests that the recognition of pain expressions does not trigger all the facial movements accompanying pain – only those of the affective dimension. Moreover, a recent study using the reverse-correlation technique (i.e., a type of masking) on pictures of avatars expressing pain proposed that the furrowing of the brows as well as the nose wrinkling and upper lip raising are the most salient facial sets in the mental representation of the facial expression of pain (Blais et al., 2019). Consequently, the results of this present research also highlight the relevance of the unpleasant aspect inherent to pain in judging others' pain by facial expressions.

Furthermore, the results gathered on the measure of intensity and unpleasantness enlighten us on the possible meaning of certain AUs in the pain expression. First, the onset of the furrowing of the brows as the last set of AUs of the expression denotes a greater intensity of the perceived pain of the facial expression of the avatar. Thus, we can hypothesize that the furrowing of the brows transmits information pertinent to the intensity of the internal state. For instance, the dynamic presentation of frowning in the animation of a joyfully laughing face is linked with the perceived laughter intensity (Hofmann, 2014). In other words, as the brows are gradually frowned, a laugh will accordingly and gradually be perceived as intense. Also, the electromyogram (EMG) amplitude of the muscle associated with frowning (i.e., bilateral *corrugator supercilii*) has been correlated with the perception of effort in physical tasks and severe-intensity aerobic exercise (de Morree & Marcora, 2010, 2012). In a nutshell, it is suggested that the furrowing of the brows (AU 4) occurring last in the expression informs us more adequately of the intensity of a strong pain expressed by the avatars. As for the nose wrinkling and upper lip raising (AUs 9 and 10), these facial movements could convey information about the valence of the internal state expressed by others, occurring before the judgment of its intensity. Indeed, the AUs 9 and 10 have been solely associated with negative affective reactions such as anger, disgust and pain (e.g. Du, Tao, & Martinez, 2014; Ekman & Wallace, 1980; Scherer & Ellgring, 2007). Thus, in the eye of an observer, the detection of the nose wrinkling and upper lip raising could be the sign of a negative state felt by the target.

4.1.3. Variations of realism and perceived pain between the dynamic facial expressions of pain.

Sequence 4 *Eyes–Nose/Mouth–Brows* was the only dynamic facial pain expression that was considered as among the most realistic, intense and unpleasant expressions of pain. This was the only sequence that showed eye-related movements appear before the nose- and mouth-related movements (i.e. higher realism), which in turn appear before furrowing of the brows (i.e. higher pain perceived). Therefore, Sequence 4 *Eyes–Nose/Mouth–Brows* could be the best dynamic facial expression to use to represent realistic pain on virtual agents.

For the other sequences of dynamic facial pain expressions, the relationship between realism and pain level was inverse: when a dynamic facial pain expression was assessed as more realistic, it was perceived as less intense and less unpleasant in terms of pain, and vice versa. Since the pain expressions depicted were conceived to be of strong intensity and the medical context provided by the instructions and the hospital background suggested to the observers the presence of some deceptive pain expressions, some facial movements might have been perceived as exaggerated. In Poole and Craig (1992), more pain was given to fake facial expressions of pain compared to genuine pain expressions. Therefore, dynamic facial expressions for which more pain was perceived could be considered less realistic because the pain wince of the avatars was perceived to originate from inconceivable pain. This is linked to a counterintuitive idea stated by Tinwell et al. (2010) suggesting that, in the case of horror movies or games, the depiction by virtual agents of exaggerate fear expressions that seem unrealistic could contribute to elicitation of the emotion of fear by triggering an eerie feeling in observers. Accordingly, the eerie feeling generated by unrealistic facial expressions could favor the experience of negative affects, such as fear and pain, in observers. In fact, the results of a study using electroencephalography suggest that observers could be more attentive of the pain of others when a negative emotional priming stimulus precedes a painful picture (Meng et al., 2012). With this in mind, instead of completely excluding what is perceived unrealistic, both realistic and unrealistic facial expressions should be used to prevent or induce eerie feeling about the avatars, depending on the context.

4.2. Effect of observer's sex and avatar's gender on realism and pain perception.

The results failed to show any difference between men and women for ratings of dynamic facial expressions on the variables realism, pain intensity and pain unpleasantness. This is not in accordance with the hypothesis and previous studies that described better skills in women compared to men at decoding emotions by nonverbal behaviors (Babchuk et al., 1985; Hall, 1978; Hampson et al., 2006; Rotter & Rotter, 1988; Thayer & Johnsen, 2000; Wingenbach et al., 2018). However, in a recent study, men showed more accuracy at detecting pain from suppressed, genuine and exaggerated pain expressions than women (Ruben & Hall, 2013). In the same study, no association was found between the emotion recognition task and pain detection accuracy, suggesting the recruitment of different skills for judging the pain compared to the emotions of others. Thus, despite the well-established fact that women have better abilities to detect emotions from nonverbal behaviors than men, this difference in sex is not as clear for pain. Considering the small sample of this study that limits the scope of the results, future studies on pain expression should take into account the impact of sex on the perception of pain to further investigate this question.

As for the effect of the gender of the avatars, the perception of level of realism and unpleasantness in the dynamic facial expression of pain varies depending on whether the avatar observed is male or female. Thus, the evaluation of realism and unpleasantness of facial pain expressions in female avatars seems to be more dependent on specific criteria of the order of AUs than in male avatars. For instance, while in female avatars the pain expressions were more realistic when movements around the eyes (AUs 6-7-43) appeared before those around the nose and the mouth (AUs 9-10) and when they did not appear immediately after the movements of the eyebrows (AU 4), it was not the case for male avatars. In the same way, while in female avatars the pain expressions were less unpleasant when all facial movements appeared at the same time compared to specific sequential onsets of facial movements, this distinction was not always present in male avatars. Thus, observers, regardless of their sex, seem more critical of the realism and unpleasantness of the dynamic expressions in females compared to that in males.

This finding could be explained by a gender bias in the perception of pain in others as found in precedent studies (Coll et al., 2012; Pronina & Rule, 2014; Riva et al., 2011; Robinson & Wise, 2003; Simon et al., 2006). The present study suggests that the influence of the gender of the face could be explained by a broader range of mental representations of dynamic patterns of pain encoded for men compared to women. Observers may be more aware of small changing pain cues from males' face because, considering that men are expected to have a greater tolerance to pain and to less express their pain compared to women (Hobara, 2005; Robinson et al., 2001; Robinson, Gagnon, Riley, & Price, 2003; Robinson & Wise, 2003), pain in men is believed to originate from a more noxious and threatening stimulus than women's when both genders expressed the same level of pain. Finally, the results of this study suggest that the analysis of the temporal unfolding of pain facial expressions could contribute to the understanding of the gender bias in the perception of pain in others.

4.3. Association between observers' characteristics, realism and pain perception.

Contrary to the stated assumptions, no relationships were found between dispositional variables and both realism and pain ratings. An explanation could be that the avatars have not achieved to elicit enough social presence among observers, i.e., the subjective experience of "being there" in a virtual environment with the virtual agents, thus leading to lower ratings of perceived pain and realism. Measures of social presence (Lessiter, Freeman, Keogh, & Davidoff, 2001; Riva et al., 2007; Witmer & Singer, 1998) could be included in future studies to investigate this idea.

A strong, although not perfect, association between intensity and unpleasantness of pain was unsurprisingly found. This result proposes the measurement of two distinct dimensions (sensory and affective) of the same phenomenon, i.e. pain. It is worth noting that this correlation between intensity and unpleasantness was significant for women but not for men. It is maybe easier for men to attribute a complex mental state to the avatar, thus helping them to judge both dimensions of pain independently. For instance, Russell, Tchanturia, Rahman and Schmidt, (2007) showed an advantage for men in the capacity to attribute physical or mental states to cartoon characters. This advantage could be linked to their more favorable attitude toward computers and video games compared to women (Bonanno & Kommers, 2008; Lucas & Sherry, 2004). For instance, in the present study, more men reported liking video games compared to women (61 % of men and 14 % of women) while more women reported disliking or to be ambivalent about video games compared to men (respectively, 41 % of women vs 22 % of men, and 45 % of women vs 17 % men). Future studies are needed to address in deeper detail this possible moderating effect of attitude toward technologies on difference between sexes.

4.4. Limitations.

A few limitations restrain the generalization of this study. For instance, it can be assumed that individual characteristics of the observer, as the culture, could affect how dynamic pain expressions are perceived. Likewise, as any other facial expressions study, the faces' physical attributes (e.g., the ethnic group, Mathur, Richeson, Paice, Muzyka, & Chiao, 2014; the structural characteristics of the face, Deska & Hugenberg, 2018; the age, Stutts, Hirsh, George, & Robinson, 2010; the attractiveness, Hadjistavropoulos, Ross, & Von Baeyer, 1990; Hadjistavropoulos, McMurtry, & Craig, 1996) could have triggered some prejudices and stereotypes in the observers and, then, influenced their perception of the facial expressions. The interaction between the characteristics of the avatars and of the sample (e.g., Bartley et al., 2015; Torres et al., 2013) should be further investigated in the context of dynamic facial expressions of pain.

Furthermore, due to the great number of factors that influences the time course of facial expressions, methodological choices were made. In fact, other temporal factors than the order of AUs could have influenced the perceived realism and pain of dynamic facial expressions of pain. For instance, the synchronized and sequential onset of AUs were examined without modulating the sequence of the AUs in the offset of facial expressions (see Reinl & Bartels, 2015, for the difference of dynamism between the onset and offset), and the time interval between onset of AUs was fixed as half the duration of the onset of the previous set of AUs. In addition, the duration of AUs and of facial expressions came from the average duration of expressions originating from a database of facial expressions of patients suffering from shoulder pain (Lucey, Cohn, Prkachin, et al., 2011). In the same way, the background and the instructions given to the participants were specific to only the context of a patient's shoulder pain in a hospital. Also, the pain expression depicted was of strong intensity and was composed of some AUs associated to the prototypical expression of pain (e.g., Kunz, Meixner, & Lautenbacher, 2019). Of course, all these parameters that were selected do not represent the great diversity of facial expressions of pain that exists (see, inter alia, Kunz & Lautenbacher, 2013), and the various contexts in which pain expressions can occur. However, considering the influence of context for the perception of affective content (e.g., Barrett, Mesquita, & Gendron, 2011; Diéguez-Risco, Aguado, Albert, & Hinojosa, 2013; Wieser & Brosch, 2012; Yannakakis, Cowie, & Busso, 2017), the current study shed light on only some of the temporal dynamics of facial expression of pain, and how they affect realism and pain perception. Current and future research examining the automatic decoding of pain expression with "Big data" (e.g. Bartlett, Littlewort, Frank, & Lee, 2014; Lucey, Cohn, Matthews, et al., 2011; Siebers, Schmid, Seuß, Kunz, & Lautenbacher, 2016) could provide guidance on the natural order of pain expressions (in AUs) in other contexts to eventually create realistically perceived dynamic facial expressions of pain in virtual agents.

5. Conclusion

This study stresses the influence of the order of AUs in the dynamic pain expression on the realism and the perceived pain from avatars. The implications of the study concern the decoding and, specifically, the production of artificial facial expressions of pain, which can impact the field of virtual reality and affective computing. This study emphasizes the need to consider the AUs order in the creation of any computer-generated humans. Indeed, knowing that a certain onset ordering of facial movements has different effects on the perception of pain, designers of interactive avatars could use these time courses to convey more or less pain by the avatars they create. Consequently, in the not-so-distant future where some of human interactions will be done through intelligent numeric assistants, the study of the dynamic facial expression of pain with avatars is essential to improve human-computer interactions through, among others, the perception of realism and the nonverbal pain information conveyed.

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The authors certify that they have no actual or potential conflicts of interest regarding the research reported in this article.

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