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ORIGINAL ARTICLE

# Social support of virtual characters reduces pain perception

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## Abstract

**Background:** Psychosocial factors, such as social support, can reduce pain. Virtual reality (VR) is a powerful tool to decrease pain, but social factors in VR-based pain analgesia have rarely been studied. Specifically, it is unclear whether social support by virtual characters can reduce pain and whether the perceived control behind virtual characters (agency) and varying degrees of social cues impact pain perception.

**Methods:** Healthy participants ($N = 97$) received heat pain stimulation while undergoing four within-subject conditions in immersive VR: (1) virtual character with a low number of social cues (virtual figure) provided verbal support, (2) virtual character with a high number of social cues (virtual human) provided verbal support, (3) no social support (hearing neutral words), (4) no social support. Perceived agency of the virtual characters served as between-subjects factor. Participants in the avatar group were led to believe that another participant controlled the virtual characters. Participants in the agent group were told they interacted with a computer. However, in both conditions, virtual characters were computer-controlled. Pain ratings, psychophysiological measurements and presence ratings were recorded.

**Results:** Virtual social support decreased pain intensity and pain unpleasantness ratings but had no impact on electrodermal activity nor heart rate. A virtual character with a high number of social cues led to lower pain unpleasantness and higher feelings of presence. Agency had no significant impact.

**Conclusions:** Virtual characters providing social support can reduce pain independent of perceived agency. A more human visual appearance can have beneficial effects on social pain modulation by virtual characters.

**Significance:** Social influences are important factors in pain modulation. The current study demonstrated analgesic effects through verbal support provided by virtual characters and investigated modulating factors. A more human appearance of a virtual character resulted in a higher reduction of pain unpleasantness. Importantly, agency of the virtual characters had no impact. Given the increasing use of digital health interventions, the findings suggest a positive impact of virtual characters for digital pain treatments.

# 1 | INTRODUCTION

Psychosocial factors can modulate pain (Krahé et al., 2013). In the context of experimental pain, social support can have analgesic effects on pain perception and related autonomic responses (Brown et al., 2003; Reddan et al., 2020; Roberts et al., 2015). However, the modulation of pain depends on the type of social support. For example, the mere presence of strangers did not reduce pain (Goldstein et al., 2016; Roberts et al., 2015), while in women, it increased pain (McClelland & McCubbin, 2008). Empirical evidence suggests that explicit verbal support with a clear positive intention reduces pain (Che et al., 2018; Krahé et al., 2013).

Virtual reality (VR) has strong analgesic effects on users and allows to address several aspects of pain perception, for example, cognitive pain targets such as distraction (Trost et al., 2021). Most of the literature has focused on distraction as an elementary mechanism (Colloca et al., 2020; Czub & Piskorz, 2012; Kenney & Milling, 2016), and on factors promoting either distraction (e.g. interactivity) or positive affect (Gutiérrez-Martínez et al., 2011; Loreto-Quijada et al., 2014; Sharar et al., 2016). A recent VR study found that a conversation with another person led to higher pain thresholds in participants (Won et al., 2020). Apart from this, studies focusing on social factors in VR are scarce.

Given the rise of digital therapy (Bouchard et al., 2020; Negreiro Achiaga, 2021) and the undersupply in the healthcare system (Rabbitt et al., 2015), virtual characters have significant potential as they exert a social influence on users (Fox et al., 2015). It is unclear whether the perceived control behind the virtual characters, also referred to as agency, or the degree of social cues is important for their social influence. The threshold model of social influence (Blascovich, 2002) emphasizes the importance of the agency of the virtual characters regarding their social influence. The control behind the virtual character can differ between avatars, referring to human-controlled virtual characters, versus agents, meaning computer-controlled virtual characters (Morkes et al., 1999). The mere perception of human control can lead to more social influence on users. For example, verbal support by avatars led to more stress reduction in social stress situations than by computer-controlled agents (Fox et al., 2015; Kothgassner et al., 2019). However, other studies have found no differences between avatars and agents, for example, in sharing personal information or feeling present in a virtual environment (Ho et al., 2018; Neumann et al., 2023). These results are in line with the Media Equation Concept which highlights the importance of social cues (e.g. human-like appearance, nonverbal feedback such as eye blinking; Nass & Moon, 2000) for the social influence of virtual characters. For example, a higher number of social cues leads to a more positive perception of the virtual character (Appel et al., 2012).

The present study investigated whether verbal social support provided by virtual characters reduces pain perception. To gain insights into which features of virtual characters are important to exert social influence, we varied the number of social cues and agency of virtual characters. Participants were assigned either to an avatar or to an agent group and underwent four within-subject conditions in immersive VR. In two conditions, virtual characters differing in the number of social cues provided verbal support during pain stimulation. In a third condition, participants heard neutral words during pain stimulation. In a fourth condition, no social support or auditory input was provided. We expected social support to have analgesic effects, that is, lower pain ratings and psychophysiological responses compared to no support conditions. Furthermore, we hypothesized that the pain-reducing effects were more pronounced in the condition with a virtual character with a high number of social cues than a low number of social cues. Regarding agency, we did not expect differences in pain responses based on our previous results (Neumann et al., 2023). In that study, we used a similar agency manipulation as in the current study, and no effects of agency on social pain modulation were revealed.

# 2 | METHODS

## 2.1 | Participants

For this pre-registered study (AsPredicted #92284: https://aspredicted.org/eu39c.pdf), we conducted a power analysis (G*Power, Version 3.1.9.4, University of Düsseldorf; Faul et al., 2007) based on a previous meta-analysis that revealed moderate effect sizes ($d=0.5$; see Che et al., 2018; $\alpha=0.05$, power of 0.80), which yielded an optimal sample size of $N=82$ (to reveal the between main effect; the optimal sample size for the other effects was smaller). To allow for a counterbalanced order of conditions, the a priori determined sample size was $N=96$. In total, 106 participants were recruited via an online platform, but nine participants had to be excluded due to not finishing the experiment ($n=2$) or not fulfilling the inclusion criteria ($n=7$). Inclusion criteria were no chronic pain nor neurological or psychiatric illness, no pregnancy, nor any intake of medication with effects on the central nervous system. Furthermore, no intake of alcohol, drugs or pain medication 12 h before the experiment (based on self-report) was allowed. The final sample of 97 participants (67 women) was on average 24.3 years old (SD = 4.00, range 18–39, see Table S1 for more sociodemographic information). Most of the participants were students (85.57% of the sample). For participation, participants either received 12.50€ or course credit. The Ethical Review Board of the Institute of Psychology, University of Würzburg, approved the study. All participants signed informed consent before participation in accordance with the Declaration of Helsinki. Due to the corona pandemic, participants wore FFP2 masks throughout the study.

## 2.2 | Study design

This study (see Figure 1) consisted of a mixed design with the between-subjects factor agency (avatar vs. agent) and the within-subject factor social cues (social support provided by a virtual character with high number of social cues vs. social support provided by a virtual character with low number of social cues vs. no social support but hearing neutral words vs. no social support).

For the agency, participants in the avatar group were led to believe that another participant was controlling the virtual characters. Participants in the agent group were told that they were interacting with a computer. In reality, in both groups, the virtual characters were computer-controlled. During the experiment, all participants underwent four within conditions in VR. In the two conditions, a virtual character was present. The virtual characters (high number of social cues, e.g. human-like appearance, and low number of social cues, e.g. static figure) provided verbal support during pain stimulation. In another condition, no support was provided, and no virtual character was present, but participants heard prerecorded neutral words (neutral words condition). This condition was added to rule out that differences in pain responses were due only to auditory input versus no auditory input, regardless of the content. In a fourth condition, no support was provided, and no virtual character was present (control condition).

## 2.3 | Stimulus material

### 2.3.1 | Setting and VR

Participants wore a head-mounted display (HMD) with headphones and held a controller in their dominant hand (HTC Vive, HTC Corp, New Taipei City, Taiwan) to view the virtual environment. The experimenter made sure that the participants found the position of the headset comfortable and whether they could see sharply. The virtual environment was created with Unreal Engine (Version 4.24.3, Epic Games, Cary, NC, USA) using the built-in VR template and assets from the 'Office Scene', 'Supermarket', 'Industry Props Pack 6' and 'Free Furniture Pack'. While immersed in VR, participants were seated in the laboratory. They saw the virtual environment depicting a virtual laboratory from a first-person perspective located in front of a virtual desk and, depending on the condition, the virtual characters (see Figure 1). Participants could explore the virtual environment via head movements but could not move through the world to prevent motion sickness.

### 2.3.2 | Virtual characters

The virtual characters were created using iClone (Version 7.91, Reallusion, San Jose, CA, USA). They differed in the degree of social cues. In the high social cues condition, the virtual character had a human appearance, facial expressions and gestures and a human voice. In the low social cues condition, the virtual character was presented as a static wooden figure without facial expressions or gestures, only with a human voice (see Figure 1). In the following, the term virtual human refers to the virtual character with a high number of social cues, and the term virtual figure to the virtual character with low social cues.

### 2.3.3 | Thermal heat pain stimulus

Thermal heat stimuli were applied using a Somedic MSA thermal stimulator (Somedic Sales AB, Hörby, Sweden) and a Peltier thermode with an active 25 × 50 mm surface attached to the ventral side of the non-dominant forearm.

For each participant, the individual pain tolerance (IPT) was determined via the method of limits (Yarnitsky et al., 1995). In four runs, participants adjusted the temperature of the thermode by pressing the controller until the stimulus felt painful. The temperature of the thermode started at 32°C, heated up at a rate of 0.5°C/s and cooled down immediately after button press at a rate of 5°C/s. The first run was a practice run; the following three runs were averaged, rounded in 0.5°C-steps and yielded the temperature for all pain stimuli during the main experiment. After determining the IPT, each participant received a test heat stimulus with the duration of the stimuli in the main experiment (plateau of 10 s, heating rate of 5°C/s). Participants were asked to rate the intensity and unpleasantness of the heat stimulus on a visual analogue scale (VAS) from 0 (*not painful*

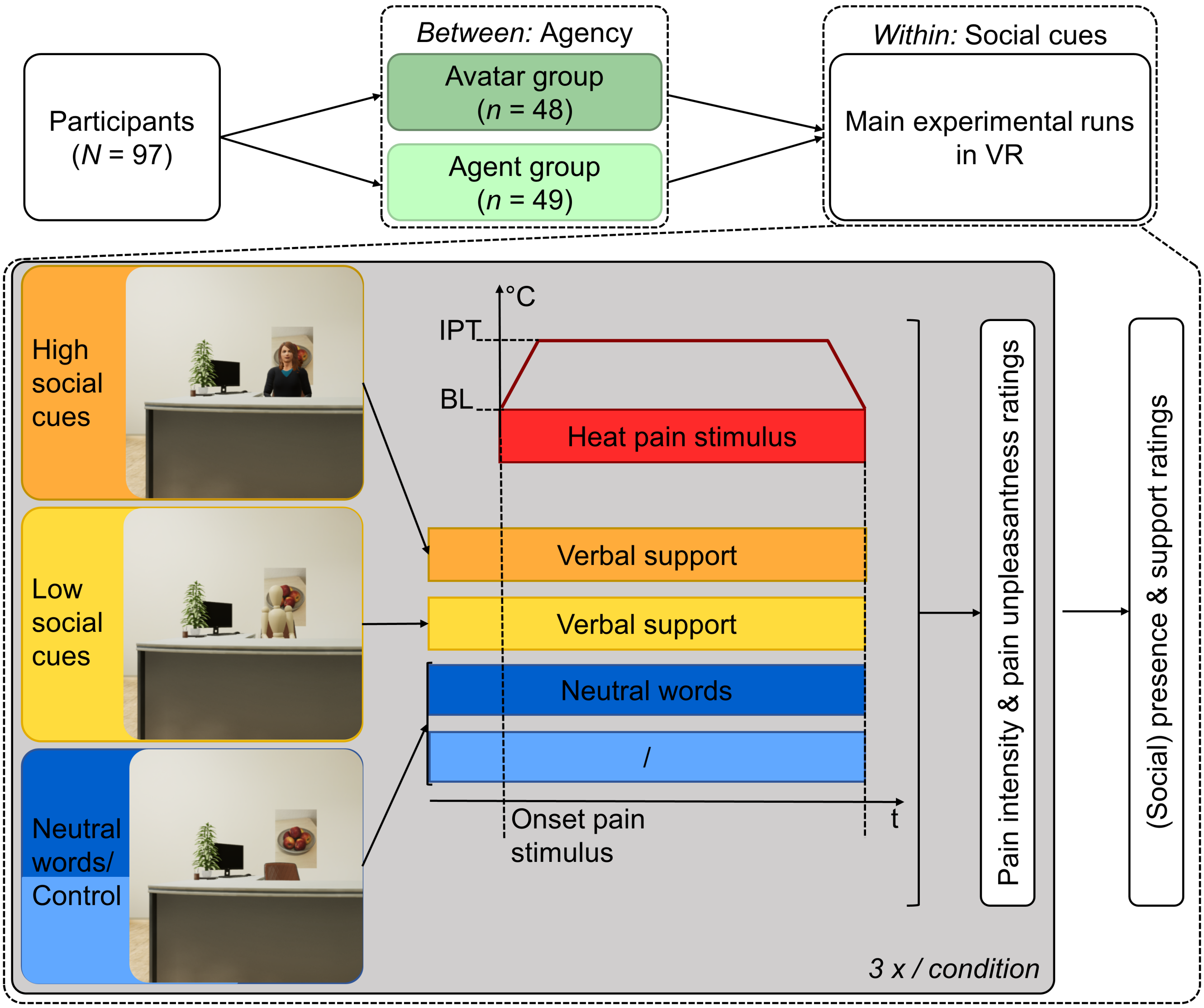


**FIGURE 1** Schematic overview of the experimental procedure. Participants got assigned to either the avatar or agent group (*between*-subjects factor). Then, they were immersed in a virtual laboratory and underwent four *within*-subject conditions in pseudo-randomized order. In two conditions, virtual characters with varying numbers of social cues (low: virtual figure, high: virtual human) provided verbal support during pain stimulation. In another condition, no support was provided, but participants heard pre-recorded neutral words (neutral words condition). In a fourth condition, no support was provided (control condition). There were three heat pain stimuli per condition. After each pain stimulus, pain ratings were assessed. After each condition, social presence and presence ratings were measured. During the whole main experiment, psychophysiological data were recorded. The virtual environment and virtual characters are depicted from the participants' view. The position of the thermode was changed after each run in virtual reality (VR). BL, baseline; IPT, individual pain tolerance.

*at all/ not unpleasant at all*) to 100 (*extremely painful/ extremely unpleasant*). If the pain intensity rating was ≥90 for the test heat stimulus, 0.5°C was subtracted. The temperature did not exceed 49°C for safety reasons. The baseline temperature of the thermode during the main experiment was 10°C below the target temperature. The mean temperature of the heat stimulus during the main experiment was 44.31°C (SD = 3.16). There was one heat pain stimulus per trial in the main experiment and three heat pain stimuli per condition.

## 2.4 | Measures

### 2.4.1 | Pain ratings (primary outcome)

Participants rated the pain unpleasantness and pain intensity. For this, a VAS ranging from 0 (*not unpleasant at all/ not painful at all*) to 100 (*extremely unpleasant/ extremely painful*) was displayed in the virtual environment in front of the participants (over-imposed on environment). Participants could move the slider (VAS) with the controllers and saw the selected value above the scale. To confirm their answer, participants had to select the displayed 'next' button. During ratings, the virtual character was hidden because the feeling of being observed by another person can influence how participants rate pain (Sambo et al., 2010). For this reason, participants of the avatar group were also instructed at the beginning of the experiment that the supposed other participant could not see their ratings.

### 2.4.2 | Skin conductance (primary outcome)

Electrodermal activity (EDA) was recorded with two 8mm Ag/AgCl electrodes (electrode gel: 0.5% NaCl) placed on the thenar and hypothenar eminence of the participant's non-dominant hand. For recording, a V-Amp amplifier and Brain Vision Recorder, V-Amp Edition 1.10, recording software (both Brain Products Inc., Munich, Germany) were used. EDA was sampled at a rate of 500Hz and filtered offline with a second-order Butterworth filter (1Hz high cut-off filter; see Boucsein et al., 2012) via Brain Vision Analyzer 2.1 software (BrainProducts, Munich, Germany). Due to technical difficulties, we had to exclude $n=4$ from the analysis.

Skin conductance level (SCL) was analysed using Brain Vision Analyzer software (BrainProducts, Munich, Germany). For each condition, the SCL was averaged for the time of the heat pain stimulation (2s heat up, 10s plateau, 2s cool down) plus 4s after heat pain stimulation offset since psychophysiological reactions to pain are delayed (as suggested in Loggia et al., 2011). Per condition, each mean SCL was averaged across conditions and baseline-corrected by subtracting a baseline of 1s before the onset of the auditory input. SCL values (expressed in microSiemens) were log-transformed to normalize the distribution. We excluded $n=1$ because of insufficient data signal.

Skin conductance responses (SCR) were analysed using Brain Vision Analyzer software (BrainProducts, Munich, Germany). The specific response was defined with an onset between 0.8 s and 4s after the onset of the heat pain stimulus to the first response peak and measured base-to-peak difference in microSiemens. Responses below 0.02 µS were coded as zero. All SCRs were log-transformed to normalize the distribution. We excluded $n=4$ as non-responder (no response in the four conditions).

### 2.4.3 | Heart rate (primary outcome)

Electrocardiography (ECG) was measured with three electrodes on the upper body (right collarbone, left lower costal arch, left lower side of the torso). For recording, we used a V-Amp amplifier and Brain Vision Recorder, V-Amp Edition 1.10, recording software (both Brain Products Inc., Munich, Germany). ECG was sampled with 500Hz and filtered offline (second-order Butterworth filter with low cut-off: 5Hz, high cut-off: 45Hz, Notch filter: 50Hz) with Brain Vision Analyzer 2.1 software (BrainProducts, Munich, Germany). We had to exclude $n=7$ due to technical difficulties (see OSF for an overview of included participants per group).

For heart rate, R-waves were automatically detected, manually checked and converted into continuous heart rate (HR;in beats per minute, bpm) with Brain Vision Analyzer software (BrainProducts, Munich, Germany). For each condition, the HR was averaged for the heat pain stimulation plus 4s and baseline-corrected by subtracting a baseline of 1s before the onset of the auditory input (Stegmann et al., 2023).

### 2.4.4 | VR ratings (secondary outcomes)

After each condition, participants were asked to fill in more ratings. First, their sense of presence on a VAS from 0 (*not at all*) to 100 (*extremely*) with a single item (*I had the feeling of being present in the virtual world*.; see Bouchard et al., 2004; Käthner et al., 2019). Presence can be defined as a mental state that one feels as being in a computer-generated world, although physically located in a different one (Slater & Wilbur, 1997). Furthermore, the feeling of social presence was measured via the five items of the *Social Presence Survey* (Bailenson et al., 2003) on a VAS from 0 (*not at all*) to 100 (*extremely*). Social presence in virtual environment refers to the feeling of sharing the virtual environment with another being (Biocca et al., 2003). Higher values represent a higher feeling of social presence.

### 2.4.5 | Manipulation checks

After each experimental run, participants rated how they perceived the behaviour of the virtual character on six opponent adjective pairs (rejecting vs. accepting, distant vs. close, cold vs. warm, not helpful vs. extremely helpful, not supporting vs. extremely supporting, unfriendly vs. friendly; adapted from Roberts et al., 2015) on a VAS from 0 (*not at all*) to 100 (*extremely*). In addition, participants were asked to fill in manipulation checks in a post-study questionnaire. Participants rated how human and how empathic they had perceived the virtual characters on a VAS from 0 (*not at all*) to 100 (*extremely*). They were furthermore asked to rate how realistic they perceived the behaviour of the virtual characters on a VAS from 0 (*not at all*) to 100 (*extremely*). All these questions served as manipulation checks for the high social cues versus low social cues condition. We also included an agency manipulation check (adapted from

Kothgassner et al., 2019) by asking them to rate the statement *I had the feeling the virtual human/wooden figure was controlled by a real human*. from 0 (*like computer-controlled*) to 100 (*like human-controlled*). We also asked participants if they were afraid that the virtual character could evaluate or judge their behaviour on a 100-point scale from 0 (*not at all*) to 100 (*extremely*) to rule out alternative explanations for group differences.

#### 2.4.6 | VR experience

They were furthermore asked to rate how realistic they perceived the virtual environment and the behaviour of the virtual characters on a VAS from 0 (*not at all*) to 100 (*extremely*). To measure potential mood changes due to the virtual experience, participants filled in the German version of the state part of the *State Trait Anxiety Inventory* (STAI-state; Laux et al., 1981; Spielberger et al., 1983). Symptoms of cybersickness were measured with the *Simulator Sickness Questionnaire* (SSQ; Kennedy et al., 1993).

#### 2.4.7 | Further questionnaires

Since interindividual factors and attachment style influence pain modulation, questionnaires addressing these factors were completed (Fillingim, 2005; Sambo et al., 2010). Therefore, the German version of the trait part of the STAI (Laux et al., 1981; Spielberger et al., 1983) was measured. The individual attachment style was assessed with the German revised short version of the *Experience in Close Relationships* (ECR-R12; Brenk-Franz et al., 2018; Wei et al., 2007). We also collected personality dimensions with the German short version of the *Big-Five-Inventory-10* (BFI-10; Rammstedt & John, 2007; Rammstedt et al., 2012). Also, to assess the tendency to catastrophize the threat value of pain, participants were asked to fill in the German version of the *Pain Catastrophizing Scale* (PCS; Meyer et al., 2008; Sullivan et al., 1995). All questionnaires were collected via an online survey platform (www.soscisurvey.de).

## 2.5 | Procedure

### 2.5.1 | Preparation and cover story for agency manipulation

Before arriving to the study, participants received an email as a reminder, and those in the avatar group, the additional information that another participant would also be taking part in the study.

After providing informed consent, participants were told about the purpose of the study: investigation of the influence of different manipulations in a virtual environment on pain processing, particularly the influence of different visualizations of virtual characters. However, in the avatar group, participants were misled about the agency of the virtual characters. In the avatar group, to reinforce the impression that another human would control the virtual characters, participants saw a short video about the experimental setup and how the other participant would control the virtual character. Participants in the agent group also watched a video but with the (true) explanation that the virtual characters were computer-controlled. Next, participants answered sociodemographic questions and filled out the STAI (Laux et al., 1981; Spielberger et al., 1983). During that time, in the avatar group, a supposedly other participant (in fact, a female confederate) came to the room to tell the experimenter she had finished filling in her set of questionnaires. The confederate and the experimenter then left the room together briefly. In the agent group, the experimenter left the room to supposedly get another pen and to keep times without an experimenter in the lab equal across both groups.

Subsequently, EDA and ECG electrodes were attached. The experimenter instructed the participants about the usage of the controller and equipped them with the HMD. The procedure in VR started with recording a 20 s baseline of psychophysiological reactions. During this time, participants were asked to look at a white fixation cross on a black screen. Next, the experimenter attached the thermode. A practice run followed to familiarize the participants with the virtual environment, the rating scales, and to determine the IPT temperature. Next, a test pain stimulus was applied (see above).

### 2.5.2 | Agency manipulation in VR

Another facet of the agency manipulation was included while starting the main experiment in VR. Participants saw a loading bar initializing the connection, which was followed by a mock error message. In the avatar group, participants furthermore heard the supposedly other participant asking for help in a distorted voice. The experimenter left the room to look for the other participant (avatar group) or to ask for help (agent group). When the experimenter returned, the programme restarted and was successful, and the main experiment started.

### 2.5.3 | Main experiment in VR

Participants underwent four within-conditions in VR presented in pseudo-randomized order. Every condition began with two questions from the Relationship Closeness Induction Task (Sedikides et al., 1999; posed by the virtual characters in the high social cues and low social cues condition) or control questions related to the poster and plants in the virtual laboratory (neutral words and control condition, see Methods S1 for the questions). The questions were included to foster relationship building between the participant and the virtual characters because social support needs some time to unfold its effects (Brown et al., 2003). Next, three trials followed per condition. Each trial consisted of one heat pain stimulus announced by pre-recorded instructions. Participants were asked to look at the virtual character (high social cues/low social cues condition) or the poster (control/ neutral words condition) to control the focus of attention. Immediately before heat pain stimulus onset (2 s before the thermode started heating up) and during the whole pain stimulation period, the virtual characters provided supporting comments (combination of reassurance and praise, e.g. *You can do it! You're doing a great job!*; see Kindness et al., 2017; Kothgassner et al., 2019; Roberts et al., 2015). To reinforce the impression that the sentences were not pre-recorded, the voice cleared their throat, or pen clicking was heard from time to time. The virtual human furthermore showed non-verbal gestures like nodding and smiling. In the neutral words condition, participants heard words like *desk* or *pencil* in the same length as the verbal support to rule out that differences in pain responses were only due to auditory input versus no auditory input, regardless of the content (words from the affective norms for German sentiment terms with valence ≤3; Schmidtke et al., 2014). After each trial, participants rated the intensity and unpleasantness of the heat pain stimulus. The VAS appeared not immediately but 4 s after pain stimulus offset to not interfere with psychophysiological responses to heat pain stimuli (Loggia et al., 2011). The subsequent trial began after both pain ratings. To prevent the effects of habituation or sensitization, there was a standardized intertrial interval of 30 s between two pain stimuli (Lue et al., 2018), and after every condition, the position of the thermode was changed (Basten-Günther et al., 2021). At the end of each experimental condition, participants rated their feeling of presence, social presence and perception of the virtual counterpart. After each condition, the light was faded out in VR and faded back in at the beginning of the next condition. In total, the VR portion of the study lasted about 30 min.

#### 2.5.4 | Post-study procedure

After the main experiment in the virtual environment, participants were asked to fill out the questionnaires. Finally, participants were debriefed and compensated for their participation.

### 2.6 | Statistical analysis

Heat pain ratings and the SCRs were averaged for each condition, resulting in four mean values per participant.

All outcome measures related to pain were analysed separately with 2×4 repeated measures analyses of variance (rmANOVA) with the between-subjects factor agency (2 levels: avatar, agent) and the within-subject factor social cues (4 levels: high social cue, low social cues, neutral words, control). Significant main effects were further analysed with post hoc *t*-tests according to the formulated hypotheses. In case of no a priori defined hypotheses, post hoc *t*-tests with Bonferroni correction for multiple comparisons were conducted. In this case, Bonferroni–Holm-corrected *p*-values ($p_{bh}$) are reported. For all outcome measures, we report means and standard deviations.

Requirements for the analyses concerning sphericity were tested with the Mauchly's test. In case the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied. Requirements regarding homogeneity of variance were tested with the Levene test. The significance level was set at $p < 0.05$. Effect sizes are reported as generalized $\eta^2$ ($\eta^2_G$). Statistical analyses were conducted in R 4.1.0 (R Core Team, 2021). The rstatix package (Kassambara, 2021) was used for the rmANOVAs and testing of related assumptions, the lsr package for post hoc *t*-tests (Navarro, 2015), the psych package for descriptives (Revelle, 2021) and the ggplot2 package (Wickham, 2016) for data visualization. Data and analysis scripts can be accessed at OSF (https://osf.io/247xm/).

## 3 | RESULTS

### 3.1 | Social influences on pain

#### 3.1.1 | Pain ratings

Pain unpleasantness and pain intensity ratings are depicted in Figure 2. Regarding pain unpleasantness ratings, there was a significant main effect of social cues, $F_{3,285} = 14.82$, $p < 0.001$, $\eta^2_G = 0.04$, but no significant main effect of agency group, $F_{1,95} = 0.12$, $p = 0.732$, $\eta^2_G < 0.01$, and no significant interaction effect between social cues and agency group, $F_{3,285} = 1.65$, $p = 0.178$, $\eta^2_G < 0.01$. Post hoc *t*-tests revealed significantly less pain unpleasantness in the high social cues condition ($M = 56.05$, $SD = 20.11$)

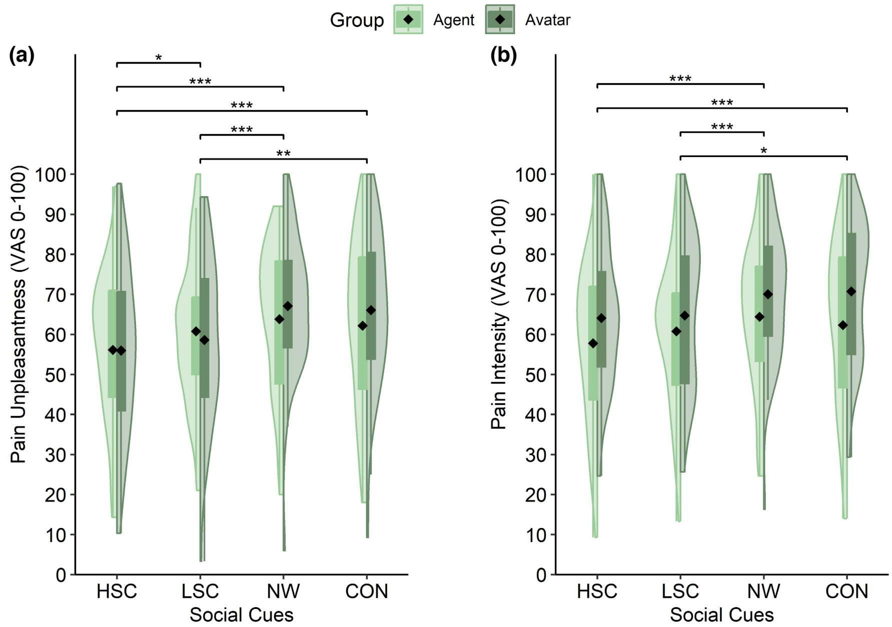


**FIGURE 2** Pain unpleasantness ratings (a) and pain intensity ratings (b) per group and condition. Figure shows means (black squares), interquartile ranges (boxes) and data distributions (violins). CON, control condition; HSC, high social cue condition; LSC, low social cue condition; NW, neutral words condition. $^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$.

compared to the low social cues condition ($M = 59.71$, $SD = 19.7$), $t_{96} = -2.26$, $p = 0.026$, $d = -0.23$, to the neutral words condition ($M = 65.45$, $SD = 18.09$), $t_{96} = -5.71$, $p < 0.001$, $d = -0.58$ and to the control condition ($M = 64.12$, $SD = 20.67$), $t_{96} = -4.82$, $p < 0.001$, $d = -0.49$. Furthermore, participants reported significantly less pain unpleasantness in the low social cues condition compared to the neutral words condition, $t_{96} = -3.87$, $p < 0.001$, $d = -0.39$, and to the control condition, $t_{96} = -2.71$, $p = 0.008$, $d = -0.28$. There was no significant difference between the neutral words and the control condition ($p = 0.362$).

Analysis of pain intensity ratings yielded a significant main effect of social cues, $F_{3,285} = 9.36$, $p < 0.001$, $\eta^2_G = 0.02$, and a trend for a significant main effect of agency, $F_{1,95} = 3.11$, $p = 0.081$, $\eta^2_G = 0.03$, but no significant interaction effect between social cues and agency group, $F_{3,285} = 0.87$, $p = 0.456$, $\eta^2_G < 0.01$. Post hoc *t*-tests revealed significantly less pain intensity in the high social cues condition ($M = 60.91$, $SD = 19.22$) compared to the neutral words condition ($M = 67.2$, $SD = 18.04$), $t_{96} = -4.49$, $p < 0.001$, $d = -0.46$, and to the control condition ($M = 66.51$, $SD = 20.08$), $t_{96} = -3.75$, $p < 0.001$, $d = -0.38$. Also, participants reported less pain intensity in the low social cues condition ($M = 62.74$, $SD = 19.05$) compared to the neutral words condition, $t_{96} = -3.37$, $p = 0.001$, $d = -0.34$, and to the control condition, $t_{96} = -2.51$, $p = 0.014$, $d = -0.26$. There were no significant differences between the high social cues and the low social cues, and the neutral words and control condition (all $ps > 0.179$).

### 3.1.2 | Skin conductance

Figure 3a depicts SCL. Regarding SCL, there was a significant main effect of social cues, $F_{2.76,248.64} = 4.59$, $p = 0.005$, $\eta^2_G = 0.01$, and a trend for a significant main effect of agency group, $F_{1,90} = 2.94$, $p = 0.09$, $\eta^2_G = 0.02$, but no significant interaction between social cues and agency group, $F_{2.76,248.64} = 0.29$, $p = 0.815$, $\eta^2_G < 0.01$. Post hoc tests yielded a significantly higher SCL in the high social cues condition ($M = 0.14$, $SD = 0.18$) compared to the control condition ($M = 0.09$, $SD = 0.15$), $t_{91} = 3.25$, $p = 0.002$, $d = 0.34$, a higher SCL in the neutral words condition ($M = 0.12$, $SD = 0.14$) compared to the control condition, $t_{91} = 2.76$, $p = 0.007$, $d = 0.29$, and a trend for a higher SCL in the low social cues condition ($M = 0.12$, $SD = 0.16$) compared to the control condition, $t_{91} = 1.97$, $p = 0.052$, $d = 0.21$. There were no significant differences between the high social cues condition and the low social cues condition, the high social cues condition and the neutral words condition, and the low social cues condition and the neutral words condition (all $ps > 0.111$).

Analysis of SCR (see Figure 3b) revealed a trend for a significant effect of agency group, $F_{1,88} = 2.67$, $p = 0.077$, $\eta^2_G = 0.02$, but no significant effect of social cues, $F_{2.64,232.67} = 1.28$, $p = 0.282$, $\eta^2_G = 0.01$, nor a significant interaction between social cues and agency group, $F_{2.64,232.67} = 0.97$, $p = 0.400$, $\eta^2_G < 0.01$. SCRs were descriptively higher in the avatar ($M = 0.23$, $SD = 0.17$) compared to the agent ($M = 0.18$, $SD = 0.15$) group.

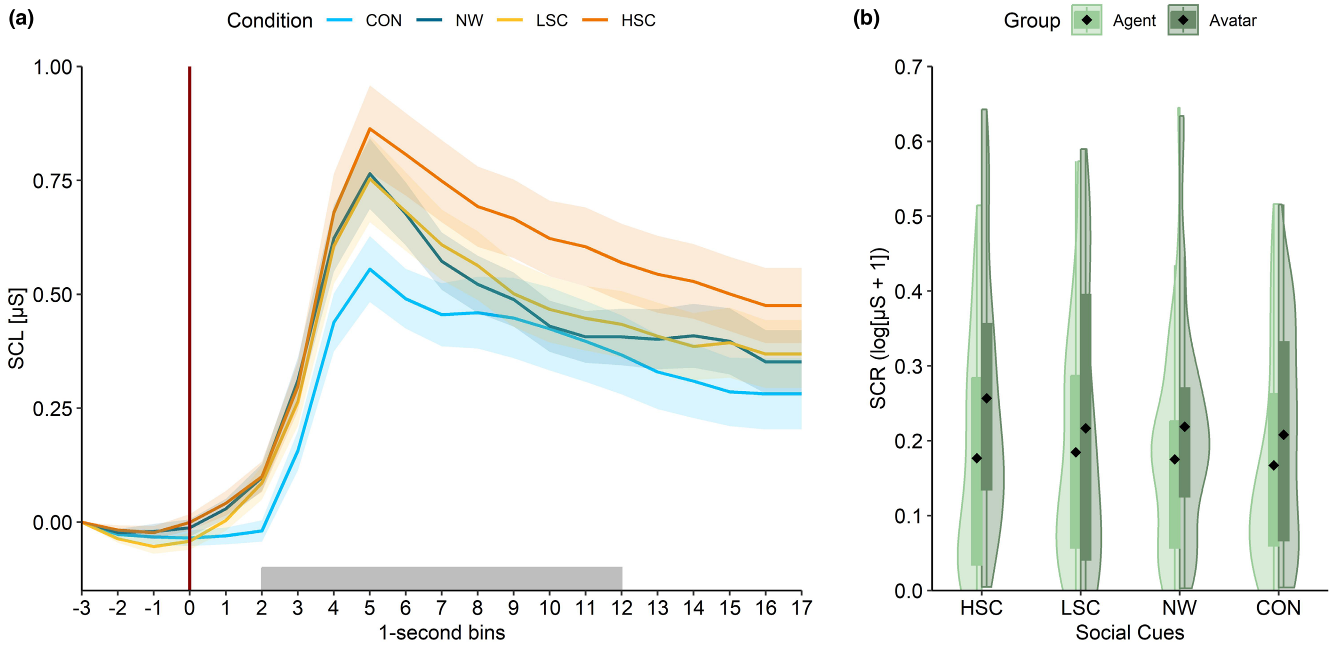


**FIGURE 3** Time course of skin conductance level (SCL; a) and skin conductance responses (SCR) per group and condition (b). (a) Analysed period was sec 0–18, red line depicts onset of pain stimulus, grey crossbars depict the plateau of heat pain stimulation. (b) Figure shows means (black squares), interquartile ranges (boxes) and data distributions (violins). CON, control condition; HSC, high social cue condition; LSC, low social cue condition; NW, neutral words condition.

### 3.1.3 | Heart rate

Analysis of HR revealed no significant effects of social cues, $F_{3,264}=0.13$, $p=0.944$, $\eta^2_G<0.01$, nor of agency group, $F_{1,88}=1.26$, $p=0.264$, $\eta^2_G<0.01$, nor a significant interaction between social cues and agency group, $F_{3,264}=0.49$, $p=0.690$, $\eta^2_G<0.01$.

## 3.2 | VR ratings

Analysis of the reported feeling of presence revealed a significant main effect of social cues, $F_{2.68,254.16}=19.55$, $p<0.001$, $\eta^2_G=0.03$, but no significant main effect of agency group, $F_{1,95}=0.09$, $p=0.759$, $\eta^2_G<0.01$, nor a significant interaction effect between social cues and agency group, $F_{2.68,254.16}=0.42$, $p=0.716$, $\eta^2_G<0.01$. Presence ratings were significantly higher in the high social cues ($M=67.23$, $SD=25.47$) compared to the low social cues ($M=60.67$, $SD=28.05$), $t_{96}=4.12$, $p_{bh}<0.001$, $d=0.42$, to the neutral words ($M=55.95$, $SD=27.09$), $t_{96}=5.47$, $p_{bh}<0.001$, $d=0.56$ and to the control condition ($M=54.69$, $SD=27.48$), $t_{96}=6.93$, $p_{bh}<0.001$, $d=0.70$. Also, there was a significantly higher feeling of presence in the low social cues compared to the neutral words, $t_{96}=2.41$, $p_{bh}=0.036$, $d=0.24$, and the control condition, $t_{96}=3.34$, $p_{bh}=0.004$, $d=0.34$. There were no significant differences in reported presence between the neutral words and control condition ($p_{bh}>0.438$).

Regarding the feeling of social presence, higher values represent a higher feeling of social presence, meaning a higher feeling of sharing the virtual environment with another being (Biocca et al., 2003). Social presence ratings yielded a main effect of social cues, $F_{1,95}=77.25$, $p<0.001$, $\eta^2_G=0.19$. No significant effects were found for agency group, $F_{1,95}=1.08$, $p=0.302$, $\eta^2_G<0.01$, nor the interaction between social cues and agency group, $F_{1,95}=0.02$, $p=0.903$, $\eta^2_G<0.01$. Post hoc *t*-test revealed a significantly higher feeling of social presence in the high social cues condition ($M=54.1$, $SD=20.66$) compared to the low social cues condition ($M=36.53$, $SD=20.02$), $t_{96}=8.84$, $p<0.001$, $d=0.90$ (see Figure S1).

## 3.3 | Manipulation checks

Regarding the social cue manipulation, we averaged the six items to one mean value for the perceived behaviour of the virtual counterpart. Higher values represent an overall more positive perception of the virtual counterpart. The overall perception of the virtual character was more positive in the high social cues condition ($M=77.73$, $SD=15.52$) compared to the low social cues condition ($M=61.23$, $SD=18.17$), $t_{96}=9.12$, $p<0.001$, $d=0.93$. In the post-study questionnaire, the virtual character was rated as more human in the high social cues condition ($M=61.59$, $SD=27.84$) compared to the low social cues condition ($M = 19.95$, $SD = 25.31$), $t_{96} = 12.79$, $p < 0.001$, $d = 1.30$, and more empathic in the high social cues condition ($M = 70.8$, $SD = 25.3$) than in the low social cues condition ($M = 37.13$, $SD = 33.87$), $t_{96} = 9.46$, $p < 0.001$, $d = 0.96$. Furthermore, the virtual character was rated as more realistic in the high social cues condition ($M = 56.76$, $SD = 25.73$) compared to the low social cues condition ($M = 34.14$, $SD = 30.05$), $t_{96} = 7.40$, $p < 0.001$, $d = 0.75$.

Regarding the agency manipulation, for the high social cues condition, participants descriptively indicated a higher feeling of human-control in the avatar group ($M = 60.52$, $SD = 33.16$) than in the agent group ($M = 48.24$, $SD = 32.78$); however, only a trend for significance was revealed, $t_{95} = -1.83$, $p = 0.070$, $d = -0.37$. For the low social cues condition, there was no significant difference between the two groups ($p_{Welch} = 0.267$). Again, descriptively, a stronger feeling of human control was reported in the avatar group ($M = 37.77$, $SD = 36.01$) compared to the agent group ($M = 30.29$, $SD = 29.68$). Participants did not report significant differences in being afraid that the virtual character could evaluate their behaviour in the two groups, $t_{95} = 0.65$, $p = 0.516$, $d = 0.13$ (see Figure S2).

### 3.4 | VR experience

Participants perceived the virtual scenario as moderately realistic ($M = 63.33$, $SD = 22.9$). There were no significant changes in negative affect in the STAI-state from before ($M = 33.31$, $SD = 7.25$) to after ($M = 32.54$, $SD = 7.77$) the VR experience, $t_{96} = 1.42$, $p = 0.158$, $d = 0.15$. Participants barely indicated cybersickness symptoms in the SSQ ($M = 26.06$, $SD = 26.92$) while being immersed in the virtual environment. In the post-study questionnaire, only eight participants reported discomfort in the virtual environment (e.g. headache, head pressure due to wearing the HMD, fatigue, mild nausea and dizziness).

### 3.5 | Further questionnaires

Results for the questionnaires STAI-trait, ECR-R12, BFI-10 and PCS can be found in Supporting Information (Table S2).

## 4 | DISCUSSION

Overall, the results of this study demonstrated a significant reduction in reported pain unpleasantness and pain intensity in the conditions with a supportive virtual character compared to the conditions without verbal support. This is in line with our hypotheses and replicates the findings of previous studies in real-world laboratory settings in which structured and positive verbal support led to analgesic effects (Brown et al., 2003; Roberts et al., 2015). Our study extends these findings and the results of a previous study investigating the effects of virtual social interactions on pain (Won et al., 2020) by showing that a technical system, more specifically supportive virtual characters, can have analgesic effects on self-reported pain. By demonstrating the potential of social virtual characters in the context of VR-based pain analgesia, this study is an important contribution to the heuristic model by Trost et al. (2021). In this model, social factors are one of the pain targets that have been understudied but may contribute to pain outcomes such as pain intensity. As an underlying mechanism in social pain modulation, it is discussed that social support serves as a safety signal that can reduce the perceived threat of a noxious stimulus and the environment (Krahé et al., 2013). This is in line with the *Social Baseline Theory*, which assumes that being in the company of others is a baseline condition in which the human body and brain are calmer and need less energy to process potential threats (Beckes & Coan, 2011). However, the effect of verbal social support on pain in the current VR study is smaller compared to most laboratory studies (Che et al., 2018; Roberts et al., 2015), indicating that the virtual character might not have been perceived as a supportive other to the same extent as a real human interaction partner.

Importantly, the results of the present study indicate that social support can be differentiated from merely auditory distraction, as participants did not report pain reduction when they heard neutral words. While previous studies examined distraction effects using reaction times to signal tones under different conditions (Master et al., 2009) or discussed distraction effects in the context of structured support versus unstructured social interactions (Brown et al., 2003), the present study extended the results of these studies by systematically comparing auditory input with a social versus a neutral content.

Contrary to our hypothesis, for psychophysiological responses, we could not find any analgesic effect of social support. This result contradicts the *Buffering Hypothesis*, which states that the presence of another person leads to a decrease in physiological activity during stressful events (Cohen & Wills, 1985). In animal models, this could be demonstrated in the hypothalamic–pituitary–adrenal (HPA) stress system (e.g. Sullivan & Perry, 2015). In humans, a buffering effect could be shown in immune responses (Cohen et al., 2015) and towards social stressors with cortisol as a marker of the HPA axis and autonomic responses such as heart rate (Ditzen et al., 2007). Few studies have investigated modulations of psychophysiological reactions to pain by verbal support. Some studies found lower SCRs with an overall small effect (Che et al., 2018). For example, previous studies reported lower SCRs to pain stimulation in conditions with observers compared to no observers (Sambo et al., 2010), while hand-holding (Reddan et al., 2020), or after a brief conversation with an in-group member compared to no or an out-group member (Platow et al., 2007). Regarding HR, there are inconsistent findings, with some studies reporting attenuation in supportive conditions (Roberts et al., 2015; Sambo et al., 2010), and other studies, as well as a recent meta-analysis finding no effects of social pain modulation (Che et al., 2018; McClelland & McCubbin, 2008).

Possibly, participants did not feel as being in the presence of another person to the degree they felt the presence of another person in previous laboratory studies. Ratings of humanness were low to moderate, and the type of interaction was less natural than with a real person. Furthermore, stimulation temperatures in the current study were lower compared to, for example, the study by Loggia et al. (2011), and pain ratings on average in a moderate range (Hawker et al., 2011). Hence, the buffering effect might be higher for stronger stressors. Because social support can influence the salience of pain stimuli (Krahé et al., 2013), participants might benefit particularly from social support if the pain is strong.

Regarding the SCL results of the current study, it has to be noted that social support or neutral words, respectively, were provided immediately before and throughout the whole pain stimulation phase. Our goal was to operationalize social support as a more holistic and naturalistic experience, that is, in real life, a person would support throughout the medical procedure, not just before it. However, a drawback of this approach is that psychophysiological responses to auditory input and pain cannot be disentangled. Although we analysed the physiological responses locked to the onset of the pain stimulus, psychophysiological responses are generally nonspecific and blend with other aspects of an experimental setting, such as novelty or habituation to a stimulus (Jamner & Tursky, 1987). Thus, skin conductance reflects a marker of general arousal (Hamm et al., 1993), independent of the hedonic value (Brouwer et al., 2013). Therefore, a possible explanation for our results could be an enhanced general arousal due to the auditory input compared to no auditory input.

Apart from investigating the potential of social factors in VR for pain modulation, another goal of the present study was to gain insights into which features of virtual characters are important for exerting social influence. A high number of social cues had a small but significantly stronger pain-reducing effect on pain unpleasantness compared to a low number of social cues. A different number of social cues did not lead to differences in pain intensity ratings. However, there is evidence that the pain affect is more sensitive to social influences on pain than the sensory pain component (López-Solà et al., 2018). It is also possible that the positive perception of the virtual human targeted more the affective rather than the sensory component of pain. In line with previous studies (Appel et al., 2012), participants perceived the virtual character in the high social cues condition as more positive, real and human than the virtual character in the low social cues condition and reported a higher feeling of social presence. Positive affect and a higher feeling of presence in VR are related to pain reduction (Hoffman et al., 2004; Sharar et al., 2016). Taken together, this suggests that a more human visual appearance of a virtual character has beneficial effects on pain perception.

For agency, we could find a trend for higher pain intensity ratings and SCRs in the avatar compared to the agent group. While some studies report attenuated stress responses following support by avatars compared to agents (Kothgassner et al., 2019), another study reports increased activity in SCRs but not SCLs during a game with avatars compared to agents (Lim & Reeves, 2010). Our findings related to social presence are consistent with other studies that also found no agency differences for social presence (Kothgassner et al., 2014, 2019). Kothgassner et al. (2019) suggest that the feeling of social presence is an automatic response. It is therefore conceivable that our participants did not distinguish between avatars and agents due to automaticity. Other studies could show beneficial effects of agents, questioning the importance of distinguishing between avatars and agents. For instance, that agents could lead to the same benefits of disclosure as humans (Ho et al., 2018) and to bonds comparable to therapeutic settings with humans (Beatty et al., 2022; Darcy et al., 2021). However, our nonsignificant results regarding agency have to be interpreted with caution, as the results of the agency manipulation check do not confirm that all participants believed in the manipulation.

Some limitations of the current study need to be addressed. For auditory input, we chose neutral words for a standardized control condition with less variability in word interpretation. However, the neutral words differed in valence from the social supportive content, which is more positive for the social support. For future studies, using whole sentences for the neutral input instead of single words or words with positive rather than neutral valence could be of interest to increase the comparability between the social and the neutral input. It has to be noted that both virtual characters were equipped with a human voice and therefore both presenting a social cue able to elicit social reactions (Nass et al., 1997). Thus, the difference in variation in social cues could have been more pronounced and could be one explanation why different social cues did not lead to large differences in pain responses. However, we wanted to overcome the limitations of previous studies which compared voices and text-based comments engaging different modalities (Appel et al., 2012). Considering the believability of the agency manipulation, we chose a human voice for both virtual characters. Future studies should consider a more pronounced differentiation in virtual characters, for example equipping the virtual character for a low social cues condition with a computer-based instead of a human voice. Also, the results of our agency manipulation checks indicate that it was only partially successful. Future studies should consider comparing the impact of social support by real persons to virtual characters and enhance the naturalism of the social interaction in the virtual environment, for example, via implementing a more individual conversation. In addition, future studies might vary the relationship closeness of the person supposedly controlling the avatar. Previous studies have shown that differences between agents and avatars in terms of the feeling of presence and engagement are more pronounced when the avatar is controlled by a friend rather than a stranger (Ravaja et al., 2006).

The current study addresses the gap in investigating the role of social factors in VR in the context of pain perception. Results of the present study revealed that virtual supportive characters have the potential to reduce pain perception, and their effects significantly differ from auditory input in a virtual environment. While the social influence of virtual characters exerted its effect independent of the perceived agency, social cues affected not only pain unpleasantness but also presence, indicating beneficial effects of a more human visual appearance on social pain modulation in VR. In line with another study (Sinha et al., 2022), this suggests that virtual humans could enhance engagement in digital health treatments, that is, a mobile app such as presented by Palermo et al. (2020). However, future research is needed to improve the humanness of virtual characters, for example, via social touch (Hoppe et al., 2020), and the naturalness of interaction with them. Given that VR has a huge potential as a non-pharmacological and cost-effective alternative for pain treatment (Pourmand et al., 2018; Trost et al., 2021), the current study is an important step in the investigation of social factors within VR-based pain analgesia.

## AUTHOR CONTRIBUTIONS

Isabel Neumann was involved in conceptualization, methodology, software, investigation, data curation, formal analysis, interpretation of data, writing—original draft, writing—review & editing, approval of the final version to be published. Marta Andreatta was involved in interpretation of data, writing—review & editing, approval of the final version to be published. Paul Pauli was involved in substantial contributions to conception and design of the article, interpretation of data, resources, writing—review & editing, approval of the final version to be published. Ivo Käthner was involved in conceptualization, methodology, interpretation of data, supervision, writing—original draft, writing—review & editing, approval of the final version to be published.

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## CONFLICT OF INTEREST STATEMENT

PP is a shareholder of a commercial company that develops virtual environment research systems (VTplus GmbH) for empirical studies in the field of psychology, psychiatry and psychotherapy. The remaining authors declare no conflict of interest.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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