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Exploring Virtual Reality and Doppelganger Avatars for the Treatment of Chronic Back Pain.

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“The desire to be rid of pain has only the pain as its object. This is shown by the fact that it doesn’t even require the idea of oneself *in order to make sense: if I lacked or lost the conception of myself as distinct from other possible or actual persons, I could still apprehend the badness of pain, immediately […]: ‘*This experience *ought not to go on,* whoever *is having it.’”*

Thomas Nagel (1986, p. 156)

CONTENTS

Page

LIST OF ABBREVIATIONS

1PP	first-person perspective
3PP	third-person perspective
AAQ	Autonomous Avatar Questionnaire
AAQmm	Autonomous Avatar Questionnaire (multi-media)
ACC	anterior cingulate cortex
ACME	average causal mediation effect (mediation analysis)
ADE	average direct effect (mediation analysis)
AIC	Akaike information criterion
AN	avatar number
ANOVA	analysis of variance
AR	augmented reality
a.u.	arbitrary units
AVA	doppelganger avatar group (experimental group in Study 2)
BB	bending backward (spinal extension)
BIC	Bayesian information criterion
BPD	borderline personality disorder
BS	bending sideward (lateral flexion of spine)
CAVE	cave automatic virtual environment
CBP	chronic back pain
CBT	cognitive-behavioral therapy
CI	confidence interval
CM	crate-moving
CN	cycle number

CR	conditioned response
CS	conditioned stimulus
deg.	degrees
df	degrees of freedom
DKB-35	Dresden Body Image Questionnaire (*Dresdner Körperbild-Fragebogen*)
DLPFC	dorsolateral prefrontal cortex
doi	digital object identifier
DTI	diffusion tensor imaging
EC	embodied cognition
EEG	electroencephalography
e.g.	for example
EMA	ecological momentary assessment
FABQ	Fear Avoidance Beliefs Questionnaire
FDR	false discovery rate
FFbH	Hannover Functional Ability Questionnaire (*Funktionsfragebogen Hannover*)
fMRI	functional magnetic resonance imaging
GBB-24	Gießen Subjective Complaints List (*Gießener Beschwerdebogen 24*)
GCP	Graded Chronic Pain Scale
IASP	International Association for the Study of Pain
ICC	intraclass correlation
ICD-11	International Classification of Diseases, eleventh revision
i.e.	that is
IPQ	iGroup Presence Questionnaire
IQR	interquartile range
IRI	Interpersonal Reactivity Index

LME	linear mixed effects
LMEM	linear mixed effects model
logLik	log-likelihood
ML	maximum likelihood
MPI	West Haven-Yale Multidimensional Pain Inventory
MR	mixed reality
MRI	magnetic resonance imaging
PAG	periaqueductal gray
PCA	principal component analysis
PFC	prefrontal cortex
PTSD	post-traumatic stress disorder
REML	restricted maximum likelihood
RH	rotation in the horizontal plane
ROM	range of motion
SD	standard deviation
SI	primary somatosensory cortex
STAI	State-Trait Anxiety Inventory
TPJ	temporo-parietal junction
TT	touching the toes (flexion of the spine)
US	unconditioned stimulus
VID	videotaped model group (control group in Study 2)
VR	virtual reality
XR	extended reality

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Pain carries with it an inescapable sense of corporeality. In its phenomenal appearance, it is one of the most intense bodily experiences humans are capable of. As such, it can distort the whole field of phenomenal experience, forcing the organism's attention towards itself. Cognitive processes and emotional states are deeply affected by pain. The phenomenal pain experience permeates the very medium of human interaction with the world, as philosopher Arne J. Vetlesen puts it:

> "*I am the pain in my body because I am that body.* And I cannot otherwise have a world, be in the world, in the manner characteristic of humans. […] My body is not an object. While I am able to leave all objects in the world, in the sense that I can influence and manipulate them, I cannot leave my body. It defines my being-in-the-world by determining and demarcating the standing point from which I at any time sense, think, feel and move around in the world. Where I am, my body is; where my body is, there am I."
>
> (Vetlesen, 2009, p. 53, emphasis original)

Conversely, pain itself is also shaped by the states and goals of the organism. Pain is characterized by an immediate bodily urge to end it by behavioral reactions, to either flee, fight, or avoid its cause. However, its burning and inescapable intensity in some cases but not others, and its surprising ineffectiveness to change behavior in situations of conflicting goals or competing sensory stimulation underline that context matters, even for pain. This transcends the concept of pain as a simple stimulus-response "alarm bell". Rather, the complex interplay between pain and affective, cognitive, and other somatic processes qualifies pain as a paramount example for a deeply embodied phenomenon: it is integrated in the causal "circularity of the embodied mind" (Fuchs, 2020), with overlapping and interloping feedback loops between perception, cognition, emotion, behavior and bodily processes shaping both its emergence and maintenance. As a deeply embodied experience of an inherently social animal, pain is formed by learning experiences, cultural templates, and social interactions, which all leave their traces in the plastic systems of brain and body. These play an especially important role in the self-sustaining dynamic process of pain that takes on a life of its own when transitioning into chronic pain. The latter phenomenon makes abundantly clear that dichotomous distinctions between somatic and psychological processes are superficial at best and cannot grasp the dynamic interplay of different levels of bodily processes.

With the development of virtual reality (VR), an inherently embodied design principle has been introduced into media technology: bodily movements during perception and action are captured and integrated into the dynamic adaptation of perspective on the computer-generated virtual world. Immersive VR technology simulates the sensorimotor contingencies between bodily movements and perceptual changes, as most paramount in the integration of head movements and shifts in visual perspective. This allows for a deeply felt presence in the virtual world. In the words of VR pioneer Jaron Lanier, these technologies implement a “substitution of the interface between a person and the physical environment with an interface to a simulated environment” by creating a “mirror image of a person’s sensory and motor organs” (Lanier, 2017, pp. 47-48). A vast variety of virtual environments and objects can thereby come into reach of embodied perception and interaction. Bodily illusions, which have already been known from real-world settings, can be amplified and extended. A user may be put in first-person perspective of a virtual body, a so-called avatar, feel touch on their own skin while visually observing another virtual body being touched, creating an illusion of twofold location. Another possible transformation of self-perception is the encounter with lookalike doppelgangers, which have long been explored in literary fiction and which can be summoned by VR setups today in a form of technological exaltation of imagination. With these possibilities, VR may create at least a glimpse into experiencing the world from another point of view than the own real-world body, and it can do so exactly because it is coupled right into the feedback loops of embodied perception. VR may arguably never overcome the most extreme forms of acute pain that throw the individual back right unto the concrete fact of their bodily existence. However, it may entrain and extend the plasticity and dynamic flexibility of the bodily self and its perception, and may thus induce alleviation of pain and its debilitating effects in a wide range of pain phenomena.

The experiments described in this thesis explore the inherently embodied technology of immersive virtual reality as a potential treatment tool for chronic back pain. They do so by employing virtual doppelgangers to elicit changes in motor behavior and cognitive-affective expectancies of pain and functional ability. In the following parts of the Introduction, we will first discuss chronic pain, its malleability by learning processes, and potential connections with existing VR technologies. The following chapter will describe the technological and computational methods that were used and developed for the experiments described here. These experiments, which investigated observational modeling of virtual doppelgangers as movement models, are discussed in the subsequent chapters. Study 1 investigated the role of model-observer similarity for different virtual characters as movement models in healthy participants. Study 2 compared pain expectancies, actual pain, and avoidance behavior in persons with chronic back pain who either observed videotaped movement models or their own virtual doppelgangers. The succeeding chapter unfolds a general discussion of our findings and closes with a short summary in the final chapter.

1.1 Chronic Pain

1.1.1 Biopsychosocial Models of Pain

Pain is a complex perceptual and experiential phenomenon. For a long time, the dominant model of pain, in both research and clinical treatment, was focused on bottom-up processes. In these approaches, pain was conceived of as a direct effect of sensory signals, which are elicited in the neural periphery of an organism and are transferred to the central nervous system for further post-processing. However, throughout the course of the last decades, unidirectional stimulus-response models of this type underwent considerable corrections and modifications. A milestone in this process was the *Gate Control Theory* by Melzack and Wall (1965). This theory allowed for an integration of empirical findings that “top-down” mechanisms in the central nervous system enhance or down-regulate the afferent “bottom-up” signal transmission on the level of the spinal cord. This was a decisive step towards the theoretical appreciation of feedback loops between central and peripheral neural regions within the nervous system (Li et al., 2019; Mansour et al., 2014).

Pain as a biological phenomenon is closely linked to behavior, and hence involved in and subject to intricate psychological mechanisms of behavioral control (Baliki & Apkarian, 2015; Flor, 2017; Flor et al., 1997). Psychological research on pain has focused on the important roles played by psychological factors in the perception and affective evaluation of pain such as attention, expectations, beliefs, emotional states, and environmental, biographical, and social context (Chandler, 2013; Flor & Turk, 1988; Naiditch et al., 2021; Snelgrove & Liossi, 2009). It has been shown that the different phenomenological aspects of pain experiences, especially sensory and affective (Beattie et al., 2004), are also accompanied by various distinctive streams of underlying neural processing (Oertel et al., 2008). In neuroimaging studies, especially those using functional magnetic resonance imaging (fMRI), this is reflected in functional diversification (Apkarian et al., 2005; Treede et al., 1999): it is possible to identify brain areas that are involved in the rather informative sensory processing of painful stimuli such as the primary somatosensory cortex (SI) and the temporo-parietal junction (TPJ). Other areas show stronger correlations with affective and emotional aspects of pain such as the anterior cingulate cortex (ACC) (Johansen et al., 2001). Some brain areas have been demonstrated to be involved in both aspects, such as the insular cortex (Lu et al., 2016). These functional distinctions are further supplemented by internal control mechanisms, among which the influence of prefrontal cortex on other brain areas and sub-cortical processes stands out (Ong et al., 2019), especially as it has been shown to link strongly to the periaqueductal gray (PAG), which plays an important role in pain modulation via the endogenous opioid system (Bagley & Ingram, 2020). These findings have been integrated in models of a cortical *pain matrix* (Lee et al., 2009; Legrain et al., 2011; Mouraux et al., 2011) or several diverse pain matrices (Garcia-Larrea & Bastuji, 2018), although the extent of specificity of pain versus other salient experiences is under debate (Talbot et al., 2019)

The pain experience arguably fulfills the function to motivate an animal organism to seek for immediate behavioral responses – to avoid, flee, terminate, or at least mitigate a cause of (potential) tissue damage, be it internal or external. This is reflected in the phenomenology of pain, which arguably cannot be conceived of without an accompanying perceived urge for it to end[1] (cf. the argumentations by Nagel (1986, pp. 156-162) Martínez (2011); Vetlesen (2009); contradicting Miyahara (2021)). Fittingly, the revised definition of pain issued by the International Association for the Study of Pain (IASP) defines pain as an "unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage" (Raja et al., 2020, p. 1978). Not in all cases, though, can the aversiveness of pain fulfill its biological function: one possibility here is that the organism may not be able to escape or overcome the pain-eliciting cause (such as in cancer pain); the other possibility is that pain, as a complex multi-level process, may decouple from its original cause and sustain itself in the absence of the former, as it appears to be the case in many chronic pain syndromes (Baliki & Apkarian, 2015; Baliki et al., 2006; Flor, 2012, 2017). In both cases, pain loses its adaptive value for the organism, and temporally well-defined episodes of *acute pain* transition into the permanent or recurrent burden of *chronic pain*. In chronic pain, the complex feedback loops involved in acute pain become even more important. These involve peripheral processes such as local nociception and inflammation, control loops originating in the central nervous system with their openness to psychological effects of expectations, emotional coloring, social interactions, and cultural imprint, and finally the overt behavior of the organism in response to and in anticipation of various reinforcers. As all these levels are shaped by past events, no pain phenomenon can be separated from the biological, psychological, and social learning history of the organism experiencing it. Rather, the complexity of overlapping feedback loops bringing about the present pain experience and plastically reflecting past experiences renders pain, and in particular chronic pain, a multi-dimensional phenomenon, which is the cornerstone of the *biopsychosocial*

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[1] This does not rule out that this urge may be overruled by other phenomenological aspects, as it is arguably the case in pain episodes that are actively pursued for cultural, social, sexual, or other reasons.

approaches in pain research and treatment (Kamper et al., 2015; Wippert & Wiebking, 2018).

1.1.2 Chronic Pain

To consider these interdependencies is especially important for *chronic primary pain*. Following the ICD-11 definition, primary chronic pain persists or recurs for more than three months, causes “significant emotional distress […] and/or functional disability”, and is characterized by symptoms that “are not better accounted for by another diagnosis” (Nicholas et al., 2019, p. 29). The latter contrasts to other forms of chronic pain that accompany illnesses such as rheumatic or tumor-related conditions, where an underlying somatic factor leads to a mechanistic treatment (cf. Treede et al., 2019).[2] Although the aforementioned feedback loops are important for these conditions as well, they have to carry a heavier explanatory weight for chronic primary pain conditions. For the latter, the present causes of pain persistence appear to lie in the dynamic interaction of biological, emotional, cognitive, behavioral and social processes. In this view, chronic primary pain is an example of a self-sustaining biopsychosocial process (Nicholas et al., 2019). On the one hand, this leads to complex difficulties in developing effective treatments for it. On the other hand, this provides pain research with a variety of possible “entry points”, i.e., different factors which can be addressed by a diversity of treatment approaches. For these reasons, the current best practice to treat primary pain syndromes consists of an interdisciplinary *multi-modal treatment approach* that recruits expertise from many different research fields and professions, such as anesthesia and pain medicine, psychotherapy such as cognitive-behavioral therapy (Flor & Turk, 2011), physio- and ergotherapy, nursing

[2] That is not to say that the medical and psychotherapeutic efforts to mitigate these types of pain are in any way straightforward and do not require the highest levels of expertise and compassion at the same time, as it is paramount in the palliative care setting.

science and other professions (for CBP, cf. Kamper et al., 2015; Wippert & Wiebking, 2018).

1.1.3 Chronic Back Pain

Chronic back pain (CBP) is usually defined as pain in parts of or the entire back which lasts for at least or has been re-occurring for more than three or six months until present (Balagué et al., 2012). It is widely prevalent and a main cause for lost workdays in industrialized countries (Guo et al., 1999). Chronic back pain thereby exerts a strong impact both on a personal (Froud et al., 2014) and a societal and economic level (Dutmer et al., 2019). Although CBP is often traceable to an initially causing event (e.g., an accident, surgery, or illness), the chronic phase is often characterized by a striking lack of explanatory power of somatic markers. For example, structural MRI studies have shown that identification of disc protrusions and extrusions is not sufficient to successfully predict whether a person suffers from chronic back pain (Ract et al., 2015). Accordingly, outcome measures of pain and quality of life show mixed results for surgical treatments of many CBP subgroups (Knezevic et al., 2021). Another common treatment approach to CBP is opioid medication, which, despite possible beneficial effects in short-term use, in many cases fails as an effective long-term treatment and is arguably relied on too heavily in clinical practice in many countries (Deyo et al., 2015). With its typical pattern of mutually enhancing tolerance development and increases in dose prescriptions, opioid treatment of back pain is a major contributing factor in the rise of opioid addictions in industrialized countries (Young et al., 2020).

One research strand on the development of chronic back pain focuses on identifying “yellow flags”, i.e., risk predictors in patients with acute (pain duration < 3 months) or sub-acute (pain duration of 3-6 months) back pain. This research aims at establishing stratified pain management treatments tailored to the patients’ risk profile (Hill et al., 2011). A variety of psycho-social predictors for the transition into chronic pain have been identified, among which are catastrophizing thoughts, fear avoidance beliefs, depression, anxiety, and socio-economic factors such as social status (Naiditch et al., 2021).

These aspects highlight the necessity not to neglect the psychological and social pillars of the biopsychosocial model of pain (Froud et al., 2014), even if the patients' own illness beliefs might rather focus on a purely biomedical model (Snelgrove & Liossi, 2009). These findings are in line with clinical evidence that treatments which take these learning factors into account, are among the most effective treatments of CBP, as has been shown for cognitive-behavioral therapy (CBT) and multi-modal treatments. The latter usually involve combinations of CBT, anesthetic intervention, and physical therapy, extending on findings that physical exercise interventions show beneficial effects in CBP (Searle et al., 2015). Nevertheless, success of current treatments mostly does not exceed moderate effect sizes (Balagué et al., 2012). These findings, together with the high prevalence in the population, render CBP a suitable "model case" for innovative treatment approaches to chronic pain syndromes in general. Therefore, in the following we will report findings for chronic back pain as examples for learning processes and mechanisms that play important roles in chronic pain in general (Turk & Flor, 2013).

1.2 Learning and Pain

Learning mechanisms in the broad sense refer to all kinds of plastic changes in behavioral patterns and biological structures based on external or internal stimulus contingencies they are exposed to (Schacter & Wagner, 2013; Sweatt, 2016). In the following overview, the different mechanisms of multi-level plasticity and their role in pain phenomena will be shortly discussed.

1.2.1 Physiological Plasticity

With respect to *physiological plasticity*, prominent mechanisms for single cells and nerve fibers are cellular sensitization (Carew et al., 1971) and cellular habituation (Pinsker et al., 1970), which describe an increase or decrease in neural excitability with time during continuous or reoccurring stimulation. A paramount example on the single-cell level is the Hebbian learning rule that connections between neurons that are active at the same time are strengthened. This results in increasingly correlated activity patterns, for example, via enhancement of synaptic transmission of signals (Hebb, 1949). Such mechanisms of neural plasticity, prominently long-term potentiation/ depression of postsynaptic signal transduction (Bliss & Lomo, 1973; Diering & Huganir, 2018; Volianskis et al., 2015) as well as dendritic spine growth (Kasai et al., 2010; Knott & Holtmaat, 2008), add to the constant plastic reorganization of complex neural systems (Ho et al., 2011). These low-level mechanisms provide a basis for the emergence of a dynamic functional organization of larger-scale brain structures (Monday et al., 2018). Here, plastic changes in response to earlier activity and stimulation could be shown for structural connectivity. The latter term refers to fiber connections between brain regions, as indirectly measurable with diffusion tensor imaging (DTI) (e.g., Blumenfeld-Katzir et al., 2011), and functional connectivity in terms of concurrent simultaneous neural activity of brain regions, as indicated by correlated metabolic activity measured with resting-state functional magnetic resonance imaging (fMRI) (e.g., Sampaio-Baptista et al., 2015).

All these mechanisms play a role in acute pain, in its transition into the chronic state, and in the perseverance of the latter. Already on the physiological level, nociceptive fibers show sensitization, and learning in the broad sense is involved in acute and chronic pain, as for example long-term potentiation of nociceptive signal transduction on the spinal and cortical level (Li et al., 2019). Based on physiological, imaging-based and behavioral findings, Baliki and Apkarian (2015) integrate the different levels of peripheral sensitization, central sensitization (spinal-cord-level), mesolimbic plasticity, cortical reorganization and learning into an account of pain plasticity, be it adaptive or maladaptive for the organism. They specifically highlight the significance of these processes for the transition from acute to chronic pain, in accordance with the high predictive power of corticostriatal functional connectivity for the development of chronic from recent acute pain states (Baliki & Apkarian, 2015). Given the short- and long-term plasticity and behavioral relevance of pain, functional similarities to other affective mechanisms involving aversive learning such as depression or anxiety can be identified (Baliki & Apkarian, 2015). This matches well with the role of emotional processing related to corticolimbic structures reported for chronic pain conditions (Vachon-Presseau et al., 2016). It has been argued that the transition from acute to chronic pain is marked by a shift from a mainly somatosensory to a predominantly affective-emotional character in processing, accompanied by changes in brain structures involved in motivational and emotional processes (Mansour et al., 2014). This is even reflected by differential processing of externally inflicted acute pain and spontaneous increases in chronic pain within the same individuals (Baliki et al., 2006).

Plasticity of these changes goes both ways, however, with effective treatments of chronic pain reversing accompanying structural and functional changes in brain circuits, as has been demonstrated for chronic low back pain (Seminowicz et al., 2011). An interesting example of relevance for our study are *changes in cortical body representation*, which have been found for a variety of chronic pain conditions (Bekrater-Bodmann et al., 2015; Foell et al., 2014; Haggard et al., 2013; Lewis et al., 2007; Lotze & Moseley, 2007; Moseley & Flor, 2012; Moseley et al., 2012; Tsay et al., 2015). Most prominently, in phantom limb pain, the somatotopic representation of the phantom has been shown to overlap with neighboring areas of unaffected body parts in SI (Foell et al., 2014). Changes in body representation have also been found for chronic back pain patients both on a cortical (Flor et al., 1997), and a cognitive-behavioral level, with patients reporting distorted body images with respect to the affected regions of their back (Moseley, 2008).

1.2.2 Respondent and Operant Conditioning

Respondent (classical) conditioning (Pavlov, 1927) enables an association of behavioral reactions to specific sensory stimuli, the so-called unconditioned stimuli (US), to other sensory signals, the so-called conditioned stimuli (CS): a behaviorally irrelevant sensory signal can develop into a conditioned stimulus that elicits an appetitive or aversive/ avoidant response when it has been repeatedly paired with an US, even in subsequent absence of the latter. Pain stimuli, due to their high behavioral significance described above, are an especially important type of aversive US that triggers strong avoidant and defensive responses. After the acquisition phase, the CS can evoke the newly conditioned response (CR) on its own. Reversely, if the CS is repeatedly present without reinforcement by the US, the former may lose its response-eliciting power again in the process of *extinction*. The potential recovery of the conditioned response if the US-CS contingency returns in a renewal phase indicates that extinction can be based on a *new* learning process of active inhibition of a latent response, rather than a mere fading of the link between CS and CR (Myers & Davis, 2007).

In *operant conditioning* (Skinner, 1938), the expression frequency of behavioral patterns, so-called operants, is increased or decreased by rewards (active reinforcers) or aversive consequences (negative reinforcers). Over time, reinforcement of a set of behaviors may also lead to the formation of new compositions of behavior, thus enabling skill learning (Siedentop & Rushall, 1972). All kinds of behavior can come under control of operant conditioning, ranging from verbal reports and questionnaire responses, over facial expressions and bodily motor patterns, to stable interpersonal behavioral patterns.

The different mechanisms of learning play an important role in the transition into chronic pain, with a strong emphasis on implicit and non-declarative mechanisms of which subjects are not aware (Flor, 2012). Pain is a strong negative reinforcer of operants. The interdependence of learning mechanisms is highlighted by an example from an operant conditioning paradigm (Becker et al., 2008), in which participants tried to adjust a painful heat stimulus to a formerly experienced level; the setup reinforced underestimation by automatically lowering the painful heat stimulus if participants' estimate was below the actual strength of the previously applied pain stimulus. After repeated application of this reinforcement schedule, participants showed a systematically decreasing level of manually selected temperatures while at the same time they reported a constant pain level. Thus, this demonstrated an effect of operant conditioning on pain perception in terms of sensitization which the subjects were not aware of (Becker et al., 2008). This fits well with other findings which suggest that the transition into chronic pain is accompanied by overt motor behavior coming under control of pain as a powerful reinforcer (van Dieën et al., 2017). This is prominent in avoidance behavior with respect to everyday movements, which has been shown in several pain conditions. In an analogy to clinical conditions involving extreme fear, the fear of movement is often also called “kinesiophobia” and appears to predict measures of disability, pain severity and quality of life, although the limited evidence calls for more longitudinal research in this respect (Luque-Suarez et al., 2019). It has been argued that in primary pain conditions, avoidance of painful movements, although initially adaptive to evade further injury, comes under control by pain detached from its initial pathogenic source, which is no longer detectable in these conditions. In these cases, punishment of bodily activity by concurrent pain due to aching muscles and musculoskeletal tensions in body parts after long periods of inactivity might have been accompanied by negative reinforcement of movement avoidance via pain relief. In a vicious circle, increasing motor avoidance will then worsen the secondary pain reactions due to prolonged hypoactivity of the musculoskeletal system and further contribute to the perseverance of pain (van Dieën et al., 2017; Vlaeyen et al., 1995; Vlaeyen & Linton, 2000).

Social reactions to behavior are also powerful positive or negative reinforcers (Fordyce, 1976; Gatzounis et al., 2012). One example is pain behavior, for example, moaning, refusing to accomplish specific tasks, expressly protective body posture, facial expression of ache (Flor & Heimerdinger, 1992) that can be reinforced by helping and solicitous reactions of others, as has been shown in fibromyalgia (Thieme et al., 2005).

1.2.3 Cognitive and Affective Factors

Another important level of learning in humans is on the *cognitive level*, in the acquisition of skills, expectancies and fears, and the formation of consciously retrievable and verbally communicable (explicit) knowledge and beliefs (Premack, 2007). All these factors are influenced by cognitive, affective and motivational states of the subject, and exert effects on these states in reverse (e.g., Grahek et al., 2020). Thereby, they play an important role in learning, with cognitive variables even playing into processes of respondent and operant conditioning (Kirsch et al., 2004).

Closely related to operant conditioning of avoidance behaviors is the formation of accompanying negative *expectancies*. Given the importance of beliefs for the regulation of behavior, the development of pain-related expectancies can influence pain behavior. Expectancies as cognitive mediators of avoidance have been shown in experiments with healthy participants (Lovibond et al., 2007), allowing for laboratory models of their role in clinical pain: not only do experiences of pain in the context of specific activities add to the negative operant reinforcement of the latter, but they may also be integrated into a firmly held cognitive belief that the according activity is indeed harmful and therefore *should* be avoided. This pattern is described by the *Fear Avoidance Model* (Lethem et al., 1983; Vlaeyen & Linton, 2000), which explains the maintenance of chronic pain as part of a vicious cycle of fear of pain, avoidance behavior, and resulting interference with daily activities and the development of negative affect, which feeds back into an amplification and continuation of pain (Vlaeyen et al., 2016). The fear avoidance model is closely linked to fear of movement and movement avoidance in musculoskeletal pain (Leeuw et al., 2007; Luque-Suarez et al., 2019). Disuse and deconditioning are discussed as important maladaptive effects of fear avoidance (Crombez et al., 2012; Valdivieso et al., 2018). However, the respective evidence is not conclusive (Verbunt et al., 2003; Verbunt et al., 2010) and other forms of defensive behavior (Pittig et al., 2020) besides complete avoidance of specific movements (Volders et al., 2015) are assumed to play an important role as well, such as safety-seeking behaviors in the form of guarded movements (Tang et al., 2007) and decreased movement variability (van Dieën et al., 2017). Nevertheless, the important role of fear avoidance beliefs in starting the described vicious circle (Pfingsten et al., 2000; Pittig et al., 2020; Waddell et al., 1993) emphasizes the conjunction of cognitions and motivational states. This links to the role of broader emotional states such as anxiety and depression, which influence cognitive evaluation of experiences and which are often better prognostic predictors of chronic pain than somatic markers (Flor & Turk, 1988).

Not only do expectancies and accompanying emotional states influence pain behavior, but they also shape the phenomenal pain experience itself. This has been made clear by research into *placebo effects*: The mere expectancy to receive an effective treatment for pain relief can suffice to elicit exactly this pain relief, even in the absence of the alleged treatment, for example, when a pill without active substance is administered (Colloca et al., 2013; Klinger, Kothe, et al., 2017). The *nocebo effect* describes the opposite mechanism of experiencing adverse effects of a treatment or action by the mere belief that these will arise (Klinger, Blasini, et al., 2017). Both effects are strongly dependent on social context and situational factors (Koban et al., 2017; Schmitz et al., 2019), although other mechanisms such as classical conditioning also contribute to it (Bąbel, 2019). Placebo effects provide a powerful illustration of cognitive "top-down" influences on pain perception (Eippert et al., 2009). In chronic pain, nocebo effects of all sorts (e.g., with respect to specific situations, movements, or other practices) can be evoked by fearful expectancies and for their part then stabilize the latter by further adding experiential episodes to underpin them, in a kind of "self-fulfilling prophecy". In contrast, placebo effects with respect to avoidance behaviors or medication can increase pain relief connected to these behaviors, and further increase the reliance on these commonly maladaptive coping strategies. However, placebo effects can also be a tool in effective treatment strategies in chronic pain (Klinger, Kothe, et al., 2017). Similarly, effects of expectancies on pain tolerance have been shown for self-efficacy (Bandura, 1977) and control beliefs, both in experimental (Litt, 1988) and chronic pain (Council et al., 1988). They are also closely related to the trait of pain resilience (Palit et al., 2020; Slepian et al., 2016), i.e., the ability to keep interference of pain with valued activities low. Taken together, all these observations highlight the need for comprehensive treatment approaches to target illness beliefs, expectancies, and emotional processing. Their close connection to behavioral patterns render them a fruitful entry point for interventions, such as in the biobehavioral treatment approach (Flor & Turk, 2011), which extends and tailors existing CBT techniques to the needs of patients in chronic pain.

1.2.4 Observational Modeling and Social Learning

In *social learning* (i.e., learning from others), cognitive processing enables an animal to learn from others' behaviors and vicarious experiences (Bandura & Walters, 1977).

This is achieved by either consciously directing one’s attention to learn new skills, or by implicit adoption of behavioral reactions without the subject’s own awareness.

Social learning has been argued to be closely linked to *observational modeling* in general (Fryling et al., 2011; Greer et al., 2006; Ramsey et al., 2021). This term comprises the different ways in which observation of other person’s actions and experienced consequences are generalized and thereby shape own expectations, beliefs, and behavioral patterns. This results either in adaptations of overt behavior expression, or in the acquisition of new latent behavioral dispositions, waiting to be activated under suitable circumstances. Arguably the most basic instance of observational modeling are imitative tendencies displayed without the subjects’ awareness, which arise early in infancy (Tomasello, 2020). Imitation may remain non-conscious but can be enhanced by attentional and volitional processes (Bek et al., 2016; Bisio et al., 2010). It has been argued that motor imitation nevertheless requires cognitive processing beyond mere stimulus-response linking, as the translation from observed to own behavior already requires computationally complex switches of perspective and pattern recognition to achieve a congruent alignment of different body-centered reference frames, i.e., from a body observed in third-person perspective onto the own body experienced in first-person perspective (Hamilton, 2015; Zentall, 2006).

Imitative tendencies have been found to be facilitated both by a perceived social-emotional affiliation with the model or a desire to establish such an affiliation, in the *chameleon effect* (Chartrand & Bargh, 1999; Lakin et al., 2003). Although this effect itself is implicit, such imitative tendencies can be mediated by processes accessible to self-report. In these cases, only the link to their own imitative behavior escapes the observers’ subjective awareness. Among such imitation-enhancing factors are identification with the model and a desire to affiliate (as in the chameleon effect), as well as perceived self-similarity of the model, the so-called *model-observer similarity* (Dove & McReynolds, 1972; Rosekrans, 1967).

For social learning in general, i.e., the acquisition of behaviors and cognitive-affective attitudes (e.g., appetitive or aversive reactions and beliefs), there is clear evidence for the interaction between cognitive, affective, motivational and behavioral factors (Bandura, 1986; Carcea & Froemke, 2019; Fryling et al., 2011; Greer et al., 2006). In analogy to operant conditioning, observational acquisition of behavioral patterns is strongly enhanced by observation of *vicarious reinforcement* (Bandura, 1965; Bandura & Barab, 1971). The influence of social affiliation and model-observer similarity, as demonstrated for pure imitation, can also be found in *observational learning of expectancies, behavioral patterns, and new skills* in general (Andsager et al., 2006; Braaksma, 2002; Stotland et al., 1961).

Pain beliefs and expectations are thus considerably shaped by *vicarious experience* of others which is either directly observed or explicitly-verbally reported in narratives of others. This lays the ground for the so-called *observational placebo effect* (Colloca & Benedetti, 2009): causes which are observed to induce analgesia in others can shape expectancies of observers and hence elicit pain relief by placebo effects. This is in line with the broader phenomenon of observational modeling as described above. As such, the observational placebo effect has been linked to other forms of observational modeling such as imitation, both on a neural and on a behavioral level (Bajcar & Bąbel, 2018). In analogy to the role of non-vicarious placebo and nocebo effects in pain chronicity, observational modeling of others' pain expectancies and behavior have also been found to play a role in the formation and perseverance of chronic pain (Goubert et al., 2011). This highlights the necessity for therapeutic interventions to take the cultural illness beliefs and social environments into account.

There are also mechanisms of *cultural learning* that go beyond mere observational modeling and that have been found only in humans so far (Tomasello, 2016, 2019): exemplary demonstrations employing willful attraction of the observer's attention, explicit verbal instruction, and dialogical discourse. These mechanisms can facilitate behavioral changes that interact with and influence all the other levels of plasticity described above. One example for this top-down influence on cognitive, affective, motivational, and behavioral factors is the client-therapist interaction in psychotherapeutic treatment and cognitive-behavioral interventions such as explicit psychoeducation (e.g., Tursi et al., 2013; Xia et al., 2011), including cognitive behavioral therapy in chronic pain (Flor & Turk, 2011).

These mechanisms of observational modeling are *promising therapeutic targets for CBT approaches based on VR methods*. Current VR systems mainly address the remote senses of vision and hearing. Therefore, they are especially suited for setups in which remote observation from a third-person perspective (3PP) is implemented for observational modeling. Nevertheless, VR experiments may also address other levels of plasticity described in the preceding sections, as, for example, in improving affective states by providing enjoyable virtual environments. Changes in body perception are also an interesting target, which can be evoked by first-person perspectives (1PP) on virtual characters, i.e., the embodiment of avatars. Virtual doppelgangers may function as a bridge between such diverse mechanisms. In the following, we will shortly describe the main functional principles of VR as an embodied medium and how this relates to treatment approaches in chronic back pain.

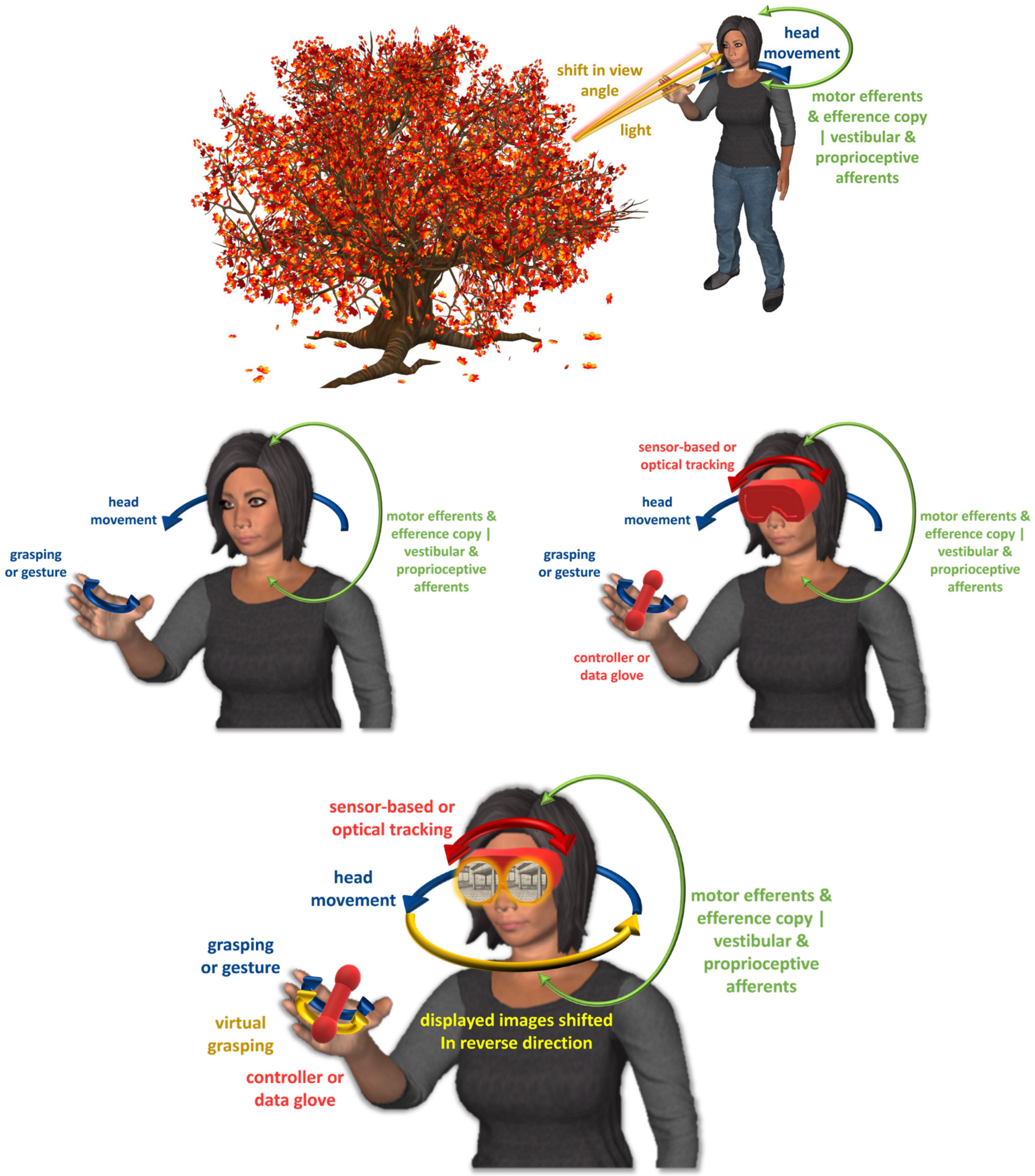


Figure 1. Schematic illustration of the functional principles of virtual reality (VR).

Displayed are the real-world interdependencies between motor behavior, geometric perspectival changes and sensory perception for a head-mounted display (HMD). **Upper panel:** The predictive brain creates predictive models of future sensory input based on self-induced motor commands and sensory afferent input, and thus sustains perceived spatial constancy and object permanence despite changing sensory input. **Middle panel:** This defines the biological requirements (**left**) for VR technology (**right**) to sense bodily movements and close these feedback loops artificially. **Lower panel:** VR technology captures bodily movements provides the brain with the changes in visual and haptic feedback from virtual objects. Based on its own motor commands, it can hence evoke the perceived reality of said objects. In this, VR extends earlier medial techniques to consider visual first-person perspective: The geometrical method of rendering the 2d images on visual display with the vanishing point method has not changed since it was adopted in Renaissance arts (although VR technology usually adds a parallax between the images, to account for stereoscopy, and minor adaptations in projective geometry to compensate for HMD optics).
Source: Own illustration. The virtual character was designed with *Adobe Fuse CC* and postured with *Autodesk MotionBuilder*. The sketch displayed inside the HMD is based on a work by Dutch artist Hans Vredemann de Vries (1605), available under a creative commons license on https://commons.wikimedia.org/wiki/File:Fotothek_df_tg_ 0007075_Architektur_%5E_Geometrie_%5E_Perspektive_%5E_S%C3%A4ule.jpg.

1.3 Virtual Reality

In the broad sense, the concept of “virtual realities” encompasses all computer-based simulations of environments which can be explored in an interactive fashion. Thus, desktop-computer games allowing for virtual navigation can fall under this term as well as smartphone games that engage the user in virtual world building. Closely related is the term of *extended realities* (XR) that refers to simulations which simultaneously mix virtual and real-world content. XR applications span a continuous spectrum that reaches from *augmented reality* (AR) with single virtual objects embedded in real-world environments (e.g., in real-time video representations on a smartphone screen) over *augmented virtuality* (AV) that embeds specific real-world objects in elaborate virtual environments (e.g., via projecting the shape or visual appearance of real-world entities) to *virtual reality* (VR), which completely reorients users’ attention from the physical towards a virtual world (Milgram & Kishino, 1994; Wienrich et al., 2021). These simulations vary considerably in the degree of *immersion* achieved by their technological implementation, i.e., their capability to fully draw in the users’ sensory attention and motivational engagement. AR and AV can be subsumed under the concept of *mixed reality* and contrasted against fully *immersive VR*, although this distinction is rather gradual.

1.3.1 VR and Embodiment

In literature on virtual reality, an ambiguity in terminology has to be considered. In the broad sense of VR, computer-based simulations in general are conceptualized under this term. This can include small screen presentation of virtual environments, such as on desktop computers or smartphones, as well as large screens or high-immersion setups, such as head-mounted displays (HMD). In the narrow sense, however, VR only refers to the latter, highly immersive technologies. Fully immersive VR differs from screen-based applications in that it tracks the user’s own head movements to adapt their virtual-world position in real-time, and thereby creates a strong illusion of the virtual world seemingly surrounding the user, the so-called *place illusion*. This can then evoke a genuine feeling of “being there”, the so-called sense of *presence* (Coelho et al., 2006; Slater & Usoh, 1993), which is also increased by the *plausibility illusion* with respect to the consistency and coherence of the simulated world (Slater, 2009). This makes the VR technology more intuitive for naïve users than desktop-based games, and at the same time strongly increases place and plausibility illusion, and hence the sense of presence.

Virtual reality is an inherently embodied technology (Riva et al., 2019). In VR setups, the tracking and display technology has to match the *neural mechanisms for spatial constancy* in motor-driven perception which the brain uses to predict changes in sensory input following self-induced movements (see Figure 1). These mechanisms are extremely accurate and rely on different streams of processing, both of efferent signals of neural motor commands as well as proprioceptive and vestibular information about head movements (Medendorp, 2011). If spatial constancy is not successfully simulated on all sensory levels, a break to the illusion or nausea and motion sickness can occur. Visual information is usually presented via helmet-like HMDs with embedded inertial sensors of acceleration and rotation, or with canvas projections viewed through stereoscopic shutter glasses which are tracked with optical camera systems, like in Cave Automatic Environments (CAVE). Stereophonic and haptic stimulation can further increase immersion, for example, by using vibrational feedback for touch of virtual objects applied by specialized gloves.

Clinical and experimental research has shown a surprisingly elastic perception of one's own body and self-concept. Most prominently, this becomes clear in illusions of embodiment: starting with the famous rubber hand (Botvinick & Cohen, 1998) there has been found illusory embodiment of mannequin bodies (Pomes & Slater, 2013) and of puppet faces, the latter realizing the special case of enfacement (Tajadura-Jiménez et al., 2012). Virtual reality setups can further explore the flexibility of body representation by embodiment of virtual limbs (Slater et al., 2008) or virtual characters, so-called avatars (Slater et al., 2009). To elicit embodiment reliably, it has been shown that 1PP in contrast to 3PP on the virtual body is a main facilitating factor (Petkova et al., 2011) as are congruent visuotactile stimulation of virtual and real-world body (Maselli & Slater, 2013), and the possibility to control the virtual body's movements

(Pomes & Slater, 2013). Hence, the current understanding is that embodiment depends on three contributing, but partially independent mechanisms, which are the *sense of colocation* with the virtual body, the *sense of ownership* for it, and the *sense of agency* with respect to its movements (Kilteni et al., 2012).

1.3.2 Virtual Reality in Pain Rehabilitation

With its inherent potential to interact with body perception and movements, VR technology is a promising tool to develop new treatment approaches in pain. Early approaches of VR application have been focused on distraction mechanisms in acute pain, such as in the pioneering HMD-based application “Snow World” for treatment of acute burn pain (Hoffman et al., 2000). Even these early approaches, however, already aimed at entraining additional mechanisms than mere *distraction* by an engaging VR game, as illustrated by the deliberate choice to present an icy virtual environment to distract from “hot”, burning pain (Hoffman et al., 2011). In line with these early tendencies, recent research on VR-based pain interventions has extended beyond distraction to exposure and CBT techniques (Gupta et al., 2018). Many of these techniques can benefit from implementation in VR. An example is VR-based mindfulness training to reduce stress, anxiety, and pain (Igna et al., 2014). Current approaches use VR setups with *gamification* elements to motivate chronic pain patients to move, thereby setting out an exposure situation to treat kinesiophobia (Hennessy et al., 2020).

The common co-occurrence of chronic pain syndromes and altered body representation provides VR interventions with an additional target (Matamala-Gomez, Diaz Gonzalez, et al., 2019; Matamala-Gomez, Donegan, et al., 2019; Riva et al., 2019). Already in experiments with visual display of participants’ real body, the visual input can function as analgesic (Löffler et al., 2017; Longo et al., 2009). The additional possibility to change the visual appearance of a virtual body in terms of color, shape and other characteristics allows for investigations of how this influences pain in acutely painful situations in healthy participants and in chronic pain. The most striking example of this is the VR extension of mirror therapy in phantom limb pain (Diers et al., 2015;

Murray et al., 2007), with amputees learning to control a virtual limb collocated with their perceived phantom limb, which has been shown to provide an effective treatment in some patients (Ramachandran & Rogers-Ramachandran, 1996). These lines of research can be extended to fibromyalgia (Garcia-Palacios et al., 2015; Ramachandran & Seckel, 2010) and other pain syndromes (Won & Collins, 2012).

1.3.3 Virtual Reality in Back Pain Treatment

As just described, VR can potentially target both changes in body representation *and* fearful expectancies and following maladaptive changes in behavior by playfully exposing to more adaptive behavioral patterns (such as movement exercises). As a common pain condition, chronic back pain is no exception from the research efforts in VR and pain described above. The specific mechanisms targeted are the same as in other research areas. The few studies using immersive VR in CBP usually try to engage the motivation of participants in movement games with awarding rewards and other gamification elements, thus aiming at an indirect treatment of kinesiophobia by exposing participants to the fearful movements (Hennessy et al., 2020). Findings on CBP-related changes in body image in non-VR studies have also been adapted to VR sessions (Alemanno et al., 2019).

In a recent systematic review, Bordeleau et al. (2022) found VR treatments described in the literature to be effective with respect to pain intensity and functional measures such as motion (Bordeleau et al., 2022). However, the authors advise caution with respect to bold claims due to the small number of studies (N = 24) and various types of bias risk they identified. They distinguish four different candidate mechanisms via which VR might alleviate pain: *distraction*, “*illusion of time acceleration*” by engaging working memory, *changes in body image by manipulations of body perception*, and motivation by *gamification* in VR-supported physical exercise (Bordeleau et al., 2022). Although the literature search also included mixed reality setups, only VR experiments in the strict sense were found. A majority (71%) of studies involved physical exercises, but other methods such as hippotherapy and motor imagery were also included, making the approach heterogeneous. In 16 of the 24 studies, the criteria for a randomized controlled trial (RCTs) were met.

With respect to the levels of immersion in VR studies on back pain, the results by Bordeleau et al. (2022) are rather surprising. The authors applied a broad-term definition of VR in their literature selection and they classified the included studies by levels of immersion. Only two of these studies, which were both not classified as RCT, were performed using *highly immersive* display technology, in these cases HMDs (Hennessy et al., 2020; Igna et al., 2014). Four studies achieved only low immersion with small 2d screens such as tablets, and the other ten studies relied on “moderate” immersion technology, such as television screens. The authors themselves did not further differentiate the latter moderately immersive technologies. However, a generous categorization can classify three studies in this group as “close to high immersion”, as they used 2d screens considerably larger than usual television screens (Alemanno et al., 2019; France & Thomas, 2018; Jansen-Kosterink et al., 2013). Nevertheless, this still leaves the field of VR applications in CBP with only five studies with rather high levels of immersion. A narrative review on the same topic by Tack (2021) did not identify additional high-immersion studies.

1.3.4 Research Gaps in VR-Based Treatments of Back Pain

These findings suggest that research in VR applications for treatment of CBP deserve further attention. Only a few studies so far have used *fully immersive VR* in movement exercise setups designed to address fear of movement and avoidance. Our experiments fill a research gap in this respect, as they employ a fully immersive virtual reality environment but also involve interaction with real-world objects such as a crate with water bottles.

With this setup, we also explore a novel *potential mechanism for VR treatment of CBP*, specifically, the possibility to present a technology-enhanced version of *high-identification vicarious learning* pushed by *maximized model-observer similarity*. Vicarious reward has been shown to motivate exercise behavior in healthy observers of virtual characters, who were facial doppelgangers of participants and experienced weight loss after simulated exercise (Fox & Bailenson, 2009). In the current studies, we explore an *observational modeling setup without explicit reward*, both *in healthy participants* and *persons with chronic back pain*. Thereby, we add a novel variant to VR treatment for chronic pain.

1.4 Concepts of Empirical Studies

We hypothesized that in chronic back pain, 3PP observation of a personalized doppelganger avatar who would perform trunk movements without display of pain, would reduce pain expectancy and avoidance and thus stimulate motor engagement in an intuitive manner even without direct positive reinforcement.

The supposed mechanisms at play can be several: (1) a chameleon effect of implicitly enhanced imitation, both in healthy observers and in those with chronic back pain; (2) non-vicarious fear extinction; (3) vicarious fear reduction; and (4) an observational placebo effect. These phenomena are closely related and will be shortly described in the following.

1. **Chameleon effect:** A generic mechanism independent of pain would be a *chameleon effect* of an involuntary increase of imitation by identification. We assumed that virtual doppelgangers, maximizing model-observer similarity, would enhance engagement in voluntary motor imitation of intuitive movements, thus eliciting a form of chameleon effect. It was hypothesized to be mediated by processes accessible to self-report. Among these are self-reported identification and similarity with and liking of the movement model.

This phenomenon was in the focus of Study 1, which was designed as a within-subject experiment that featured different virtual characters as movement models, with varying degrees of realism and similarity to the observers.

The other assumed mechanisms are overlapping and specific for chronic back pain.

2. **Non-vicarious fear extinction:** Extreme levels of identification could lead to *non-vicarious extinction of conditioned fear of movements*. Observing virtual

doppelgangers who performed potentially painful movements without any signs of avoidance, pain or effort could influence observers' expectancies and behaviors. For high identification with the doppelganger and if they are perceived as the own body's duplicate, the displayed painlessness in movements could extinguish conditioned fear of these movements in participants themselves: the absence of punishment, such as pain attacks following the movements, would thereby decrease pain expectancy and concurrent avoidance behavior.

3. **Vicarious fear reduction:** Another supposed mechanism was *fear reduction by vicarious experience*. In this case, own pain expectancies would be shaped by observing the virtual character and how it experienced no adverse effects from the movements. The hypothesis was that this observation would elicit a reduction of fear of movements from vicarious experience.

4. **Observational placebo:** With respect to pain experience itself, virtual doppelgangers were also hypothesized to evoke an *observational placebo effect* in participants with chronic back pain. It was assumed that it would be amplified by the high model-observer similarity.

Experimental differentiation of these three mechanisms is challenging. They would all lead to reductions in fear and avoidance. The latter would show up as stronger motor engagement.

One potentially differentiating factor for observational placebo effects would be that these could occur without an explicitly reported reduction of fear. This is because placebo effects in general can be at work without subjects' awareness. However, if a fear reduction would be present, this would also increase placebo-based pain reduction. In this case, observational placebo effects would be indistinguishable from fear reduction effects on avoidance behavior. However, observational placebo could still be identified by post-hoc self-reports on how painful the movements were.

The discrimination of non-vicarious fear extinction from vicarious fear reduction was assumed to be a rather gradual one. It would depend on the degree to which participants felt that the observed model was “themselves”. Self-reports on identification were therefore assumed to shed light on underlying mechanisms, if fear reduction would be observed in all.

The main focus of the experiments was to establish the general viability of using virtual doppelgangers for achieving *clinically relevant outcomes*, namely *reductions in fear of movements, movement avoidance, and pain during movements*. Therefore, Study 2 included several questionnaire assessments pre and post avatar exposure. Pain expectancy was assessed as a measure of fear of movement prior to the movement experiment. Self-reported motor engagement, experienced pain, and functional ability during the potentially pain-evoking movements were assessed with questionnaires afterwards.

Study 2 was designed as a between-subject randomized controlled trial. It compared virtual doppelgangers and videotaped real-world movement models in participants with chronic back pain. The technological implementation of this immersive virtual encounter with personalized doppelganger avatars and the analyses of behavioral data will be described in the following chapter.

2 MATERIALS AND METHODS

A main contribution of this project was the development and implementation of a technical setup to create and present *virtual doppelgangers as movement models* in an *immersive virtual environment* with elements of *augmented virtuality*, i.e. real-world objects to interact with. In the following, technical details and implementation to enable other researchers to replicate and adapt the technical design will be described. The actual experimental designs, analysis methods and results are then presented in the following chapters.

2.1 Experimental Setup

2.1.1 Virtual Characters

Virtual characters as animatable objects consist of at least two main elements: *skin mesh* and *kinematic skeleton*. The skin mesh defines the surface of the character that is visually displayed (*rendered*) and visible to the user. It is defined as an assembly of geometrical polygons (triangular or ideally tetragonal). Color information for virtual diffuse reflection is either attached via a 2d image texture wrapped around the 3d object, with a so-called UV map defining the texture patch for each face (*face coloring*), or by assigning each vertex point of the mesh their specific color value (*vertex coloring*). Other optical properties (e.g., transparency, glossiness, specular reflection depending on view angle) may be added as additional texture map layers, thereby increasing computational load for real-time rendering in VR applications.

The *kinematic skeleton* is defined as a hierarchical chain of virtual bones, i.e., one-dimensional axes of fixed lengths and three rotational degrees of freedom while staying attached to their respective parent bone. A so-called root bone hierarchically parents all other bones and defines the spatial location of the character (usually located in the virtual pelvis to reflect the center of mass in humanoid biomechanics). This allows for data-efficient definitions of character animations: for a skeleton with N bones, whole-body movements and posture changes only need ($3*N+3$) time series channels, storing the trajectories of three spatial coordinates (of the root bone), and in addition three rotational trajectories for each bone in the skeleton.

Once a suitable character skeleton is defined, the character mesh needs to be attached to it, such that skeleton animations will deform the character mesh accordingly. This is achieved by a so-called *skin modifier* which defines an additional mapping between mesh vertices and the respective bones "dragging" the mesh vertex with them during animations (and the relative weights of the respective bones assigned to a vertex). The definition of a skin map is referred to as the *rigging* process of the character mesh, or alternatively the *skinning* of the skeleton.

Another type of dynamic mesh deformation in character animations is the use of mesh *morphs*, which is realized by defining several versions of vertex locations (i.e., mesh deformations) with constant mesh topology, which allows for morphing between these different mesh forms. This is often used in the definition of facial expressions (facial blendshapes). In our studies, however, we did not implement this feature in our characters, as our focus was on body movements and appearance.

In the first study, we used *four different types of virtual characters*, referred to by an "avatar number" *AN*. Besides the personalized doppelganger characters (*AN*=4), which will be described in the next section, we designed an abstract faceless stick-person character with humanoid shape (*AN*=1), and two generic characters. For one of the latter, we designed the bodily and facial proportions based on cartoon characters (*AN*=2), whereas the other one was provided with proportions as natural as possible (*AN*=3). We tried to design the appearance of all three generic characters as gender-neutral and added participants' ratings of their apparent gender as to our questionnaires to control for it. The character mesh of the stick person was created using the 3d design software applications *3d Studio Max 2017-2020 (3ds Max)* (*Autodesk*, San Rafael, CA) and *MeshLab* (Cignoni et al., 2008). The cartoon and realistic character were both assembled with the character mesh design software *Fuse CC* (*Adobe*, Mountain View, CA). The character meshes were then converted to the *filmbox (fbx)* file format and rigged using the half-automated skinning procedure by

Adobe Mixamo. We applied final refinements and adaptations with *Vizard Inspector* (*WorldViz VR*, Santa Barbara, CA) and finally exported the ready-to-use characters in *open scene graph binary (OSGB)* format.

In the second study, the process for creating the personalized doppelganger was the same as in the first study. The control group watched a 2d video of a real person, which was presented on a virtual screen in the 3d virtual environment. In this case, the "character presentation" was thus realized with quite a different workflow: we post-processed and converted the video recordings into the *MPEG* file format and applied them as a dynamic texture to a virtual canvas object.

Figure 2. Scanning procedure for doppelgangers.

Personalized virtual characters, or “doppelgangers”, were designed based on 3d scans obtained from participants. To this purpose, a *Kinect sensor* (*Microsoft*, Redmond, WA) was used as a handheld 3d scanner. This device was originally developed for entertainment movement games for the *Xbox* (*Microsoft*) but also offers a functionality to scan small objects for 3d printing. Based on this function, we developed a low-cost method to create virtual doppelgangers from separate 3d scans of different body parts, scanning the lower body, the torso and the upper limbs, and the head. For lower and upper body scans, participants were either placed on a slowly rotating plate in Study 1 (**left panel**) or stood stationarily in Study 2 (**middle panel**), with the examiner slowly moving around them. In both cases, participants took the so-called *T-pose* with arms widely stretched, to allow for a full coverage of textile surfaces. Close-fitting, long-sleeved clothing was required to avoid shape artifacts due to loose textile parts and to allow for an easy reconstruction of hands and shoes, which could not be captured satisfyingly with the *Kinect*. Head scans were obtained from participants in a stationary seated position with the examiner slowly moving the sensor around them. The resulting doppelganger avatars (**right panel**) were later presented as life-size virtual movement models in the virtual reality setup.

2.1.2 Virtual Doppelgangers

For the creation of virtual doppelganger characters, we developed an extensive *processing pipeline* to establish a *low-cost solution* to move from 3d photographs to an animatable virtual character. Our “raw material” consisted of 3d photographs, or 3d “scans”, of the participants (Figure 2), which we acquired with a hand-held *Kinect sensor* (Microsoft, Redmond, WA) used in scanning mode, employing the software *Microsoft 3D Scan*. The scanning procedure was performed in three parts, to reach three-dimensional raw mesh data (*wavefront/OBJ* format with bitmap texture maps) of the lower body (legs and hips), the upper body (torso and arms) and the head and neck.

Participants were asked to bring close-fitting, long-sleeved and comfortable clothing for the *3d photo session*. For the body shoots, they had to stand still either on a rotating plate (Study 1) or remain stationary (Study 2), with legs apart, and for the upper-body with arms stretched horizontally in the so-called *T-pose*. For the head photograph, participants were seated on a chair in a stationary manner and asked to keep their head and eyes fixated, with fixed facial expression – showing a smile with mouth closed.

These instructions and settings were optimized in extensive pilot trials and test shootings with volunteers. For example, we had found that longsleeve, close-fitting and colorful clothing yield the best results. It allows for a detailed capture of body shape while at the same time providing the *Kinect* registration algorithms the optical details for aligning the underlying point clouds better. In addition, the hand-guided shooting with the Kinect sensor requires an intricate choreography of walking around the participant to cover different camera angles on part of the experimenter. Multiple repetitions also demanded some patience from participants, with photo sessions taking between 20 and 60 min in total. Current developments in more automated low-cost avatar personalization may improve this process in the future (Wenninger et al., 2020), although arguably the regularly reported artifacts will still require extensive manual post-processing.

The *processing pipeline* developed for manual character design from these 3d scans uses several software packages, file formats and processing steps. It contains seven main steps. For the sake of study reproducibility, they will be shortly described here.

1. **Compartment preparation** (Figure 3): using *Microsoft 3D Builder* and *3ds Max*, the raw 3d meshes are cleaned of artifacts (mainly by faces removal, insertion of new polygons) and manually aligned to each other; minor geometry errors may be reconstructed by smoothing or remodeling the local surface; as hands and shoes are not captured well by the Kinect (mainly due to the small-scale detail geometry

of hand geometry and transition between shoes and floor), these were added and adapted based on template avatar meshes; end products were exported in *fbx* format.

2. Merging and remeshing (Figure 4): after some further preprocessing (closing holes, removing corrupt faces and vertices), and making use of the advanced mathematical remeshing methods in *MeshLab*, the mesh compartments of the body are merged; the body surface is reconstructed over a series of different remeshing steps; most importantly, the *Poisson Resampling* method allows for arriving at a water-tight surface. To maintain the fine-grained geometry of hands, shoes and head, these mesh parts are kept as separate objects.

3. Color correction and recoloring (Figure 4): projecting the texture colors to a new layer of vertex color allows for manual correction and local recoloring with the different vertex color painting tools in *MeshLab*. This is especially important for partially obscured surface areas which are often captured poorly by the Kinect color cameras (e.g., around the armpits and on the inner sides of the trousers). The successfully repainted body mesh is then exported in a file format that stores color information (*Autodesk Collada dae* format).

4. Texture baking (Figure 5): back in *3ds Max*, the newly created full-body mesh needs to obtain a new texture mapping because the current vertex coloring is not suitable for most game engines, i.e., real-time rendering solutions for computer games. We used the *Unwrap UV* modifier solution in *3ds Max* for this purpose. After the new UV mapping (3d face to 2d texture file) is defined, the vertex colors can be projected and stored as a new texture map, a process called *baking*.

5. Optimizing mesh resolution (Figure 5): the head mesh with its mostly unchanged, detailed original geometry (as created in the scanning procedure) as well as the body mesh acquired with remeshing techniques both have a high spatial resolution at this stage (in the order of 10^5 to 10^6 vertices) which is not suitable for real-time rendering. Hence, we had to considerably reduce the spatial resolution to values in the order of 10^4 vertices at most, for which we used the *Optimize* modifier in *3ds Max 2018*. The newly introduced and mathematically advanced *Retopology* method in more recent versions of *3ds Max* may become an interesting and helpful tool to further improve this process and lower the resolution even more without too much loss of optical detail. The final version of the remeshed, recolored and optimized set of character meshes was exported in the *fbx* format again.

6. Rigging (Figure 6): the rigging of the character, i.e., the attachment of an animatable skeleton, was achieved with the server-based *Adobe Mixamo* rigging tool, just like for the generic characters described in the previous section.

7. Preparation for animation transfer (Figure 6): using *Autodesk MotionBuilder*, the rigged *fbx* files were finally prepared for motion-capture animation transfer by matching their skeleton to the humanoid *Character* template in *MotionBuilder*, which allows for a half-automated transfer of animations from one skeleton to another, provided some basic humanoid topology requirements are met.

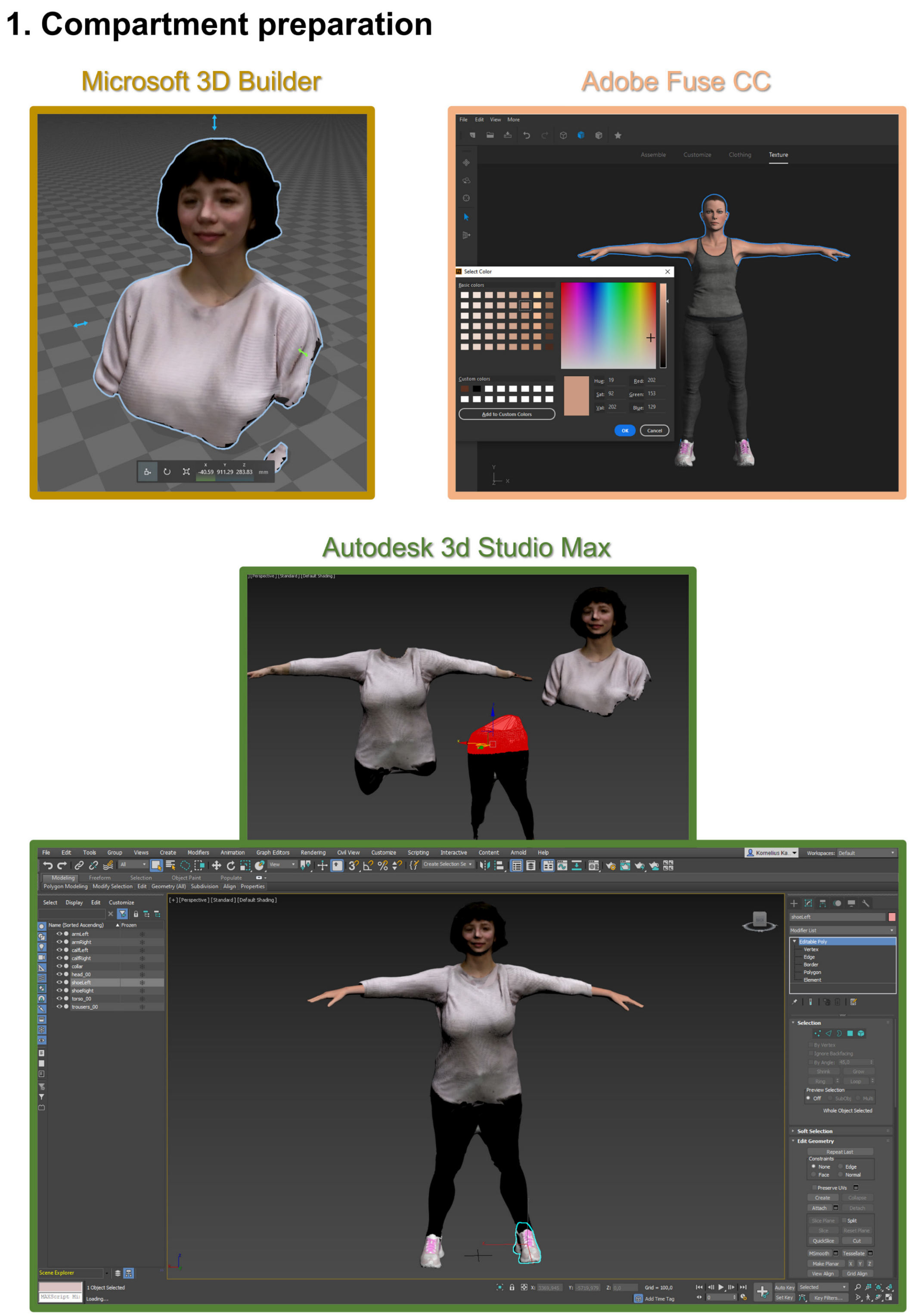
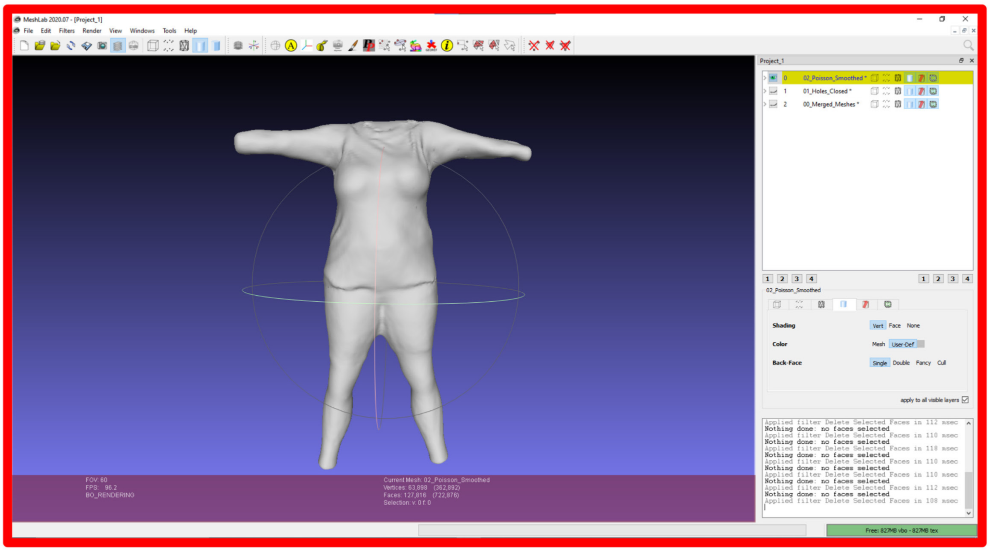


Figure 3. Doppelganger creation: combination of compartments.

The figure illustrates **Step 1 (Compartment Preparation)** of the doppelganger design pipeline. Depicted are a raw *Kinect* scan object opened in *Microsoft 3D Builder*, the creation of virtual hands and shoes (matched in texture and design to their real-world models) with *Adobe Fuse CC*, and the cleanup and alignment of scan compartments with *Autodesk 3d Studio Max*. The resulting 3d object is an immobile combination of unconnected irregular mesh compartments.

2. Merging and remeshing

Meshlab



3. Color correction and recoloring

Meshlab

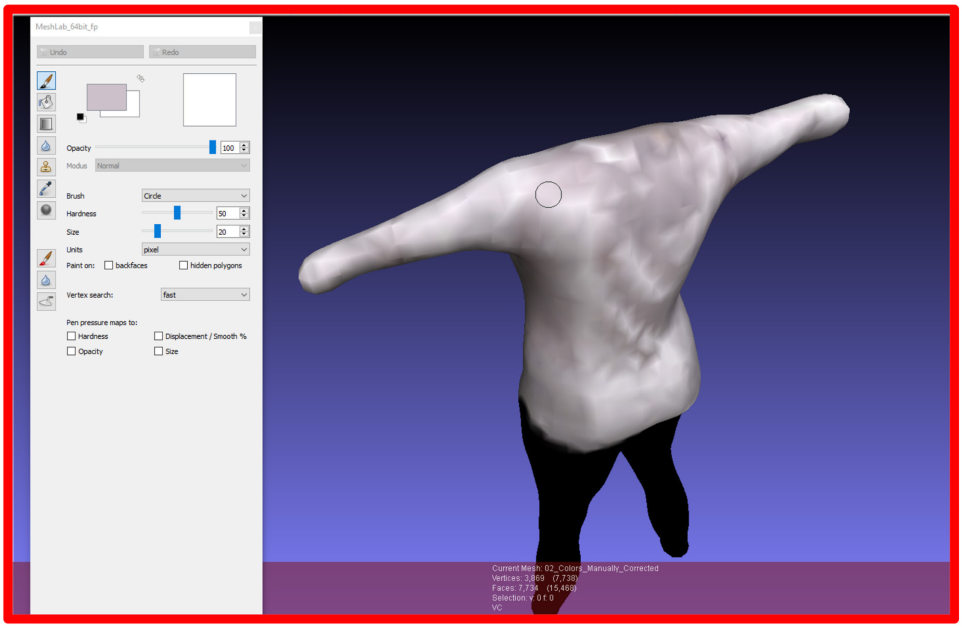
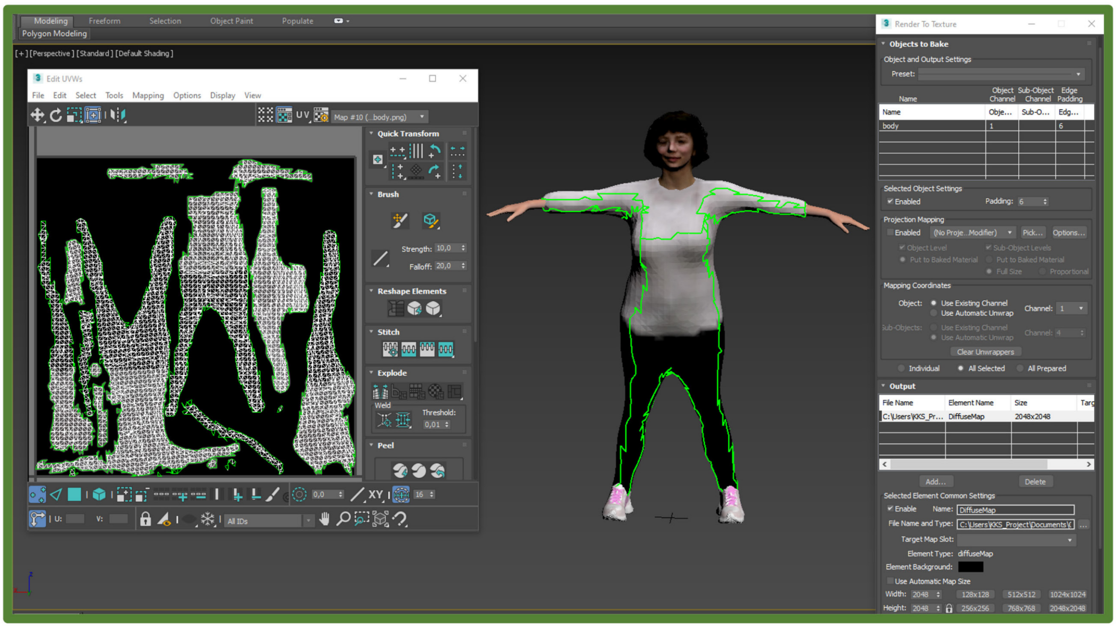


Figure 4. Doppelganger creation: mesh and color.

Starting from aligned and cleaned compartments, the meshes for lower and upper body parts are combined to one mesh in **Step 2 (Merging and remeshing)**. After some intermediate steps (cleanup of vertices and polygons, closing of holes), the virtual body is remeshed by surface reconstruction via so-called *Poisson Resampling* in *Meshlab*. The resulting mesh is colorless. In **Step 3 (Color correction and recoloring)**, colors can be transferred from the texture maps of original scans by first converting this color information into vertex colors, which can then be transferred to the remeshed body based on spatial proximity of vertices. Manual repair and recoloring are then performed with color brush tools in *Meshlab*.

4. Texture baking

Autodesk 3d Studio Max



5. Optimizing mesh resolution

Autodesk 3d Studio Max

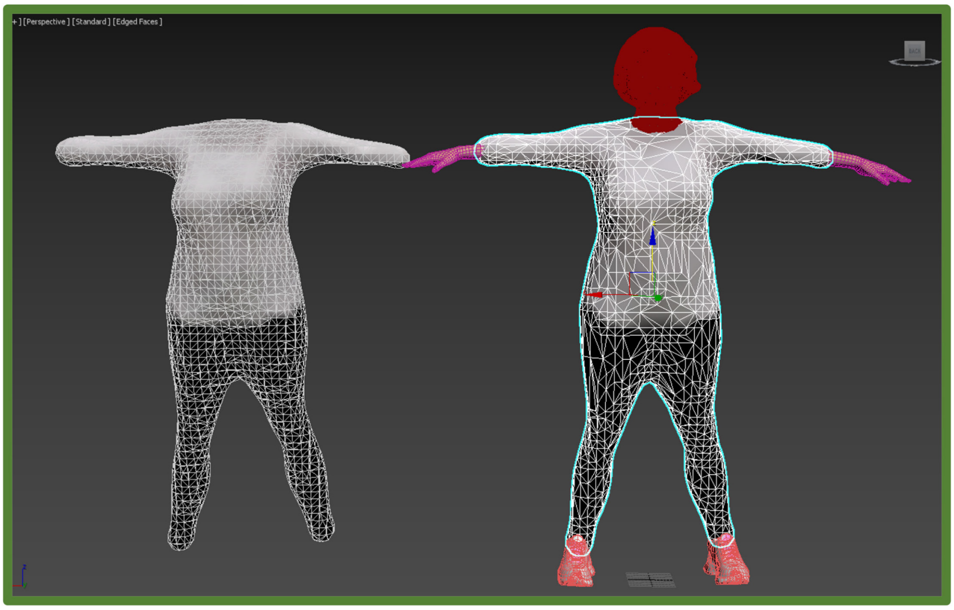


Figure 5. Doppelganger creation: texture and mesh resolution.

In **Step 4 (Texture baking)**, repaired and edited vertex colors of the remeshed body are transferred back unto a new texture map for the virtual body. This is obtained by first creating a new UV mapping for the new whole-body mesh in *Autodesk 3d Studio Max*, which is then used for so-called *Texture Baking* of vertex colors unto the texture image file. In **Step 5 (Optimizing mesh resolution)**, the spatial resolution (i.e., the polygon count) of the body mesh is reduced by *Mesh Optimization* with the respective tools in *Autodesk 3d Studio Max*.

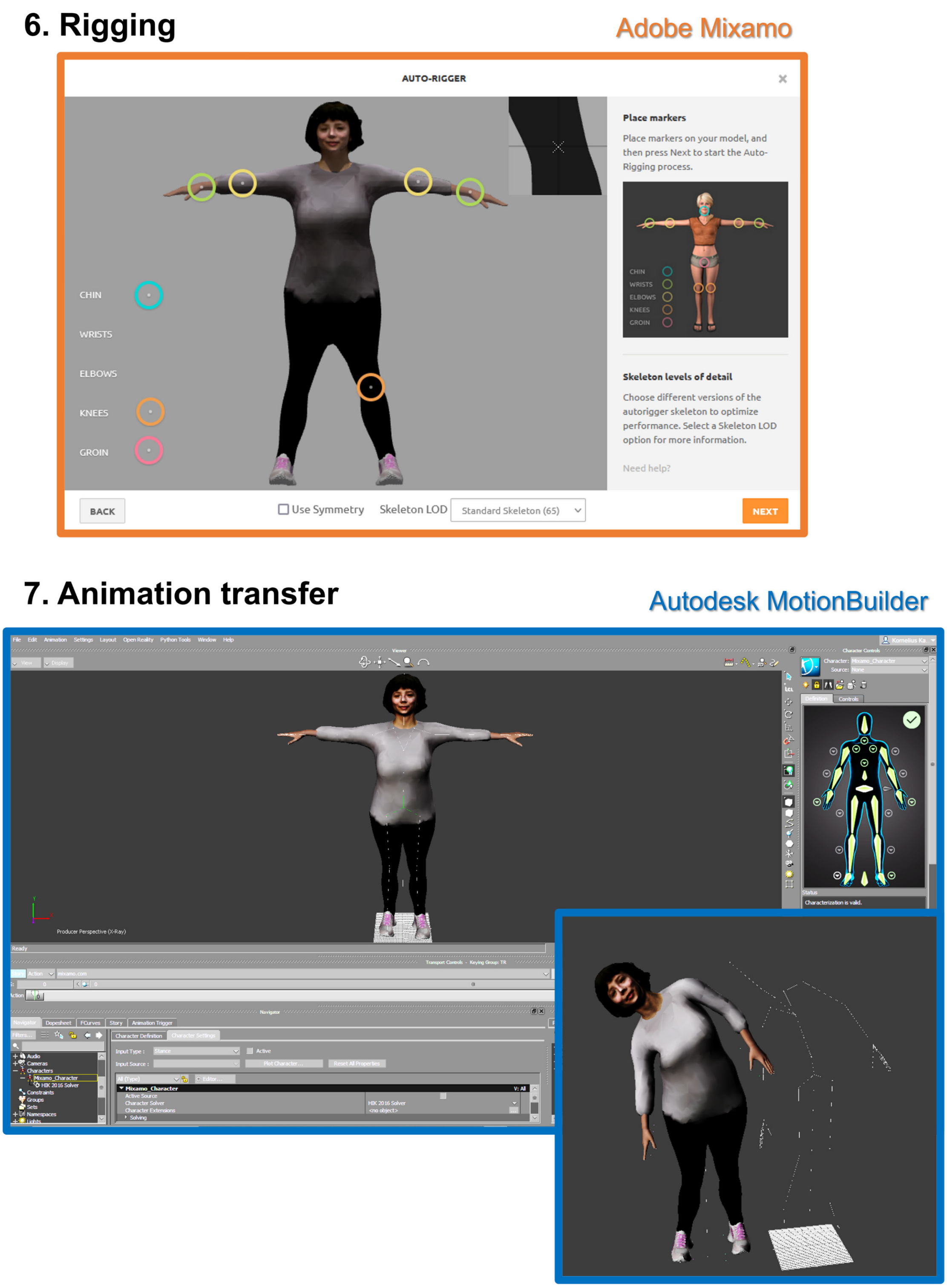


Figure 6. Doppelganger creation: rigging and animation transfer.

The optimized body mesh is now in alignment with the head mesh, for which only moderate optimization methods are used, in order to preserve the spatial geometry and texture for photorealistic details. Together with the hand and shoe meshes, these meshes are now rigged with an animatable kinematic skeleton in **Step 6 (Rigging)**, using a half-automated procedure from the *Adobe Mixamo* platform. In **Step 7 (Animation transfer)**, *Autodesk MotionBuilder* is used to match the avatar to a humanoid *Character* template, unto which prepared animations are transferred, manually adjusted and corrected. Finally, the resulting movement data are baked into the rig as a standalone animation of the avatar, which is then ready to be used in virtual reality applications.

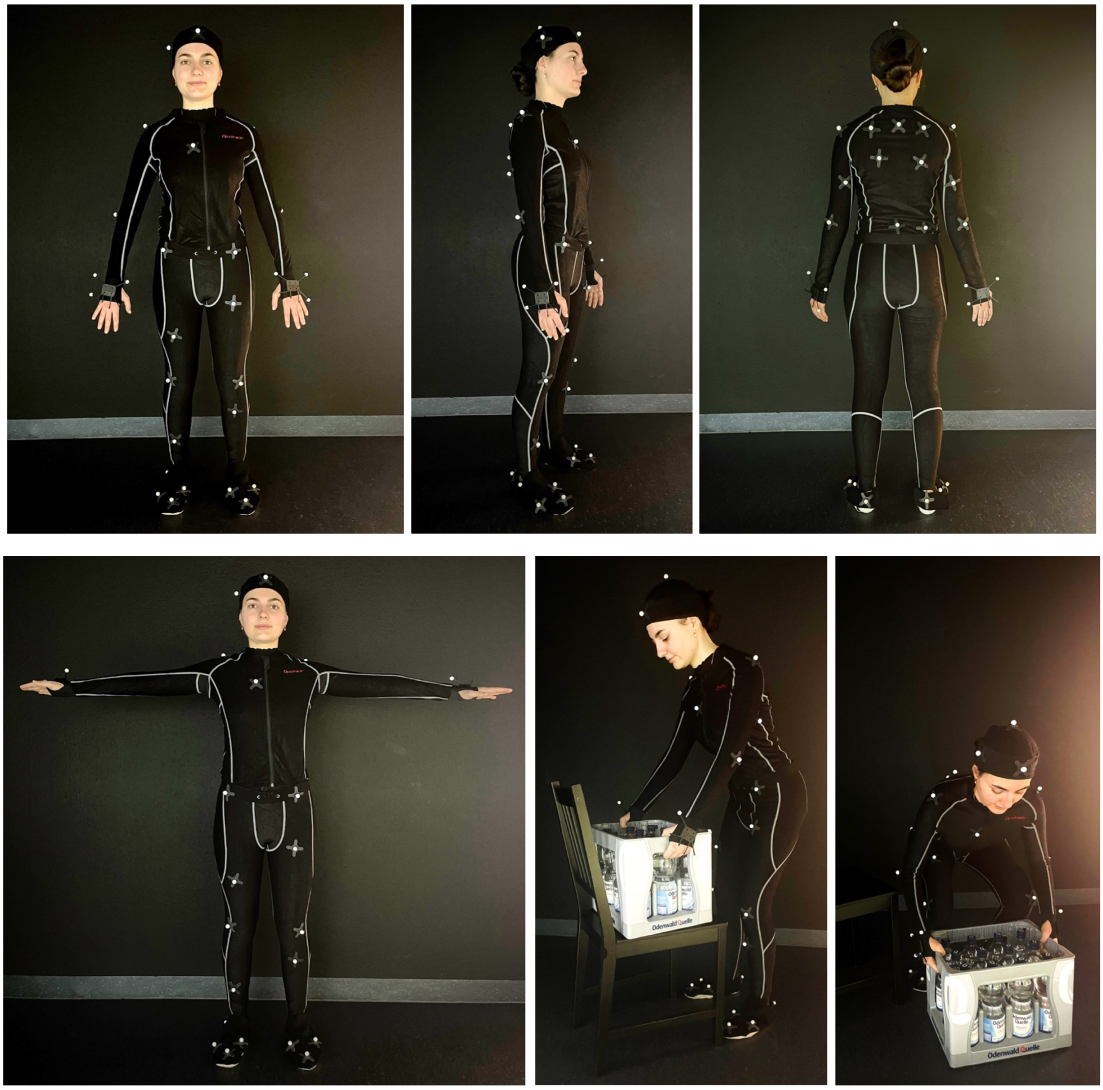


Figure 7. Motion capture for character animation.

Restaging of the motion capture setup for generating animations from real-world movement models. Both in Study 1 and Study 2, a twelve-camera optical motion capture system was employed, which works with infrared illumination, the reflection of which is measured by the cameras which are mounted to a scaffold hanging from the room ceiling in a square configuration (*OptiTrack*, Corvallis, OR). Three-dimensional position in space is inferred from parallaxes between different camera views on the same markers, with an accuracy in the sub-millimeter range. In both studies, we used this technique to design the movement animations for the respective model movements, which were later transferred unto the personalized doppelganger avatars. **Upper row**: configuration of optical markers for motion capture. The model is wearing a motion capture suit to which 41 passive reflective markers (white spheres) can be attached in accordance with the individual physique. Note the deliberate asymmetries in some limb marker positions, which allows for a distinction between left and right body site, most prominently for thigh, shin, and head markers. Most other markers are positioned according to anatomical musculoskeletal landmarks (joints and bones), as for example knees, elbows, hipbones, shoulders and shoulder blades. Orientation of the hands is tracked with a fixed two-dimensional marker configuration, a so-called rigid body. **Lower row:** procedure of a motion capture take. The calibration of the individual humanoid kinematic skeleton requires the movement model to stand stationarily with arms stretched and legs apart (T-pose, **left panel**), to ensure unobstructed optical pathways from all reflective markers to as many cameras as possible. After calibration, complex movements can be captured, such as the crate-moving movement used in Study 2 (**middle and right panel**). Especially for movements like this, in the course of which optical markers are easily hidden by other body parts or objects, artifacts from shadowing of markers and hence missing trajectory parts are common. Therefore, capturing these movements requires careful positioning of the model with respect to the cameras and a frequent repetition of takes to obtain motion capture data sets with enough non-missing data, which can then be post-edited manually (in our case, with *Autodesk MotionBuilder*).

2.1.3 Character Animation

The animations displayed on the virtual characters were designed based on motion capture data of healthy volunteers (Figure 7). We used several animations in our two studies: *bending sideward* (BS), *bending backward* (BB), *rotation in the horizontal plane* (RH), touching the toes/ floor (TT), *moving a crate* of water bottles from the floor on a chair and back (CM). For the first study with healthy participants, we recruited six volunteers to record their performances of these movements and chose our final takes among all their recordings. For the second study, we recorded the movements again, in this case from one single person who is a certified physical therapist. The recordings of the movements were acquired with an optical motion capture, using an *OptiTrack* (*OptiTrack™*, Corvallis, OR) setup with twelve infrared cameras and 41 reflective markers attached to the motion capture suit worn by the movement models (capture rate 120 Hz, spatial accuracy in the sub-millimeter range according to calibration). Motion capture data were exported in the *biovision hierarchical format (bvh)*, which stores the movement information efficiently as a time series of rotational and translational degrees of freedom of virtual bones ordered in a humanoid skeleton.

Post-processing of motion capture data was performed with *Autodesk MotionBuilder*. It focused on repairing of motion capture artifacts (unnatural switches and twists in bone positions) by deletion of corrupted parts and manual insertion of corrected positions per time frame (so-called *keys*). We also applied bandpass filtering (usually with filter windows of ca. 1-60 Hz) to remove motion artifacts and to achieve smooth movements of natural appearance.

The set of cleaned and post-processed movements was stored as a ready-to-use set of animations by transferring it to a humanoid template character with the *MotionBuilder Character* tool. For every virtual character (generic or personalized), we then transferred this template animation to its specific skeleton in *MotionBuilder*. Although the main aspects of an animation usually translate quite well from one virtual body to the other, the process still requires some manual fine-tuning. The latter is achieved by adjusting the transfer weights for rotation values for the extremities and by manual repositioning of positions and rotations for each time frame (key adjustment) if rendered necessary by geometric idiosyncrasies such as differences in body size between light- and heavy-weighted characters, or different lengths of the arms and legs. After successful animation transfer and final adjustments, the characters were then converted from *fbx* to the *osgb* file format used by our presentation application.

2.1.4 Virtual Environment

In contrast to experiments exploring the potential of VR for entertainment or for the purpose of gamification, the virtual environment was not the main focus of interest but rather a potential confounder in our studies. We designed the virtual environment in *Autodesk 3ds Max* and in *Worldviz Vizard Inspector*, based on a template environment provided by *WorldViz Vizard* (Figure 8). We selected the latter in accordance with the following criteria.

1. The environment should induce a rather *relaxing atmosphere*: as we wanted to test virtual character influence on inclination to imitate and on observational shaping of non-fearful expectancies with respect to movements, a comfortable “baseline atmosphere” appeared desirable to not overwrite any smaller effects by aversive feelings evoked by the environment. Therefore, we opted for an environment with an appealing interior design and warm lighting.

2. The *lighting conditions* in the virtual environment should roughly meet the rather dimly lit real environment surrounding the CAVE, as the participants’ attentions should not be drawn to a potential mismatch of the different components of the mixed reality design, potentially limiting immersion. We assumed that this would be even more important as we asked the participants to perform movements during which they partially lost the CAVE canvasses from their sight (especially when looking upward and backward). Therefore, we opted for an indoor setting for our virtual environment. These two criteria led us to the selection of a virtual indoor room with vaguely “East-Asian” design that resembles a “dojo”, i.e., a training hall

Figure 8. Virtual environment.

We designed the virtual environment used in our studies based on a template room delivered with *Vizard 6* (*WorldViz VR*, Santa Barbara, CA), which we used for programming and running the experiments. We extended the virtual training room ("dojo") with decorative elements to make participants more comfortable during immersion. Besides esthetic aspects, the fountain placed on the left side fulfilled two additional purposes. Firstly, it allowed for the intuitive embedding of localized sound into the virtual world, hence overriding surrounding real-world sounds. Secondly, the fountain served as a visual anchor to which participants could orient their heads towards and keep them stationarily. This was necessary for the initial calibration of the rigid-body marker configuration for optical motion capture, which was mounted on the 3d shutter-glasses worn by participants in the CAVE.

for martial arts. To further increase the optical appeal, we added virtual plants and other design objects.

3. Our third criterion was that our setup should *divert the participants' attention from real-world sounds* (e.g., noise from air conditioning) towards elements in the virtual world to increase immersion. For this reason, we added a virtual indoor fountain that emitted a constant gurgling sound, which participants anecdotally indeed described as quite calming and comfortable.

4. Another criterion was the necessity to include *virtual "anchors of description"*, i.e., objects to which we could unequivocally refer to in our instructions. For example, we also used the indoor fountain as a virtual fixator object at which participants had to look during the initial calibration of the tracking of the 3d glasses. Similarly, we inserted a virtual training mat to the floor, to provide participants with a visual indicator of the central area they were asked to perform their movements in to optimize both their perspective on the avatar and acquisition of motion capture data in the center of the four-camera system.

2.1.5 Hard- and Software for VR Presentation

For sensory presentation of our virtual environment, we used a *Cave Automatic Virtual Environment* (*CAVE*, Figure 9). For this purpose, we took a four-sided setup into service, which was installed at the *Center for Innovative Psychiatric and Psychotherapeutic Research (CIPP)* at the *Central Institute of Mental Health* (Mannheim) by *Engineering Systems Technology* (*EST*, Kaiserslautern). Four 3d projectors screen the images unto three canvasses (left, front, right) and on the coated floor (bottom), with stereoscopy enabled by opposed polarization of the two image signals. Users wear polarization-selective shutter-glasses, as they are regularly used in 3d cinema. Auditory stimuli are added via a stereo surround system with five speakers. As in every immersive VR technology, head movements are tracked in real-time. In our CAVE setup, this is realized by a four-camera optical tracking system (*OptiTrack*), which emits infrared light and tracks its reflection on passive markers attached to the shutter-glasses worn by the user. For this purpose, the optical markers are arranged in a fixed configuration, a so-called *rigid body* assembly, to allow for an unequivocal identification of the unique spatial “footprint” of the object. The CAVE setup is operated with six synchronized high-performance desktop computers with state-of-the-art gaming graphics cards (*Nvidia Corp.*, Santa Clara, CA). One of them processes the optical tracking data, another runs the animation, calculates the virtual viewpoint and coordinates the remaining four, which are devoted to high-resolution rendering of the images to be projected on each canvas.

This setup comes with several advantages for our studies:

1. The *optical tracking system* allows for a concurrent *motion capture* of selected body parts of the user by attaching rigid body marker configurations to the latter.

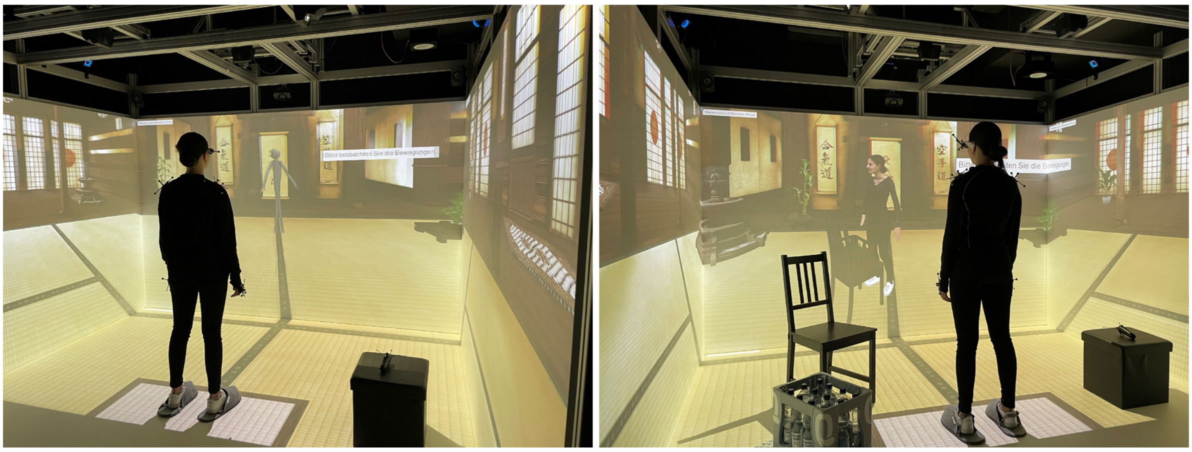


Figure 9. CAVE Setup.

Restaging of the experimental in the four-sided Cave Automatic Virtual Environment (CAVE). Participants wear light-weight shutter glasses equipped with optical markers for real-time motion capture. The scaffolding hanging from the ceiling carries four infrared cameras for motion capture (bluish lights), sound system boxed, and four 3d projectors to screen the rendered images unto the canvasses and the floor of the CAVE. In Study 1 (**left panel**), the CAVE was used for an immersive virtual reality setup, with the only real-world object being a stool to place the remote control when the latter was not currently used for answering questions inside the virtual environment. In Study 2 (**right panel**), the setup was extended with real-world objects for the participants to interact with, namely a beverage crate and a chair to put it on during the crate-moving task. Hence, Study 2 employed an immersive virtual reality design with mixed-reality elements (according to fine-grained definitions, this would qualify it as an "augmented virtuality" study). Both studies used a virtual training mat as a marker for participants to position themselves on during the movements (except for the crate-moving task in Study 2).

2. The *light-weight and wireless shutter-glasses* enable the participant to *move freely*, both in terms of walking around and in terms of complex bodily movements.

3. The *high optical resolution* facilitated by large-screen projection allows for presenting virtual characters in high *optical detail*, and in addition it possibly enhances immersion.

4. The use of shutter-glasses keeps *real-world objects visible*, thus enabling a *highly immersive mixed-reality*.

In our first study, the last point (mixed reality) affects only the participants' own bodies, which remain visible to them, hence avoiding distractions or aversive feelings by changes in (or a lack of) their body viewed in 1PP (which was not our focus of study). We also expected that having an own visual body, would increase so-called co-presence (Bailenson et al., 2005; Schroeder et al., 2001) with the virtual counterparts they were facing. In our second study, in contrast, the visibility of real-world objects was essential. A real-world box filled with water bottles was placed in the CAVE, together with a chair unto which participants should place the box several times during the experiment. Thus, this allowed for including a complex movement regularly linked to fear avoidance behavior in CBP (Alemanno et al., 2019; Klinger, Kothe, et al., 2017; Schmitz et al., 2019; Strand, 2017; Strand et al., 2002), in close resemblance to everyday contexts: the crate-moving (CM) task. This mixed reality solution was chosen to circumvent the extreme technological challenges of simulating gravity (which would require an advanced active robotic device to exert the necessary counter-forces to participants' movements). Also, including a virtual replica of the real-world box into an HMD setup would have required almost perfect optical tracking of the box, coming with considerable safety issues if tracking would have failed.

The VR experiment was programmed and run on *Vizard 6* (*WorldViz*, Santa Barbara, CA). This software allows for the integration of a diverse set of hardware devices and provides the image rendering in real-time. The application comes with a set of *Python* libraries, thereby allowing for full scripting of the experimental flow in *Python* syntax. We set up the experimental flow and implemented a custom-tailored solution for data acquisition via questionnaires to be answered with a remote control inside the CAVE.

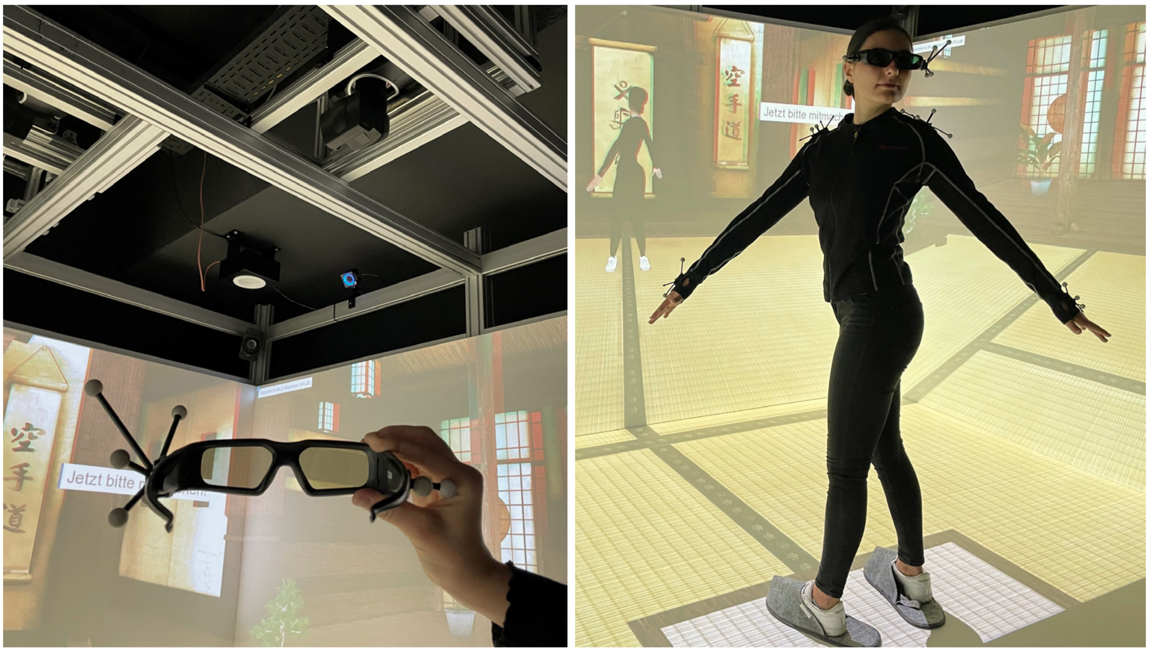


Figure 10. CAVE Motion Capture.

Motion capture in the CAVE was conducted with an optical system (*OptiTrack*, Corvallis, OR), which was similar to the one used for capturing movements for animation, except for the reduced number of only four cameras mounted to the CAVE scaffolding. **Left panel:** the 3d shutter glasses worn by participants in the CAVE are equipped with a rigid-body configuration of six spherical passive-reflective markers, which were tracked in real-time by the cameras (blue light), which actively emit infrared light and register its reflection. Real-time tracking of the glasses was used to infer participants' head movements and to adjust the user viewpoint in the virtual environment. **Right panel:** Similar rigid-body marker configurations were attached to a motion capture jacket worn by participants, in order to acquire motion trajectories of body parts. Based on these, objective measures of motor behavior (ranges of motion) were constructed in later analyses, particularly focusing on trajectories of those markers which were attached to participants' shoulders.

2.2 Data Acquisition and Analysis

2.2.1 Motion Capture

Our movement measurements were conducted with the four-camera optical motion capture setup (*OptiTrack*) which was also used for head-motion tracking in the CAVE (Figure 10). The optical motion capture system consists of infrared cameras with infrared illumination devices attached to them. Highly reflective spherical markers attached to the subject's body reflect the infrared light emitted by the illumination devices. The parallax inference from the camera views of each marker then allows for a 3d reconstruction of its position in space (given suitable calibration beforehand). Note that these markers are physically passive devices, as the tracking signal emitted by the illuminators is only reflected by them. Here lies an important difference to systems with active markers, which emit radio-frequency signals, as they are commonly used in commercial home-use VR systems (e.g., the *Oculus Rift* or the *HTC Vive*). As the spherical markers are indistinguishable, we attached them to frames to form so-called rigid bodies (RBs): each frame carries several markers in a distinctive three-dimensional pattern, such that the respective rigid body has an individual “marker position footprint” and can therefore be identified unambiguously by the tracking system.

We used seven rigid bodies in our measurements. Using more rigid bodies was not feasible due to our limited number of tracking cameras and the accordingly limited number of different view angles: as a rule of thumb, the more cameras can be used for tracking, the more rigid bodies can be distinguished unambiguously, as each additional view angle adds an additional two-dimensional representation of marker positions – and thereby information which can be used to distinguish more rigid-bodies by their three-dimensional marker configurations from each other.

Due to the passive reflection, this type of motion capture is prone to missing data (and sometimes artefacts of false attribution of markers to RBs) due to hidden markers, i.e., shadowing. During post-processing of the motion capture data, we accounted for this by close inspection of the recorded RB trajectories and removed any conspicuous data frames. This resembles methods of artefact correction in other time-series data, for example, EEG signals. Based on the cleaned trajectories, we extracted *ranges of motion* (ROM) for the movements, as explained below in Study 1.

2.2.2 Linear Mixed Effects Models

Linear mixed effects models (LME models) try to describe the respective data with an extension of multiple regression, which takes into account the dependence of data points to each other if they belong to the same class (Hox et al., 2018; Singmann & Kellen, 2019). The single measurements are referred to as level-1 data, the classes to which they belong as level-2 data, with possible extension to arbitrarily more higher levels of grouping. LME models are widely used in psycholinguistics (e.g. (Sedlmeier et al., 2016)), but can also applied to any problem for which the grouping criterion is unequivocally defined for every data point.

In LME terminology, the model parameters from multiple regression (regression slope and intercept) are referred to as the *fixed effects* for the entire (grand) sample. They are complemented by *random effects*, which capture group-specific deviations from the grand sample values. This means that for every regression parameter that describes the grand dependence of the criterion variable *y* on any predictor *x* (i.e., the respective slope m_x), and the grand intercept (grand mean value of *y* for the values of all predictors set to 0) are accompanied by *N* group-wise deviation values for *N* groups – the respective random effects and the group-wise random intercept. Under these basic assumptions, optimization of a performance criterion for fitting a model to the data is not analytically possible, in contrast to normal regressions. Therefore, there are several methods with specific additional assumptions to estimate the optimal model. Fitting an LME model therefore requires several design choices that require careful considerations of the properties of the data and about the numerical limitations imposed by the limited number of data points. Three important choices in this respect are: (1) the decision of whether to only add group-wise random intercepts or to also include random slopes for the different predictors; (2) the decision of whether to allow for full covariance matrices for all estimated parameter values – if so, this adds many more parameters to be estimated, namely the covariance values; (3) the choice of estimation method and optimization criterion, with two common approaches being to optimize the likelihood of the data themselves given the model (*maximum likelihood [ML]* approach) or of a transformation of the data (*restricted maximum likelihood [REML]* approach).

In our studies, the repeated-measures design implied a grouping per subject (i.e., each group in the data represents one participant). We usually restricted the random part of the model to random intercepts, hence increasing numerical stability. Usually, our model assumptions allowed for a full covariance matrix, which limits numerical stability (and the number of predictors possible to include) but has been reported to arrive at more conservative estimates for the *fixed effects*, which were in our focus of interest. As optimization method, we usually chose the ML approach, because the latter allows for comparisons between nested models with respect to whether the inclusion of an additional predictor significantly improves model performance (Hox et al., 2018).

2.3 Differences in Experimental Setups

When interpreting the results of our studies, which are reported in the following, the *differences in experimental design* have to be taken into account. Study 2 differed from its pilot study, Study 1, in several aspects.

1. The *set of movements* was not exactly the same (Study 1: BS, RH, BB, TT; Study 2: RH; BS; CM). This also implied that Study 2 included *mixed-reality elements*, as one of its movements (CM) required interaction with real-world objects in form of a beverage crate and a chair. In contrast, the only real-world object positioned in the CAVE in Study 1 was the remote control and the low stool to put it down on (see Figure 9).

2. Study 1 investigated *within-subject* differences in healthy participants during *one session*, whereas Study 2 explored *differences between participants* randomly assigned either to the experimental or control group, who completed *three sessions*.

3. Study 1 asked participants to join into a *synchronous movement* with the avatar after observing their movements, whereas Study 2 let the model stop moving after observation and asked participants to *imitate it afterwards*. This gave participants with chronic back pain the opportunity to choose their own pace of movement. This was necessary for general safety considerations on the one hand (especially for the crate-moving task), and, on the other hand, in order to give participants the opportunity to express safety behavior in any possible form including slowed movements.

All of these design differences were due to the *different purposes of the experiments*: Study 1 was set up as a pilot study investigating the usefulness of personalizing movement models to enhance imitative tendencies, and it did this in a healthy sample for which the movements were mostly not painful. Study 2, in contrast, set out to explore said movement models as potentially beneficial therapeutic tools in participants with chronic back pain, as compared to a state-of-the art procedure employing a different type of movement models (real-world persons, presented on videotapes). Therefore, Study 2 would have been more amenable to demand characteristics (i.e., study participants actively trying to help confirm the guessed hypotheses of an experiment) in a within-subject design than Study 1, which used different versions of the same type of models (virtual characters). In addition, its multi-session design was necessary to detect any clinically relevant effects. Due to these design differences, the two experiments shed light on different aspects of behavioral reactions to virtual doppelgangers.

Other *technical differences between experiments* were also present: Study 2 substituted the scanning procedure with rotating plate from Study 1 with a stand-still solution for the older and potentially more disabled participant sample. As the scan quality stayed roughly the same for the new procedure, this most probably did not affect the appearance of doppelganger avatars between experiments. In addition, our quantitative analyses of motion capture data in Study 1 used mean ROM values per avatar level, whereas analyses in Study 2 treated every single movement occurrence as a separate data point. The rationale behind the decision to pre-average the data in Study 1 had been to avoid data sets with too heavy imbalance of missing data between conditions, as this can lead to numerical issues in model estimation (Singmann & Kellen, 2019). However, the moderate number of missing data for RH and BS in Study 1 let this precaution appear unnecessary and hence was abandoned in favor of greater statistical power in Study 2. As LME approaches aim at estimating mean values, quite analogous to linear regression, this methodical difference does not impair comparisons between experiments. Both studies and their respective results will be described in detail in the following two chapters.

3 STUDY 1: EXPLORING VIRTUAL DOPPELGANGERS AS MOVEMENT MODELS TO ENHANCE VOLUNTARY IMITATION[3]

3.1 Abstract

Virtual Reality (VR) setups offer the possibility to investigate interactions between model and observer characteristics in imitation behavior, such as in the chameleon effect of automatic mimicry. We tested the hypothesis that perceived affiliative characteristics of a virtual model, such as similarity to the observer and likability, will facilitate observers' engagement in voluntary motor imitation. In a within-subjects design, participants were exposed to four virtual characters of different degrees of realism and observer similarity (avatar numbers AN=1-4), ranging from an abstract stickperson to a personalized doppelganger avatar designed from 3d scans of the observer. The characters performed different trunk movements and participants were asked to imitate these. We defined functional ranges of motion (ROM) for spinal extension (bending backward, BB), lateral flexion (bending sideward, BS) and rotation in the horizontal plane (RH) based on shoulder marker trajectories as behavioral indicators of imitation. Participants' ratings on avatar appearance, characteristics and embodiment/ enfacement were recorded in an Autonomous Avatar Questionnaire (AAQ), factorized into three sum scales based on our explorative analysis. Linear mixed effects models revealed that for lateral flexion (BS), a facilitating influence of avatar type on ROM was mediated by perceived identificatory avatar properties such as avatar likability, avatar-observer-similarity and other affiliative characteristics (AAQ1). This suggests that maximization of model-observer similarity with a virtual

[3] Published paper: Kammler-Sücker, K. I., Löffler, A., Kleinböhl, D., & Flor, H. (2021). Exploring Virtual Doppelgangers as Movement Models to Enhance Voluntary Imitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *29*, 2173-2182. https://doi.org/10.1109/TNSRE.2021.3120795.

Note: Numbering of sections, figures and tables adjusted for consistent labeling throughout this thesis.

doppelganger may be useful in observational modeling and this could be used to modify maladaptive motor behaviors in patients with chronic back pain.

Index Terms: Virtual Reality, Virtual Doppelgangers, Range of Motion, Voluntary Motor Imitation, Model-Observer-Similarity, Intuitive Movements

3.2 Introduction

Human behavior can adapt to manifold environments and contexts, due to its extreme plasticity. Exposing humans to virtual environments with immersive virtual reality (VR) technology allows for differentiating the influence of situational variables on behavior in a highly controlled manner. Immersive virtual environments are designed to evoke a sense of presence, of “being there” (Slater & Usoh, 1993), (Coelho et al., 2006). Ideally, the “place illusion” of being relocated to another place is complemented by the “plausibility illusion”, meaning that the virtual course of events appears as actually occurring (Slater, 2009). Given these preconditions, VR can stimulate a sense of co-presence in interactions with virtual characters, whether they are controlled by other humans (Schroeder et al., 2001) or by algorithmically controlled virtual agents (Slater et al., 1999). This allows for the creation of “virtual sociality”. Besides this, perception of the bodily self can also be modified in VR (Lenggenhager et al., 2007). This line of research extends findings of real-world objects being incorporated into neural body representation, for example, by congruent visuotactile stimulation in illusory ownership of a rubber hand (Botvinick & Cohen, 1998) and a mannequin body (Petkova & Ehrsson, 2008). These illusions can be replicated in VR when subjects embody virtual body parts such as an arm (Slater et al., 2008) or even whole virtual bodies (Slater et al., 2009), so-called “avatars”. Several aspects can contribute to ownership of virtual bodies, especially spatial colocation with the physical body, visuotactile contingencies and the sense of agency when perceiving motor control over virtual limbs (Maselli & Slater, 2013). Further, one crucial factor for embodiment of a virtual body is the visual first-person perspective (1PP) of the virtual body (Maselli & Slater, 2013; Petkova et al., 2011), which can suffice for virtual touch illusions (Fusaro et al., 2021) and illusory agency for virtual walking (Kokkinara et al., 2016). Even when presented in third-person perspective (3PP), avatars that are controlled by the users' movements and therefore elicit a sense of agency may also evoke some ownership and sense of self-location (Debarba et al., 2017; Gorisse et al., 2019; Pomes & Slater, 2013). Together, the senses of ownership, agency and self-location compose the sense of embodiment (Kilteni et al., 2012). Embodiment of virtual bodies can alter bodily self-perception, both of one's own limb movements (Bourdin et al., 2019) and body shape (Normand et al., 2011), without the subject's awareness. Similarly, the sense of enfacement emerges when users 'embody' virtual faces viewed in 3PP or in a virtual mirror (Sforza et al., 2010), an effect amplified by realism in facial animations (Gonzalez-Franco et al., 2020).

In addition to interaction with virtual characters as "others" and embodiment of avatars as "virtual selves", VR facilitates situations that subvert this distinction (Bailenson, 2012), allowing users to meet their own "doppelganger", a lookalike character viewed in 3PP. Doppelgangers can be designed based on 2d photographs or 3d scans (of either the face or the whole body), and may be inanimate (Mölbert et al., 2018), controlled by the user's actions (Gorisse et al., 2019), or move 'autonomously' (Fox & Bailenson, 2009). Users may even swap in and out of the doppelganger, switching between 1PP embodiment and a 3PP doppelganger encounter (Slater et al., 2019).

This facilitates VR research on the interaction between model and observer characteristics in the complex phenomenon of imitation (Zentall, 2006), which is a distinct form of modeling behavior (Greer et al., 2006) alongside other forms such as observational learning (Bandura, 1986). Imitative tendencies are closely linked to these other forms of modeling and social learning, both functionally (Fryling et al., 2011) and on a neural level (Carcea & Froemke, 2019). Imitation may be expressed automatically, such as in mimicry of facial expressions, motor and verbal patterns (Duffy & Chartrand, 2015) as well as voluntarily. Automatic imitation and the observer's perception of the model's characteristics are interdependent, which is paramount in the "chameleon effect", i.e. the tendency to imitate others and to affiliate more with those mimicking one's own behavior (Chartrand & Bargh, 1999). A desire to create rapport enhances mimicry (Lakin & Chartrand, 2003), and a positive first impression increases walking synchronization with a stranger (Cheng et al., 2020). It has been argued that the mutually facilitating influences between social affiliation and behavior matching played an important evolutionary role as “social glue” (Lakin et al., 2003). This fits with the influence of perceived model-observer similarity on imitative behavior in many settings (Bussey & Bandura, 1984; Rosekrans, 1967; Stotland et al., 1961). Model-observer similarity is often established by similar sociodemographic traits, such as gender (Bussey & Bandura, 1984) or social background (Rosekrans, 1967), and seems to enhance identification with the model (Stotland et al., 1961). In these studies, imitation is usually quantified by expression frequencies of distinct behavioral patterns but imitative tendencies can also be detected in temporospatial characteristics of movement execution: kinematic similarity of imitative to modeled movement is larger for voluntary than for automatic imitation (Bisio et al., 2010) and can be further enhanced by employing attention and imagery (Bek et al., 2016). An indirect effect of imitative tendencies on the perceptual-motor level is motor interference (Kilner et al., 2003), i.e. the disturbance in movement kinematics when a counterpart performs conflicting movements. This low-level interference does not depend on model-observer similarity in visual appearance (Gandolfo et al., 2019), but rather on similarity in motion kinematics and joint configuration (Kupferberg et al., 2012).

Considering these research strains, virtual doppelgangers can add an interesting tool to investigate the effects of model characteristics on imitative behavior and chameleon effects in VR (Bailenson & Yee, 2005b). With respect to visual appearance, doppelgangers allow to push model-observer similarity to an extreme. At the same time, the use of biological motion patterns retrieved from motion capture can contribute to an appropriate degree of realism, which can be essential for co-presence (Bailenson et al., 2005) and will thus plausibly stimulate the tendency to imitate movements. Among others, this opens up new possibilities for rehabilitation research: both observational modeling mechanisms (Goubert et al., 2011) and (maladaptive) motor behaviors (van Dieën et al., 2017) play important roles in the development of chronic pain, and both mechanisms may be studied and can be therapeutically influenced in combination with virtual doppelgangers.

The current VR study aims at establishing an experimental model for change of motor behavior related to psychosocial processes of identification. It analyzes the interplay of perceived model characteristics and the extent of voluntary motor imitation in healthy volunteers. The specific setup was designed as a pre-study for potential future studies of motion behavior in persons with chronic back pain. We presented characters with different degrees of realism, among them a personalized virtual doppelganger, and let them perform movements with biological kinematics based on motion capture. Participants were asked to imitate these in a joint movement with the model. Our hypothesis was that participants would show more engagement in motor imitation when they associated their counterpart with properties indicating affiliation, model-observer similarity, realism and competence. We designed a questionnaire to assess perception of the characters. We did not try to evoke embodiment for the avatars in our 3PP setup, but still included questions about embodiment (Gonzalez-Franco & Peck, 2018) and enfacement (Tajadura-Jiménez et al., 2012) to explore the potential overlap with these phenomena. We chose intuitive movements that engage the whole body for which we could expect intra-subject variance in movement performance. We explored whole-trunk movements engaging the different degrees of freedom of the spine: flexion, extension and rotation (Laird et al., 2014). As these movements are also influenced by physiological short-time effects such as tiring or stretching (Lima et al., 2019), we randomized the order of appearance of the characters between subjects and treated the loop number of the current movement cycle ("cycle number") as a confounder. To quantify movement engagement, we defined functional Ranges of Motion (ROM), which target the end effectors of a movement (thereby abstracting from the respective solution to the inverse-kinematic motor problem) that can be traced using optical motion tracking both in robotic (Müller et al., 2021) and human movements (Nagymáté & M. Kiss, 2018). We expected that the within-subject average level of motor imitation would be influenced by factors such as trait anxiety, trait empathy, body acceptance, bodily complaints, and social aspects such as gender. However, during exploratory data-driven model selection, these variables did not show relevant effects on average ROM (see supplements), so these trait variables were not further analyzed.

Figure 11. Study 1: Experimental procedure.

In a preparatory session, 3d photographs of the participants were taken with a hand-held Kinect Sensor, for which they were standing on a rotating plate (left panel); head scans were taken separately with subjects seated stationarily (not shown). During the experiment in the four-sided CAVE, participants watched a virtual character (middle panel) and then joined the movement of the latter (right panel).

Figure 12. Study 1: Virtual Characters displayed in the experiment.

Avatar number (AN) labels the equally distanced contrast for the different levels of character realism and personalization. The personalized character (“doppelganger”, AN=4) was designed manually based on 3d photographs (Kinect sensor).

3.3 Materials and Methods

3.3.1 Experimental Design

Thirty-three participants were recruited (mean age 22.3±3.2 years, range 18-30 years, 6 males). Exclusion criteria were neurological preconditions and back pain which had lasted or had reoccurred for more than 6 months. Our final sample size was N_{tot}=30 (two data sets were excluded due to technical problems, and one because the subject had guessed our hypothesis, possibly leading to demand characteristics). The immersive VR was presented using a four-sided Cave Automatic Virtual Environment (CAVE), with participants wearing active shutter glasses to enable stereoscopic vision (Figure 11). Thus, they could always see their own real-world body and move freely without obstruction by a weighty head-mounted display. Motion capture data were acquired with a four-camera optical infrared system using passive reflective body markers (OptiTrack™, Corvallis, OR). Virtual characters were manually crafted using several 3d design software packages, in case of personalized avatars based on 3d photographs acquired with a Kinect Sensor (Microsoft^{TM}, Redmond, WA), using it as a hand-held 3d scanner in a preparatory laboratory session. Psychological characteristics were assessed with on-screen questionnaires and the questions on experiences in the virtual encounter were answered inside the virtual environment with a remote control. In the main session, participants received the instruction to join into the movements of various virtual characters (indexed by avatar number AN, Figure 12) “as much and as well as they could”. Inside the virtual environment, participants would then meet a character performing four different movements: After a phase of watching two movement repetitions in an upright standing position, participants were invited to imitatively join in the movement for five repetitions. The movement series was the same for all movement cycles (indexed by CN, ranging from 1 to 4), each featuring a new character. The order of appearance for the characters was randomized between subjects.

3.3.2 Virtual Characters

Characters were designed with different degrees of realism and similarity to the subject, with a discrete “avatar number” contrast AN indicating the respective level (Figure 12): Avatars 1-3 were generically the same for all subjects (AN=1 for an abstract and faceless stickperson; AN=2 for a humanoid character with body proportions resembling cartoon characters; AN=3 for a generic character with natural proportions). They were designed as gender-neutral, and subjects were later asked for their impression of the characters’ gender (Table 1). Character AN=4 was the custom-tailored personalized “doppelganger”. All characters displayed the same movement animations. These animations were based on post-processed motion capture data of healthy volunteers, recorded with an infrared 12-camera system (OptiTrack™, Corvallis, OR).

3.3.3 Movements and Range of Motion

We defined a set of four movements, which employ the whole body in all anatomical planes and for which we expected some intra-subject variance: extension of the spine (bending backward, BB); lateral flexion of the spine (bending sideward, BS); rotation of the upper body in the horizontal plane (RH); flexion of the spine (“touch your toes” with knees unbent, TT). The movement data for TT were not analyzed, as 25 of our participants could touch the floor, creating a boundary effect. We focused on endpoints of the end effectors of the movements, ignoring the individual kinematic trajectories of the musculoskeletal system. For our motion measurements, we attached 7 optical rigid-body markers to the 3d-glasses, shoulders, hands (only used for TT) and feet (to check that participants had not changed their standing position). We defined an ROM for each movement separately, all based on the shoulder marker positions (Figure 13): For BS and RH, the ROM uses the connecting line between the shoulder markers as a measure for rotation of the upper torso, defining the range of its oscillatory angular deflection as the respective ROM (averaged over all measurable repetitions during one cycle, i.e., five at most). For BB, we define the respective ROM as the extent to which the shoulders go down, taking the height difference between the resting-state standing position and maximal extension (again averaged over the measured repetitions during one cycle). To account for differences in body size, we normalized this ROM measure by dividing the height difference in meters by the subjects' resting-state eye position height (measured with the markers attached to the glasses). This is not necessary for the angular measures defined for BS and RH. Ideally, we have four ROM data points per subject and movement, one for each avatar number. We assessed normality of the ROM data (Q-Q-plots to check outliers; Kolmogorov-Smirnov tests, dataset threshold $p>0.1$) and excluded participants for whom more than two movement cycles had missing ROM data due to failing optical marker detection (3 subjects for BS). The number of subjects eligible for analysis was $N_{BB}=N_{RH}=30$ (BB and RH), and $N_{BS}=27$ (BS). The ROM value ranges for the movements are listed in Table 2 (raw data in Figure 14). The high values of conditional intraclass correlation coefficients (Lüdecke et al., 2021) indicate that intra-subject variation was considerably smaller than inter-subject variation.

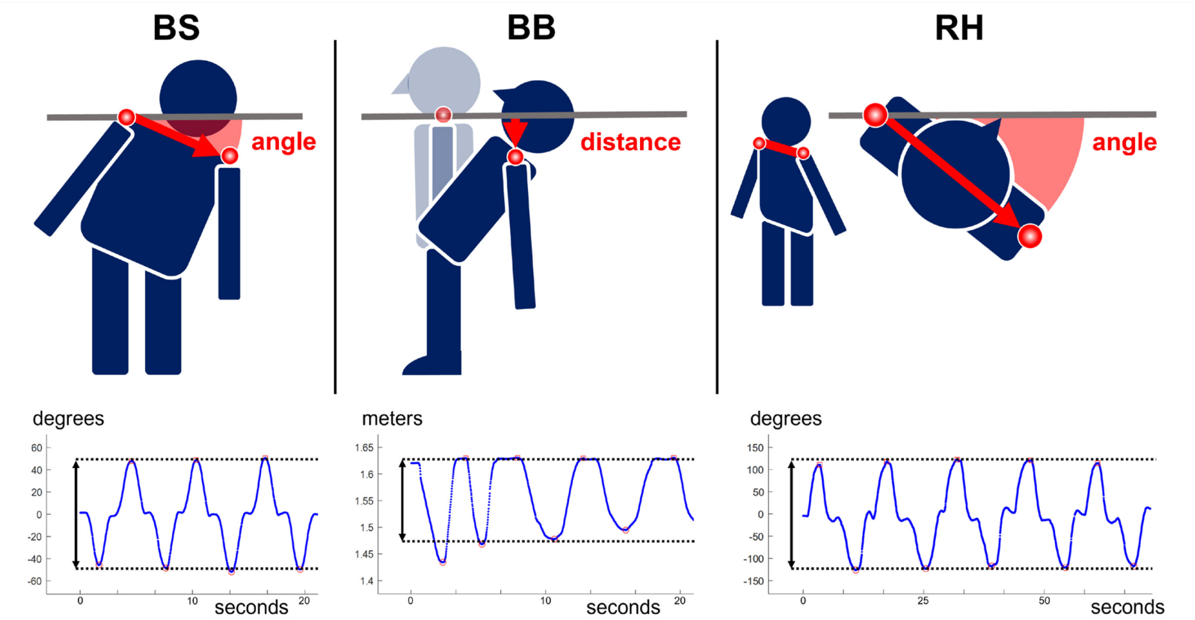


Figure 13. Study 1: Trajectories of end effectors.

Trajectories of end effectors for the three movements analyzed: lateral flexion (BS: bending sideward, left panel), spinal extension (BB: bending backward, middle), rotation in the horizontal plane (RH, right). Rigid-body motion-capture markers placed on the shoulders are shown as red dots. The top row visualizes the definitions for functional Ranges of Motion (fROM), based either on the distance to upright position or rotation angle. Bottom rows: Example data. The respective fROM is the difference between the average local maximum and the average local minimum of the trajectory (for the distance measure in BB, these are normalized by view height in meters).

3.3.4 Principal Component Analysis of Avatar Questionnaires

The questions asked after each cycle were compiled from questionnaires on embodiment (Gonzalez-Franco & Peck, 2018) and enfacement (Tajadura-Jiménez et al., 2012), and complemented with other questions on the avatars' appearance, likability, similarity to the participant, and other characteristics (7-level discrete response scales). We have a rather unusual experimental situation with “autonomous” doppelgangers as movement models. Therefore, we expected that some of the embodiment items, designed for 1PP on a user-controlled avatar, would be understood differently in our setting (e.g., those concerning agency and control) and align with items assessing interpersonal and social aspects of identification and mirroring –

whereas others would assess a sense of bodily identification with the avatar (e.g., “shape-shifting” experiences).

We wanted to differentiate these different levels of identification to analyze their possible role as mediators in ROM enhancement and we conducted an exploratory factor analysis of the questionnaire responses (with four responses per subject, i.e., 120 pooled ratings for each item). We identified the most prominent dimensions in the correlation matrix with a principal component analysis (PCA), which revealed 3 main dimensions according to the component eigenvalues (scree plot). To construct three sum scores, we rotated the respective subspace-projections of our data to optimize the *varimax* criterion. We then assigned each questionnaire item to the axis for which the absolute value of its load was maximal, defining new provisional sum scores (with the sign of each load defining the scoring direction for the item), which we label *Autonomous Avatar Questionnaire* (AAQ) scales 1-3. Scale AAQ1 was later identified as a mediator of AN influence on ROM (BS) and is displayed in Table 1 (AAQ2 and AAQ3 in the supplement). Our post-hoc interpretation of AAQ1 is that it represents avatar naturalism, likability and similarity to the subject, i.e., *perceived ‘identification-enhancing’ avatar characteristics*. For AAQ1, linear mixed effects models for the item ratings, with CN and AN as intra-subject predictors, showed generally moderate effect sizes of AN in the order of 0.4-0.5.[4] The second scale AAQ2 mainly contains items related to the (perceived) *pleasantness of the situation* in reference to both the virtual character and the subjects themselves. The third scale AAQ3 contains items that refer to actual changes in *body perception*. Participants generally gave rather low ratings on this scale, indicating that they perceived the situation rather as an encounter with a

[4] Some examples: β_z=0.5427 for the character’s resemblance to one’s own body, β_z=0.5073 for self-reported identification with the character, β_z=0.4804 for realness of the character, and β_z=0.3881 for perceived likability of the character; for the interpretation of β_z as an analogue to Cohen’s *d*, see section 3.3.5.

virtual “other” than as a virtual mirror situation. A descriptive overview of sum scores on the AAQ scales can be found in Table 2, raw data are shown in Figure 14.

3.3.5 Linear Mixed Effects Modeling

To model the ROM data from our repeated-measures design, we used the approach of linear mixed effects (LME). Conceptually, LME models can be seen as an extension of linear regression for data structured in statistically dependent classes: the measures varying within subjects are level-1 variables (in our case AN, CN, ROMs, AAQs), which have subject-specific deviations (“random effects”) from the generic regression coefficients β for the entire sample (“fixed effects”). (Subject traits would be level-2 variables in our design.) We only assessed first-order effects (for numerical limitations) but allowed for a full covariance matrix of random effects, which is the most conservative approach (Barr et al., 2013; Singmann & Kellen, 2019). For all our fits, we used the *R* package *lme4* function *lmer* to fit the LME models (Bates et al., 2015b), estimating the model coefficients with the maximum likelihood (ML) approach, which allows for a quantitative model selection criterion. All data were centered and generally z-standardized, and therefore the corresponding fixed effects coefficients β_z give a straightforward measure of effect size in analogy to Cohen’s *d* (Hox et al., 2018). CN and AN were not standardized, as in this case the non-normalized weights indicate how strongly two neighboring contrast levels differ in their effects. In this case, effect sizes β_z were later determined by dividing the β weights by the standard deviation of the variable (Hox et al., 2018).

We modeled ROM as a dependent variable in three steps (for each movement separately, see Figure 15). (1) We fitted a simple LME model to the data, with predictors CN and AN, allowing for random intercepts. We acquired confidence intervals and p values (p_{PB}) for the effects via parametric bootstrapping (n_{sim}=10,000, using the *afex* package by Bates et al., 2015).[5] (2) If the effect of AN on ROM was at least marginally significant (p_{PB}<0.1), we started a model selection process to assess whether the AAQ scales should be added as potential mediators to a level-1 model for ROM (with random intercept, CN and AN). For this, we started with AAQ1 as reflecting the most important component in our PCA, and applied a deviance criterion to assess whether the next AAQ scale should be added.[6] (3) For those AAQ sum scores included in the resulting model (a), we fitted a simple LME model for AN effect on the respective AAQ (b). Based on this, we conducted a mediation analysis (c) to estimate the *average causal mediation effect* (ACME) of AN on ROM via AAQ as well as the *average direct effect* (ADE) of AN on ROM, retrieving confidence intervals and *p* values with quasi-Bayesian Monte Carlo simulation methods (Imai et al., 2010) (n_{sim}=10,000, *R* package *mediation*, “treatment level” set to AN=4, “control level” set to AN=3).

Among our several exploratory research threads, we had one quantitative hypothesis: virtual doppelgangers will engage subjects more strongly via identification. To ascertain whether our ROM data supported this, we applied the false discovery rate correction (FDR) (Benjamini & Hochberg, 1995) to the numerically estimated *p* values for the model coefficients, including all coefficients for AN and CN in the models from steps 3, and to the results of the mediation analysis where it was actually calculated, i.e. ACME and ADE from step 4 (in this case we did not include the step-3 *p* value for AN effects, as the latter had been decomposed into ACMEs and ADEs). In our case,

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[5] There are several methods to estimate *p* values for LME models. We also calculated p_{SM} values using the Satterthwaite method, which is usually quite conservative for LME models (Luke, 2017), but in our case was less so than p_{PB}.

[6] We assessed whether the extended model showed an increased deviance *D*, which can be explained by chance with a probability of less than *p*=0.2. This is an anti-conservative method; the thorough inspection follows in step 3 when the actual model analysis is performed. *D* is calculated via doubling the negative log-likelihood of the data given the model; differences in *D* between nested models follow a chi-square distribution and therefore provide a quantifiable measure to assess an increase in explanatory power by adding a variable.

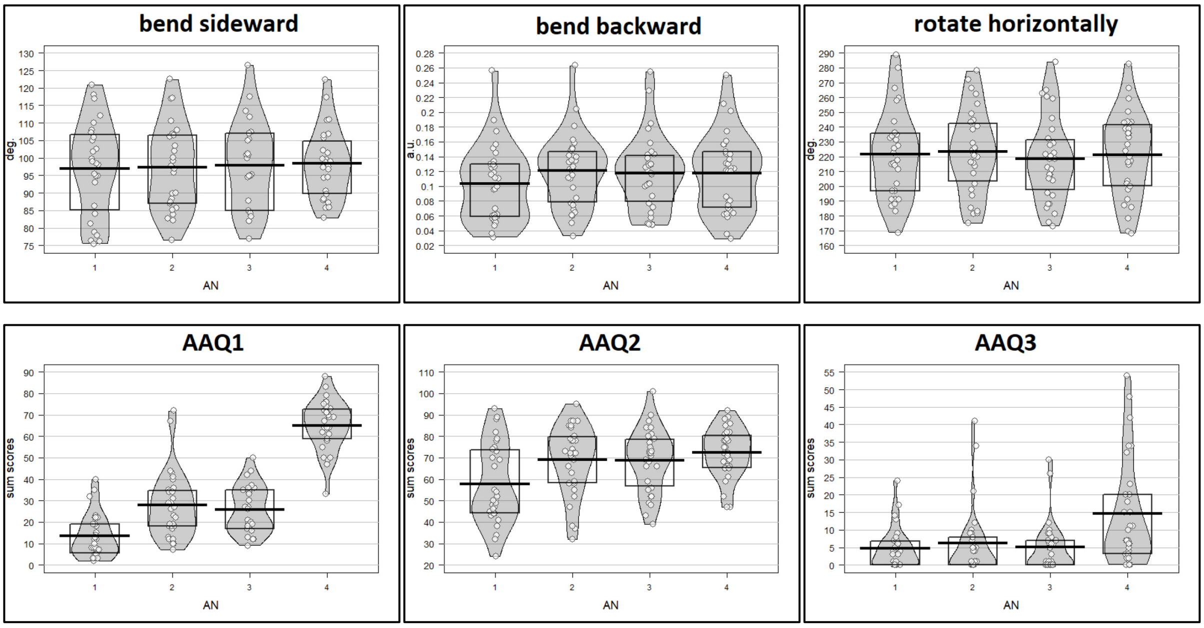

Figure 14. Study 1: Raw data.

Ranges of Motion (ROM) in top row and sum scores for the Autonomous Avatar Questionnaire (AAQ) in the bottom row, per avatar number (AN). The graphs combine scatter plots for the raw data, box plots describing the median (center bar) and the interquartile range (box ends), and smoothed density curves of the respective data distributions; for further descriptive statistics of the data, refer to Table 2. ROMs are given in degrees (deg.) or arbitrary units (a.u.), dependent on their respective definition as described in the main text and in the caption of Figure 3.

Among the ROMs, only for BS ('bend sideward', top left graph) there is a weak positive trend with AN, which is confirmed as marginally significant in the respective linear mixed effects (LME) model (see Table 3). Here the LME analysis reveals an effect that is almost hidden in the raw data graph, as the LME model can take into account the intra-subject dependencies in the data.

Note the strong influence of AN on AAQ1 (indicating perceived *avatar characteristics*) in the bottom left panel, which also shows up in the LME analysis (see Table 4, BS (b)). The other scales, AAQ2 (indicating *situational pleasantness*) and AAQ3 (indicating changes in *body perception*), appear to show some influence of AN as well but were not analyzed quantitatively, as they did not explain a considerable amount of variance in ROM, as required by our model selection process.

we thus included 7 variables in our FDR for the corrected p^* values: two for BB (AN, CN) and RH (AN, CN), and three for BS (CN, ACME of AN on ROM via AAQ1, ADE of AN on ROM).

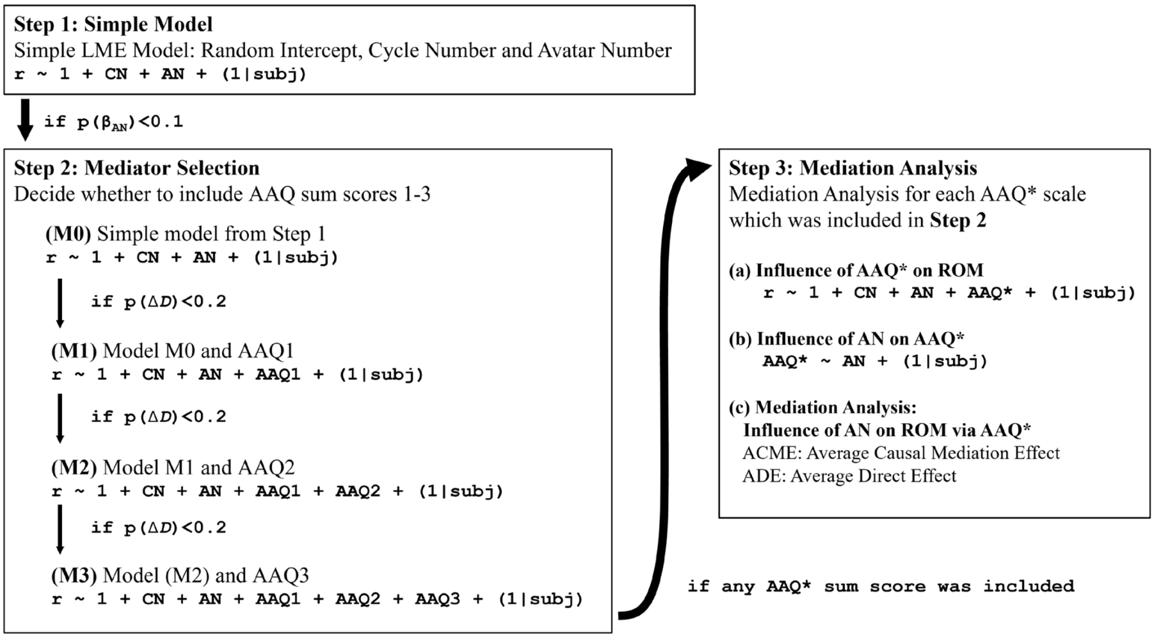

Figure 15. Study 1: Model analyses of Range of Motion (ROM) data.

In step 1, a simple linear mixed effects model with predictors CN (cycle number) and AN (avatar number) is fitted to the ROM as the dependent variable. *R* pseudo-code is given (r = ROM; subj = subject ID; CN = cycle number; AN = avatar number). Step 2 is the selection of model complexity for the mediation analysis, which starts if the effect of AN on ROM in Step 1 is marginally significant ($p<0.1$): Starting from model M0, the respective AAQ scale is only added as a predictor if the decrease in deviance D (2 × negative log-likelihood) meets the criterion $p<0.2$ (chi-square test). It starts with the direct model M0 for CN and AN (step 1 in the main text); then the model selection runs through models M1-3, stopping when the deviance criterion is not met (AAQ*: Autonomous Avatar Questionnaire sum scores). Step 3: The model selection procedure from step 2 then defines which possible mediators (AAQ1-3) should be analyzed in a mediation analysis, with models (a) and (b) to be analyzed in (c).

Table 1. Study 1: Items of the Autonomous Avatar Questionnaire, Scale 1 (AAQ1).

Load	Source	Question
0.6544	B19	At some point it felt that the virtual character resembled my own body in terms of shape, skin tone or other visual features.
0.6360	F8	The character's face began to resemble my own face, in terms of shape, skin tone, or some other visual feature.
0.6140	F3	I felt as if the character's face were my face.
0.5872		I identified myself with the character.
0.5740		The character was the spitting image of myself.
0.5084		How well could you put yourself in the character's shoes?
0.5024		I could empathize with the character quite well.
0.4902	B1	I felt as if the virtual character were myself.
0.4689		Did the character appear as rather male or female?[a]
0.4155		The character was well-dressed.
0.3838		The character was attractive.
0.3767		The character appeared real like a genuine person.
0.3517		The character appeared cheerful.
0.3481		The character was likable.
0.2473	B18	At some point it felt as if my real body was starting to take on the posture or shape of the virtual body that I saw.
0.0803[b]		During the movements, the characters went to the limits of their capacities.

English translation of the German questions. Scales were constructed via *varimax* rotation using the 1st principal component of the correlation matrix for the character ratings as given by all subjects. Items from embodiment (B) (Gonzalez-Franco & Peck, 2018) and enfacement (F) (Tajadura-Jiménez et al., 2012) questionnaires are labeled with their index number, all other items were defined anew. To obtain the sum scores for AAQ1, the respective ratings (ranging from 0 for *"(I do) not (agree) at all"* to 6 for *"(I) totally agree"*) on all items listed above are simply added up.

[a]This item had the anchors "male" (0) and "female" (6) to the sides of the rating scale and was inverted for self-identified male participants (creating a variable "perceived gender match"). [b]This item was ultimately excluded from the AAQ1 scale, due to its low load value.

3.4 Results

For *lateral flexion (BS)*, the positive regression coefficient for AN was marginally significant (β=0.0619, p_{SM}=0.0771, p_{PB}=0.0975, Table 3). This indicated a linear trend in ROM with growing AN (see Figure 14), justifying our further search for mediators among the AAQ sum scores. Besides this, the simple-model LME analysis (step 1) did not show significant effects for CN. In the following mediator selection (step 2), only the scale AAQ1 considerably reduced model deviance. Therefore, it was analyzed as a possible mediator in step 3 (results in Table 4 and Table 5): The LME model (a), which added AAQ1 to AN and CN (which still showed no significant effect: β=0.0494, effect size β_z=0.0440; p_{SM}=0.2712, p_{PB}=0.3030; FDR: p_{PB}^*=0.4242) yielded a significant small-to-medium effect of AAQ1 on ROM (effect size β_z=0.1563; p_{SM}=0.0082, p_{PB}=0.0210). In turn, AAQ1 was strongly dependent on AN in the respective single-predictor LME model (b) (β=0.6637, effect size β_z=0.5864; $p_{SM}<2\times10^{-16}$, p_{PB}=0.0010). Not surprisingly, the following mediation analysis (c, Table V) thus showed a significant effect which survived false discovery rate correction (ACME, β=0.1039, effect size β_z=0.0918; p_{MC}=0.0064, p_{MC}^*=0.0329). There was no significant direct effect of AN on ROM (ADE, β=-0.0508, effect size β_z=-0.0449; p_{MC}=0.3670, p_{MC}^*=0.4282), showing that AAQ1 was a relevant mediator for AN effects on ROM for BS.

In case of *spinal extension (BB)* and *rotation in the horizontal plane (RH)*, our analyses (step 1, see Table 3) did not reveal any relevant effects of avatar number (AN), neither for BB (β=0.0531, effect size β_z=0.0473; p_{SM}=0.1039, p_{PB}=0.1116, p_{PB}^*= 0.1953) nor for RH (β=-0.0203, effect size β_z=-0.0181; p_{SM}=0.4870, p_{PB}=0.5206; p_{PB}^*=0.5206). Therefore, both movements did not enter the mediator-exploration process (step 2). Both movements, however, showed an interesting effect of cycle number (CN), with small effect sizes which remained significant after FDR. For BB, there appeared to be a tiring effect (negative sign for CN: β=-0.1063, effect size β_z=-0.0947; p_{SM}=0.0115, p_{PB}=0.0141; p_{PB}^*=0.0329). Regarding RH, subjects apparently got better with growing CN, arguably due to stretching/ warming-up (β=0.0917, effect size β_z=0.0817; p_{SM}=0.0064, p_{PB}=0.0111; p_{PB}^*=0.0329).

Table 2. Study 1: Descriptive statistics of behavioral measures.

Variable[a]	Descr. [b]	Mean	SD[c]	Median	Min	Max	ICC[d]
BS	ROM [deg.]	97.6532	12.0770	98.2964	75.5187	126.5552	0.9248
BB	ROM [a.u.]	0.1148	0.0511	0.1203	0.0289	0.2634	0.9508
RH	ROM [deg.]	221.0679	28.4249	220.2689	168.2170	288.6591	0.9435
AAQ1	Sums 15 items, range 0-90	33.0417	22.7992	27	2	88	0.0668
AAQ2	Sums 17 items, range 0-102	67.0167	16.3208	71	24	101	0.3128
AAQ3	Sums 11 items, range 0-66	7.6667	10.8297	5	0	54	0.5276

ROMs (Ranges of Motion) for the three movements analyzed, and sum scores for the ratings on the Autonomous Avatar Questionnaires (AAQ1-3). Scatter and box plots of the raw data are shown in Figure 4. For detailed statistics per avatar condition, see supplements. For the ROM definitions, see Figure 13. Rotational ROMs (bending sideward, BS, and rotating horizontally, RH) are measured in degrees [°]; in contrast, translational ROMs (bending backward, BB) are in arbitrary units [a.u.] (maximal distance of the end effector, divided by the subject's view height). Note the high intraclass correlations for all movements, indicating the intra-subject variation was considerably smaller than inter-subject variation. AAQ1-3 are sum scores, based on the first principal components of the correlation matrix for pooled ratings (*varimax* rotation for scale definition): Characters were rated during the experiment, with integer response levels from 0 to 6; questions were compiled from embodiment (Gonzalez-Franco & Peck, 2018) and enfacement (Tajadura-Jiménez et al., 2012) questionnaires and new items defined for this experiment. Possible post-hoc interpretations are AAQ1 indicating *positive avatar characteristics* (cf. Table 1), AAQ2 indicating *situational pleasantness*, and AAQ3 indicating *body perception changes* (see supplements). The low intraclass correlation coefficient for AAQ1 suggests that subject-specific biases were not as important for this scale as for the others.

[a]BB = bending backward, RH = rotation in the horizontal plane, BS = bending sideward, AAQ = Autonomous Avatar Questionnaire. [b]Description of the respective variable: ROM = Range of Motion, deg. = degrees, a.u. = arbitrary units (in this case: ROM [meters] divided by view-height of subjects [meters]). [c]SD = standard deviation. [d]ICC = conditional intra-class correlation, determined with *R* package *performance* (Lüdecke et al., 2021).

Table 3. Study 1: Parameters for direct LME models.

M.[a]	Pred.[b]	β	Std. Error	CI Lower	CI Upper	df[c]	t[c]	$p_{SM}(t)$[c]	p_{PB}	p_{PB}*	Effect Size β_z
BS	Int.	0.0459	0.1867	-0.3187	0.4079	26.5315	0.2460	0.8076	---	---	---
	AN	0.0619	0.0334	-0.0041	0.1270	22.6705	1.8520	0.0771	0.0975	---	0.0547
	CN	0.0413	0.0435	-0.0447	0.1271	26.7273	0.9500	0.3508	0.3374	---	0.0367
BB	Int.	3.31e-15	0.1706	-0.3339	0.3328	30.0000	0	1	---	---	---
	AN	0.0531	0.0317	-0.0094	0.1156	30.6100	1.676	0.1039	0.1116	0.1953	0.0473
	CN	-0.1063	0.0395	-0.1843	-0.0285	29.9900	-2.693	0.0115*	0.0141*	0.0329*	-0.0947
RH	Int.	-6.29e-16	0.1733	-0.3434	0.3499	30.0000	0	1	---	---	---
	AN	-0.0203	0.0288	-0.0774	0.0361	28.2500	-0.7040	0.4870	0.5206	0.5206	-0.0181
	CN	0.0917	0.0313	0.0311	0.1535	30.4200	2.9300	0.0064*	0.0111*	0.0329*	0.0817

Results of linear mixed effects (LME) analysis of possible within-subject effects of avatar number (AN) and cycle number (CN) on functional Range of Motion (fROM). Given are the regression weights for fixed effects, β, in the direct LME models to fROM data, with confidence intervals (CI), *p* values (SM = Satterthwaite Method, PB = Parametric Bootstrapping) and effect sizes (β_z). Corrected *p* values (p_{PB}*) are stated for those model parameters which went into the False Discovery Correction, as described in the text. For BS, there are no corrected *p* values, because in this case a more in-depth mediation analysis was conducted. The results of this analysis are reported in Tables IV and V; the *p* values reported there were also included in the False Discovery Correction.

[a]Movements: BB = bending backward, RH = rotation in the horizontal plane, BS = bending sideward. [b]Predictors: Int. = Intercept, AN = Avatar Number, CN = Cycle Number. [c]Values estimated with the Satterthwaite Method.

Table 4. Study 1: Model Fits for later mediation analysis.

M.	Pred.	β	Std. Error	CI Lower	CI Upper	df	t	p_{SM}(t)	p_{PB}	p_{PB}*	Effect Size β_z
BS (a)	Int.	0.0438	0.1872	-0.3196	0.4001	26.5992	0.2340	0.8169	---	---	---
	AN	-0.0521	0.0544	-0.1629	0.0556	70.6093	-0.9590	0.3408	0.3744	---	-0.0461
	CN	0.0494	0.0440	-0.0375	0.1368	27.3959	1.1230	0.2712	0.3030	0.4242	0.0440
	AAQ1	0.1563	0.0564	0.0413	0.2728	43.2267	2.7720	0.0082	0.0210*	---	0.1563
BS (b)	Int.	0.0136	0.0668	-0.1135	0.1418	26.6042	0.2040	0.8400	---	---	---
	AN	0.6637	0.0565	0.5515	0.7776	77.6671	11.7470	<2e-16	0.0010***	---	0.5864

Preparation of Mediation Analysis (steps 3 a and b in Figure 15) for lateral flexion (bending sideward, BS). In step (a), influence of AN, CN and AAQ1 on ROM are analyzed; in step (b), an LME model for AN predicting AAQ1 is fitted. Abbreviations like in Table 3.

Table 5. Study 1: Results of mediation analysis.

M.	Effect Category[a]	Estimate	CI Lower	CI Upper	p_{MC}	p_{MC}*	Effect Size
BS (c)	ACME	0.1039	0.0306	0.1800	0.0064**	0.0329*	0.0918
	ADE	-0.0508	-0.1620	0.0600	0.3670	0.4282	-0.0449
	Total Effect	0.0531	-0.0262	0.1300	0.1984	---	---

Final Mediation Analysis (step 3 c in Figure 15) for the influence of AN via AAQ1 on fROM (for movement BS), based on the LME models in Table 4. Treatment level is set to AN=4, control level on AN=3. Most abbreviations follow those in Table 3 and Table 4.

[a]ACME = Average Causal Mediation Effect, ADE = Average Direct Effect.

3.5 Discussion

3.5.1 Assessment of Functional Ranges of Motion

We established a method of quantitative functional assessment of whole-body motion behavior by tracking trunk-based end effectors of the respective movements. From the oscillatory trajectories of these markers, we derived functional ranges of motion (ROM), which abstract from the individual musculoskeletal kinematic realization of the movement. These ROM values showed sufficient within-subject variation to investigate influences of variables under experimental control, as in our case the avatar number. This opens up new approaches to assess subjects' engagement in virtual reality tasks in an implicit way besides explicit self-report. Due to the importance of collaborative and imitative behavior in general, we recommend to assess such functional ranges of motion in VR experiments, if a movement end effector can be defined and tracked. As the ROM definitions abstract from subject size, they allow for at least an exploratory assessment of the influence of psychological traits. Although we did not find any significant effects of trait variables in our case, inclusion of such variables in future experiments may be a promising way to investigate possible influences on subjects' engagement in VR setups.

3.5.2 Autonomous Virtual Characters in Joint Movements

Our experiment set up a virtual encounter situation with characters of different degrees of realism and similarity to the subjects. In contrast to many setups with virtual characters controlled by or reacting to the user's actions, our setup shows a reversion of initiative, as the avatars moved on their own, autonomously. The instruction to observe the character emphasized the initial agentic asymmetry of the situation. Therefore, our setup cannot easily be fit into embodiment or encounter paradigms, especially for the doppelganger: neither is the character under control of the user, as in VR setups showing an avatar in 1PP or in a virtual mirror, nor is it a virtual counterpart interacting in a complementary way with the user. In addition, the doppelganger clearly displays visual properties closely linked to the subject's appearance, as indicated by the high ratings on AAQ1 items such as similarity and likability for these characters. Therefore, several items based on scales of embodiment and enfacement became disentangled and reallocated over all three AAQ scales, derived from our exploratory PCA: Many items from embodiment and enfacement questionnaires significantly correlated with items aiming at social identification with role models, and aligned along the same principal component. This indicates that in our setup, many of the embodiment/ enfacement items measure a different phenomenal aspect than in their original contexts (e.g., those items asking for an increasing resemblance of avatar appearance or posture to the subject). However, this was an explorative analysis, with the limitation that the results of our PCA of grouped data (four ratings per subject) may partially depend on subject-specific idiosyncrasies, and our doppelganger situation is highly specific. Nevertheless, the alignment of "likability" and "similarity" strongly suggests a correlation of these aspects as suggested by social learning theory (Bandura, 1986) and theoretic accounts of the chameleon effect (Lakin et al., 2003). In our experimental setup, the correlational alignment of all these different items assessing affiliative characteristics prevents a more detailed differentiation of underlying mechanisms, which would be an interesting research question to be addressed with more sophisticated avatar manipulations using morphing techniques. We suggest that our exploratory AAQ scales may be used as a starting point to investigate perception and behavior in VR setups examining observational modeling of autonomous virtual characters.

3.5.3 Virtual Characters as Movement Models

Behavioral modeling arises in observational situations of various forms (Bandura, 1986): from intentional learning by observation (Greer et al., 2006) to nonconscious mimicry (Chartrand & Bargh, 1999) and motor interference between one's own and others' coincident movements (Kilner et al., 2003). In our case, participants were explicitly asked to imitate the virtual character's autonomous movements as best as they could. Thus, participants' attention was explicitly drawn to the model's behavior, without them being aware of the task objective of motor enhancement. We tested the hypothesis that observers' self-reported perceptions regarding model-observer similarity, identification with and positive properties of the model would enhance engagement in modeling, thereby mediating an effect of character realism and personalization (AN) on Range of Motion. VR made it possible to push model-observer similarity to the extremes, with a faceless stickperson on the one end and a photorealistic doppelganger on the other end of the spectrum.

Two of the experimental movements (RH and BB) showed only stretching or fatigue effects. For one movement (BS), however, we could indeed substantiate our hypothesis, as adding the variable AN (avatar number) considerably decreased the deviance of our LME models (hence added explanatory power) and showed a marginally significant effect in the resulting model (p_{SM} and p_{PB}). Starting there, we analyzed further whether any of the new AAQ scores showed a significant effect on functional ROM when included into the LME models, which was the case for the scale which indicated perceived affiliative avatar characteristics (containing items related to the observed model's appearance, likability, observer-model similarity and identification, all of which correlated significantly): the analysis showed that AAQ1 exerted a significant small-to-medium effect on ROM. On the other hand, AN predicted the AAQ1 ratings with a large effect size. Our final mediation analysis revealed a significant effect of AN on ROM mediated by the AAQ1 score, which remained significant after FDR correction.

A post-hoc interpretation of this finding could be that BS was the only movement for which the virtual model could be kept in view for the entire movement cycle. Temporally looking elsewhere, as required in RH and BB, may have limited the perception of and attention towards the character and the joint movement synchronization. This suggests that these factors may be pivotal, which could be tested in future experiments by manipulating character visibility and diverting attention with distractors. Future research may also use morphing techniques to continuously vary model-observer-similarity and perceived affiliation, which may reveal different sub-processes and enable larger effect sizes in VR setups exploring functional motor engagement in imitation of virtual movement models.

3.5.4 Application in Pain Research and Beyond

Our study could show an enhancement of imitative motor behavior by perceived affiliative/ identificatory model characteristics. This is a novel approach, which explores virtual characters as imitation models for pain-related movements (although as a pilot in a healthy sample) using a CAVE. Given the functional and neural interconnections between imitation and other modeling phenomena (Bandura, 1986; Carcea & Froemke, 2019), a natural next step would be to couple the virtual characters' movements with the presence of positive reinforcers or an absence of aversive consequences, i.e., by adding vicarious reinforcement (Bandura, 1965). A study with virtual (facial) doppelgangers experiencing weight-loss after exercise found that observers' own exercise behavior was facilitated by identification with the models (Fox & Bailenson, 2009). Thus, VR setups with virtual doppelgangers promise to establish a powerful tool, potentially drawing on both observational/ vicarious learning and operant conditioning.

This could open a new approach to VR-based treatments for pain, which have evolved from treating acute conditions based on distraction analgesia (Hoffman et al., 2000), over analgesic effects of seeing one's virtual body (Nierula et al., 2017), to actively changing the appearance of embodied virtual limbs to address chronic pain (Matamala-Gomez, Diaz Gonzalez, et al., 2019). Especially the latter approach is a promising tool in novel treatments of changes in body representation in chronic pain (Matamala-Gomez, Diaz Gonzalez, et al., 2019). Further expanding the increasingly differentiated approaches to VR treatment (Donegan et al., 2020), we suggest bringing VR to the realm of overt motor behavior and pain. The latter are closely interdependent in the transition from acute to chronic pain, which is often accompanied by fearful expectancies, such as fear avoidance beliefs (Vlaeyen et al., 2016), and avoidance behaviors with respect to everyday movements (van Dieën et al., 2017). Here as well as in general, non-vicarious (operant and respondent) conditioning (Gatzounis et al., 2012; Thieme et al., 2005) and observational learning from vicarious experience (Goubert et al., 2011) contribute to the multi-faceted complex of chronic pain (Flor, 2017). This is mirrored by observational placebo effects, i.e. analgesic effects from placebo treatments previously observed to succeed in others (Colloca & Benedetti, 2009), a phenomenon closely linked to modeling and social learning (Colloca et al., 2013). Effects of vicarious experience on pain and motor behavior have also been found with virtual models in 3PP, both in healthy participants (Fusaro et al., 2016) and in chronic back pain (Alemanno et al., 2019). We suggest that an "observational operant conditioning" setup in VR could be integrated into existing operant conditioning and exposure treatments of fear of movement and avoidance behavior in chronic back pain (Flor & Turk, 2011; Vlaeyen et al., 2012). Virtual doppelgangers would show pain-free behavior as highly relatable models, and the mere absence of negative reinforcers on their behavior, indicated by displayed smoothness and painlessness, could provide vicarious reinforcement to the observers and diminish their avoidance beliefs and behavior.

Beyond this specific area, our functional ROMs based on trunk end effectors offer an assessment of motor engagement independent of self-report, applicable to different VR setups addressing psychological aspects of interpersonal behavior. Research on imitative/ collaborative virtual encounter situations may also use our AAQ1-3 scales to assess phenomenal experiences, although future analyses may suggest considerable adaptations. Our finding that enhancement of voluntary motor imitation of lateral flexion (BS) is mediated by perceived characteristics of a virtual character supports the idea that perceptual, motivational and cognitive systems engaged in imitation and social learning extend to fictional models (Bandura, 1986), offering a promising line of future research with further enhanced identification with characters in immersive VR.

3.6 Acknowledgement

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4 STUDY 2: EFFECTS OF PERSONALIZED MOVEMENT MODELS IN VIRTUAL REALITY ON PAIN EXPECTANCY AND MOTOR BEHAVIOR IN PATIENTS WITH CHRONIC BACK PAIN[7]

4.1 Abstract

Cognitive-behavioral models of chronic pain assume that fear of pain and subsequent avoidance behavior contribute to pain chronicity and the maintenance of chronic pain. In chronic back pain (CBP), avoidance is often addressed by teaching patients to reduce pain behaviors and increase healthy behaviors. The current study explored if personalized virtual movement models (doppelganger avatars), who maximize model-observer similarity in virtual reality (VR), can influence fear of pain, motor avoidance and movement-related pain and function. In a randomized controlled trial, participants with CBP observed and imitated an avatar (AVA, N=17) or a videotaped model (VID, N=16) over three sessions, where moving a beverage crate, bending sideward (BS), and rotation in the horizontal plane (RH) were shown. Self-reported pain expectancy, as well as engagement, functional capacity and pain during movements, were analyzed along with and range of motion (ROM). The AVA group reported higher engagement with no significant group differences observed in ROM. Pain expectancy increased in AVA but not VID over the sessions. Pain and limitations did not significantly differ. However, we observed a significant moderation effect of group, with prior pain expectancy predicting pain and avoidance in the VID but not in the AVA group. This can be interpreted as an effect of personalized movement models decoupling pain behavior from movement-related fear and pain expectancy. Thus,

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Note: Numbering of sections, figures and tables adjusted for consistent labeling throughout this thesis.

personalized virtual movement models may provide an additional tool for exposure and exercise treatments in cognitive behavioral treatment approaches to CBP.

4.2 Introduction

Learning processes such as operant and respondent conditioning are thought to play a major role in chronic primary back pain (CBP), where they lead to fear of pain and avoidance behaviors (Flor & Turk, 2011; Lethem et al., 1983; Vlaeyen & Linton, 2000, 2012). It is assumed that pain and catastrophizing thoughts feed into the development of pain-related fears, which lead to the avoidance of activities such as movement. This acquired behavior, which interferes with daily-life activities, results in maladaptive consequences, which contribute to pain perseveration such as disuse, functional disability, negative affect and depression (Crombez et al., 2012). Avoidance can take different forms, from complete avoidance of specific movements (Volders et al., 2015) to safety-seeking behavior in guarded movements (Tang et al., 2007) and decreased movement variability (van Dieën et al., 2017). Cognitive-behavioral treatments focus on the reduction of catastrophizing and pain-related fear and avoidance by having patients execute feared pain-related movements in a safe environment (Flor & Turk, 2011; Main et al., 2014; Vlaeyen et al., 2012). In these treatment approaches, therapists and other patients can serve as models for the execution of feared pain-related behaviors and behaviors are often videotaped and fed back to the patients. Showing patients how to perform adaptive healthy behaviors is also important in physical therapy related to chronic pain (e.g., Marich et al., 2018). Modeling and social learning are important modulators of both acute and chronic pain (Goubert et al., 2011) and can thus be important techniques in pain treatment. Virtual reality (VR) can be employed to stimulate modeling in new ways. Virtual characters that resemble their observers in facial features and perform sportive exercise with concurrent virtual weight loss can motivate exercise behavior in healthy observers (Fox & Bailenson, 2009). Stimulating physical exercise is also a main goal of VR applications in chronic pain, as a recent review of VR studies in CBP has highlighted (Bordeleau et al., 2022). However, only few studies use highly immersive technology for this purpose, usually by motivating movements via game-like elements (France & Thomas, 2018; Jansen-Kosterink et al., 2013) or by feedback displayed on a virtual character (Alemanno et al., 2019), with a recent study successfully adapting such an exercise game to graded exposure schedules (Hennessy et al., 2020). Other approaches address the significance of the plasticity of self-perception (Matamala-Gomez, Donegan, et al., 2019) in modulating pain. For example, the embodiment of virtual limbs, which may be evoked by colocation and synchronous visuotactile stimulation of the real limb and its virtual counterpart, can lead to a type of visually induced analgesia in both experimental pain settings (Nierula et al., 2017) and with respect to chronic pain (Matamala-Gomez, Diaz Gonzalez, et al., 2019). VR also enables encounters with virtual doubles, or “doppelgangers”, in a third-person perspective (Bailenson, 2012). This can be used to stimulate observational modeling by maximizing model-observer similarity. For example, high identification with doppelgangers was found to mediate an increased imitation in lateral spine flexion in healthy participants (Kammler-Sücker et al., 2021). The current study explored if the demonstration of back-related movements by a virtual doppelganger compared to videos of these movements would lead to reduced fear of pain and better performance of the movements as assessed by motion tracking. By repeating the virtual experience for a total of three sessions we could also test if this effect would be immediate or required training.

Table 6. Study 2: Demographic and clinical characteristics of the participant sample.

TABLE A	AVA	VID	Statistic	Test
***N* (in final data set)**	17	16		
Gender	5 males	7 males	Odd's Ratio: 0.55	Fisher's Exact Test: $p = 0.48$
Level of Education				
(Upper secondary, Bachelor's equivalent, Master's equivalent)	(11, 4,2)	(6, 7, 3)	$X^2 = 2.46$	Pearson's Chi-squared Test: $p = 0.29$

TABLE B	AVA		VID			
	mean (sd)	median (IQR)	mean (sd)	median (IQR)	Brown-Forsythe	Mann-Whitney *U*
Age	46.12 (17.61)	51 (34)	51.88 (17.39)	59 (30.25)	$F_{(1,30.92)} = 0.89$, $p = 0.35$	$W = 101.5$, $p = 0.22$
Pain Years	17.80 (15.28)	16 (21)	12.69 (11.50)	9 (15.88)	$F_{(1,30.92)} = 1.19$, $p = 0.28$	$W = 162.0$, $p = 0.36$
GCPS Grade	1.94 (0.83)	2 (2)	1.75 (0.93)	1.5 (1)	$F_{(1,30.03)} = 0.39$, $p = 0.28$	$W = 157.0$, $p = 0.43$
MPI Pain Intensity	2.69 (0.92)	2.67 (0.67)	2.38 (1.10)	2.50 (0.83)	$F_{(1,29.27)} = 0.77$, $p = 0.39$	$W = 162.0$, $p = 0.35$
MPI Interference	2.15 (1.37)	1.9 (1.25)	1.70 (1.07)	1.75 (1.47)	$F_{(1,29.94)} = 1.08$, $p = 0.31$	$W = 160.5$, $p = 0.39$
MPI Affective Dist.	2.57 (1.28)	2.67 (1.67)	2.33 (0.82)	2.33 (0.75)	$F_{(1,27.32)} = 0.40$, $p = 0.53$	$W = 154.0$, $p = 0.53$
MPI Social Support	2.57 (1.32)	3.00 (1.33)	2.85 (1.70)	2.67 (2.75)	$F_{(1,28.27)} = 0.29$, $p = 0.60$	$W = 127.0$, $p = 0.76$
MPI Life Control	3.82 (1.25)	3.67 (2.00)	4.33 (0.99)	4.33 (0.75)	$F_{(1,30.11)} = 1.69$, $p = 0.20$	$W = 98.5$, $p = 0.18$
FFbH FC	89.78 (8.57)	92.11 (15.79)	93.91 (6.64)	96.05 (11.18)	$F_{(1,29.93)} = 2.41$, $p = 0.13$	$W = 96.0$, $p = 0.15$
FABQ PA	8.00 (5.01)	8 (8)	10.69 (7.00)	9.5 (13.25)	$F_{(1,27.06)} = 1.59$, $p = 0.22$	$W = 110.0$, $p = 0.36$
HADS Anx.	7.29 (3.82)	7 (4)	7.19 (3.41)	7 (3.75)	$F_{(1,30.92)} = 0.01$, $p = 0.93$	$W = 133.0$, $p = 0.93$
HADS Dep.	5.12 (3.02)	4 (4)	4.00 (2.61)	4 (2.25)	$F_{(1,30.79)} = 1.30$, $p = 0.26$	$W = 163.0$, $p = 0.33$

Values were assessed at baseline in the preparatory session (Session 0). With respect to categorical variables (upper table, TABLE A), no significant group differences were detected. The same held with respect to numerical variables (lower table, TABLE B), for which Brown-Forsythe Tests for differences in variance and Mann-Whitney *U* Tests did not reveal significant differences.

Abbreviations: Affective Dist. – affective distress; AVA – experimental group (avatar); VID – control group (videotaped model); sd – standard deviation; IQR – interquartile range.

Questionnaires: FABQ PA – Fear Avoidance Belief Questionnaire, Physical Activity Subscale; FFbH FC – Hannover Functional Ability Questionnaire, Functional Capacity Score; GCPS – Graded Chronic Pain Scale; HADS – Hospital Anxiety and Depression Scale (Anxiety, Depression); MPI – West Haven-Yale Multidimensional Pain Inventory.

4.3 Methods

4.3.1 Participants

We tested 34 participants with chronic back pain. Eligibility criteria were chronic back pain lasting for more than 6 months and an age of 18-75 years. Exclusion criteria were any acute primary causes for back pain (e.g., injuries or inflammation), acute neurological complications, and inability or medical prohibition to lift weights of up to 15 kg. Eligibility and exclusion criteria were checked in an initial telephone interview and confirmed upon arrival in the laboratory. Participants were randomly assigned to the two intervention groups AVA (experimental group: doppelganger avatar) and VID (control group: videotaped movement model). All participants completed the experiment. Data of one participant were excluded from the analysis due to concurrent migraine that had not been reported in the initial evaluation. The two groups did not significantly differ in gender, age, level of education and pain characteristics (see Table 6). Participants were mainly recruited by press releases issued online and in local newspapers. Informed consent was obtained and the study was approved by the Ethics Committee II of the University of Heidelberg (Medical Faculty Mannheim).

4.3.2 Baseline Assessment

In the baseline assessment, the in- and exclusion criteria were verified and the participants completed a set of questionnaires that included a description of their pain and related clinical variables. We employed the German version of the *West Haven-Yale Multidimensional Pain Inventory* (Flor et al., 1990; Kerns et al., 1985), which assesses the impact of pain on respondents' daily lives, the reactions of others to their pain, and to which extent the patients participate in daily activities. We focused on the first section with five subscales (Pain Intensity, Interference, Affective Distress, Social Support, Life Control). Sum scores are retrieved from the average responses to the scale items on a seven-point rating scale (0 to 6). Participants also completed the *Graded Chronic Pain Scale* (GCPS) (Von Korff et al., 1992), which allows for a grading of chronic pain (grades 1 to 4), based on intensity and pain-related disability inferred from responses on ten-point rating scales. To assess potential symptom burdens of anxiety and depressive mood, we also administered the *Hospital Anxiety and Depression Scale* (HADS) (Herrmann et al., 1995; Zigmond & Snaith, 1983), which measures these two dimensions with separate scales (scored 0 to 21), summing up responses on four-point rating items. To assess functional capacity in daily life, the *Hannover Functional Ability Questionnaire* (FFbH) (Raspe et al., 1990; Raspe & Kohlmann, 1991) was used, which uses three-point rating scales to derive a percentage score for functional capacity (0 to 100). Cognitive Expectancies related to fear and avoidance were assessed with the *Fear Avoidance Belief Questionnaire* (FABQ) (Pfingsten et al., 2000; Waddell et al., 1993), which has two subscales with pain beliefs and harm expectations with respect to physical activities in general, and to job-related activities in particular. We used the physical activities subscale, which retrieves a sum score (0 to 24) from responses on six-point rating scales.

4.3.3 Experimental Design

The experiments were conducted in a four-sided Cave Automatic Virtual Environment (CAVE; setup by *Engineering Systems Technology*, Kaiserslautern, Germany) in the VR Core Facility at the Center for Innovative Psychiatric and Psychotherapeutic Research (CIPP) at Central Institute for Mental Health (Mannheim, Germany), and comprised three experimental sessions and a preparatory and baseline assessment session (Figure 16). During the baseline assessment and preparatory session (session 0), participants were informed about the experimental procedures and data management, signed informed consent and completed the assessment. They were familiarized with the laboratory environment and had their 3d photographs taken. The subsequent three experimental sessions (sessions 1-3) were at least 4 and a maximum of 117 days apart. Due to the pandemic situation we had to reschedule the participants when there was a ban on laboratory activity. The mean duration between sessions was 13.65 ± 16.08 days and not significantly different between the groups (Mann-Whitney U test, $W = 620$, $p = 0.32$). In each VR session, an initial assessment of pain expectancy and current pain state (see the section on questionnaire assessment below) was followed by the actual VR experiment. Participants in the experiment group encountered their virtual doppelganger avatars in the virtual environment (AVA), whereas the control group saw a virtual 2d screen inside the virtual environment showing a videotaped movement model (VID). Both groups were not aware of the other branch of the experiment, the two-group design was disclosed to the participants only after the last session. In the virtual environment, participants watched the virtual movement model perform a specific movement and the participants copied the movement three times based on a virtual sign and an auditory signal.

The demonstrated movements were adapted from recent studies on pain-related movement kinematics (Laird et al., 2014) and expectancies (Klinger, Kothe, et al., 2017; Schmitz et al., 2019): lateral flexion of the spine ("bending sideward", *BS*), spinal rotation in the horizontal plane (*RH*) and picking up a crate with water bottles (weight: 13 kg), putting it on a chair and moving it back to the floor ("crate-moving", *CM*). This procedure was repeated for all three movement types, with three repetition cycles for the entire sequence (order of movement types randomized between cycles). In total, participants were asked to repeat each movement 9 times during each session. They could skip or shorten any movement cycle with a hand gesture at any time. After the experiment and still immersed in the VR, participants used a remote control to give ratings on a numeric ratings scale (NRS) on questions regarding the virtual model and virtual environment. Following the VR sessions, they answered questions about the movements and accompanying pain in paper and pencil format (described below).

4.3.4 Technical Setup

In the four-sided CAVE, participants wore stereoscopic light-weight shutter-glasses (*Optoma*, New Taipei City, Republic of China). Head-tracking and motion capture for movement analysis was realized using an optical four-camera system (*OptiTrack*, Corvallis, OR) to track the movements of passive reflective markers on the subject's shutter-glasses and shoulders. The CAVE setup allowed for the implementation of a highly immersive mixed-reality design, as participants could still see real-world objects clearly through the shutter-glasses. Hence, they could interact both with the crate of water bottles and the chair located in the CAVE with them, as well as with a hand-held remote control waiting to be picked up for answering questions inside the virtual environment. The VR experiment was run on *Vizard 6* (*WorldViz VR*, Santa Barbara, CA).

4.3.5 Stimulus Design

The virtual environment used in the experiment was designed to provide a distraction-free, yet esthetically pleasant indoor environment with light conditions matching those of the real-world laboratory. The virtual room resembled a dojo training room equipped with green plants and a room fountain emitting a gurgling sound. The only difference between groups was that the room contained either a virtual chair with a beverage crate object (AVA) or a “cinematic” virtual 2d screen for presenting the video recordings (VID). A virtual training mat served as an orientation mark in the middle of the CAVE. All virtual objects and the environment were designed using commercially available 3d design software. The personalized doppelganger avatars (see Figure 17) were based on 3d photographs taken with a *Kinect* Sensor (*Microsoft*, Redmond, WA), which was used as a hand-held 3d scanner and slowly moved around the subjects, who stood still with arms stretched out (for scans of the torso, arms and legs, see Figure 18) or sat on a chair (for scans of the head and face). Surface meshes for the virtual avatars were manually designed through a pipeline that included several 3d design software packages, particularly *3ds Max 2019* (*Autodesk*, San Rafael, CA) and *MeshLab* (Cignoni et al., 2008). Avatar rigging and animation with prerecorded movements were achieved using *Mixamo* (*Adobe*, Mountain View, CA) and *MotionBuilder* (*Autodesk*, San Rafael, CA). To maximize comparability of movement stimuli, movement recordings by videotaping and motion capture (using an infrared 12-camera system, *OptiTrack*, Corvallis, OR) were obtained from the same model.

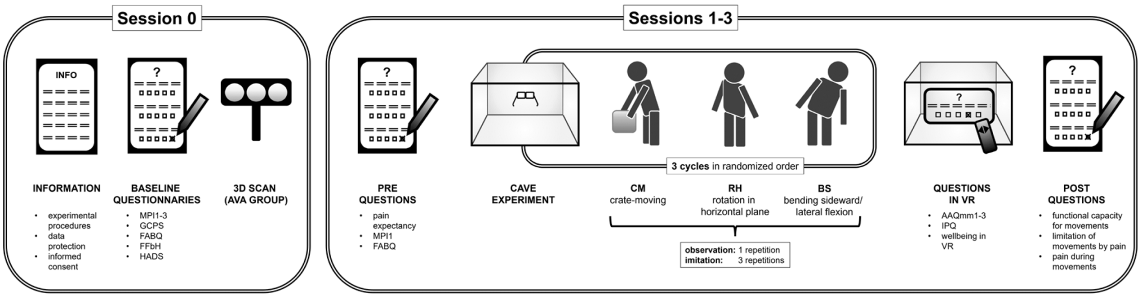

Figure 16. Study 2: Experimental setup (A) – flow of experimental sessions.

In a preparatory and baseline assessment session (session 0), participants were informed about the experiment, answered pen-and-pencil questionnaires, and were 3d-scanned (AVA group). In sessions 1-3, the actual VR movement experiment took place, accompanied by pre and post questionnaires (pen-and-pencil and with a remote control within-VR).

Questionnaires: FABQ PA – Fear Avoidance Belief Questionnaire, Physical Activity Subscale; FFbH FC – Hannover Functional Ability Questionnaire, Functional Capacity Score; GCPS – Graded Chronic Pain Scale; HADS – Hospital Anxiety and Depression Scale (Anxiety, Depression); MPI1 – West Haven-Yale Multidimensional Pain Inventory, Part 1 (Pain Intensity, Interference, Affective Distress, Social Support, Life Control).

Figure 17. Study 2: Experimental setup (B) – sample avatars of participants.

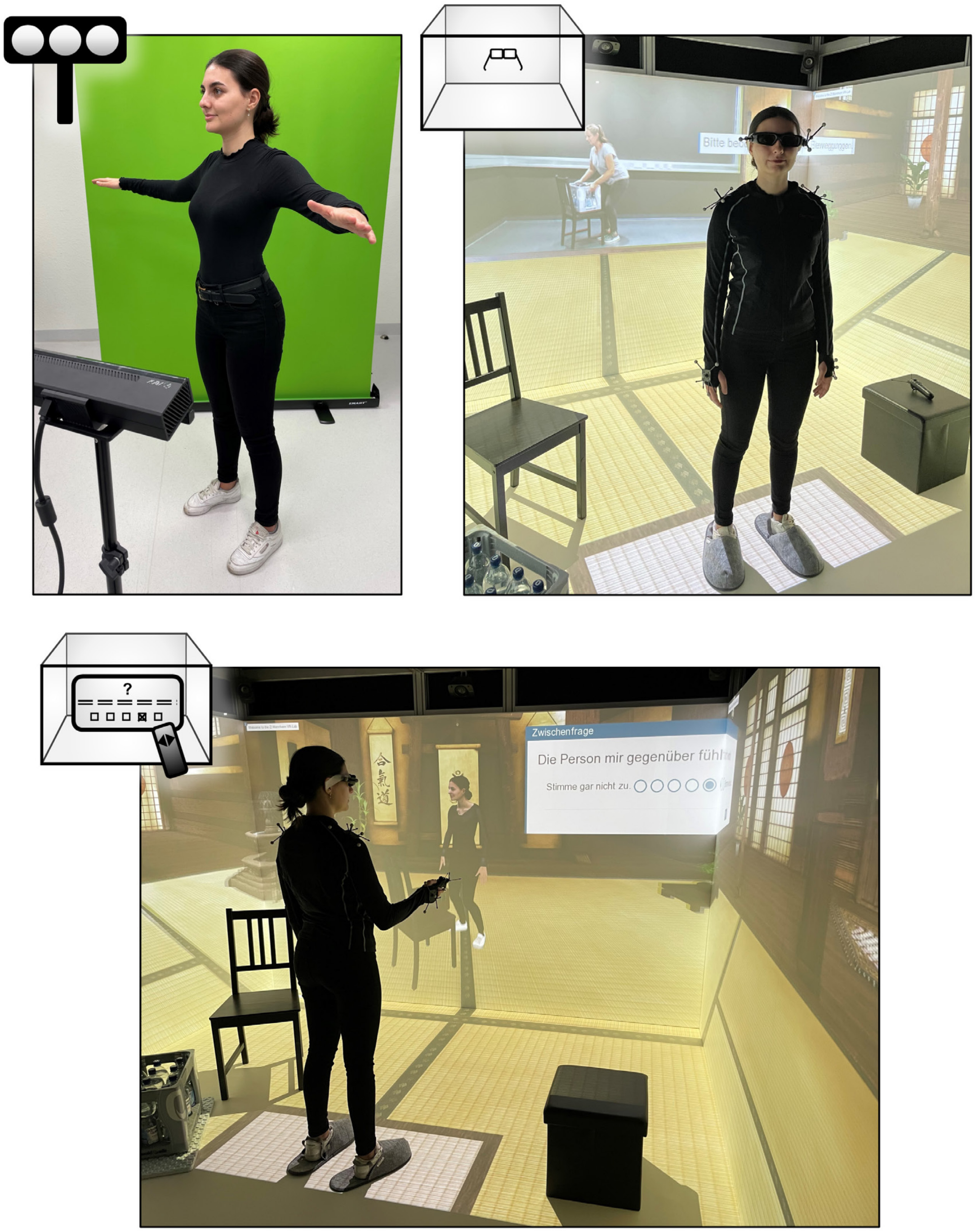

Figure 18. Study 2: Experimental setup (C) – re-staging of experimental procedures.

Re-staging of: scan procedure with handheld Kinect sensor (upper left), CAVE setup and motion capture markers (upper right), and within-VR questionnaires (lower panel).

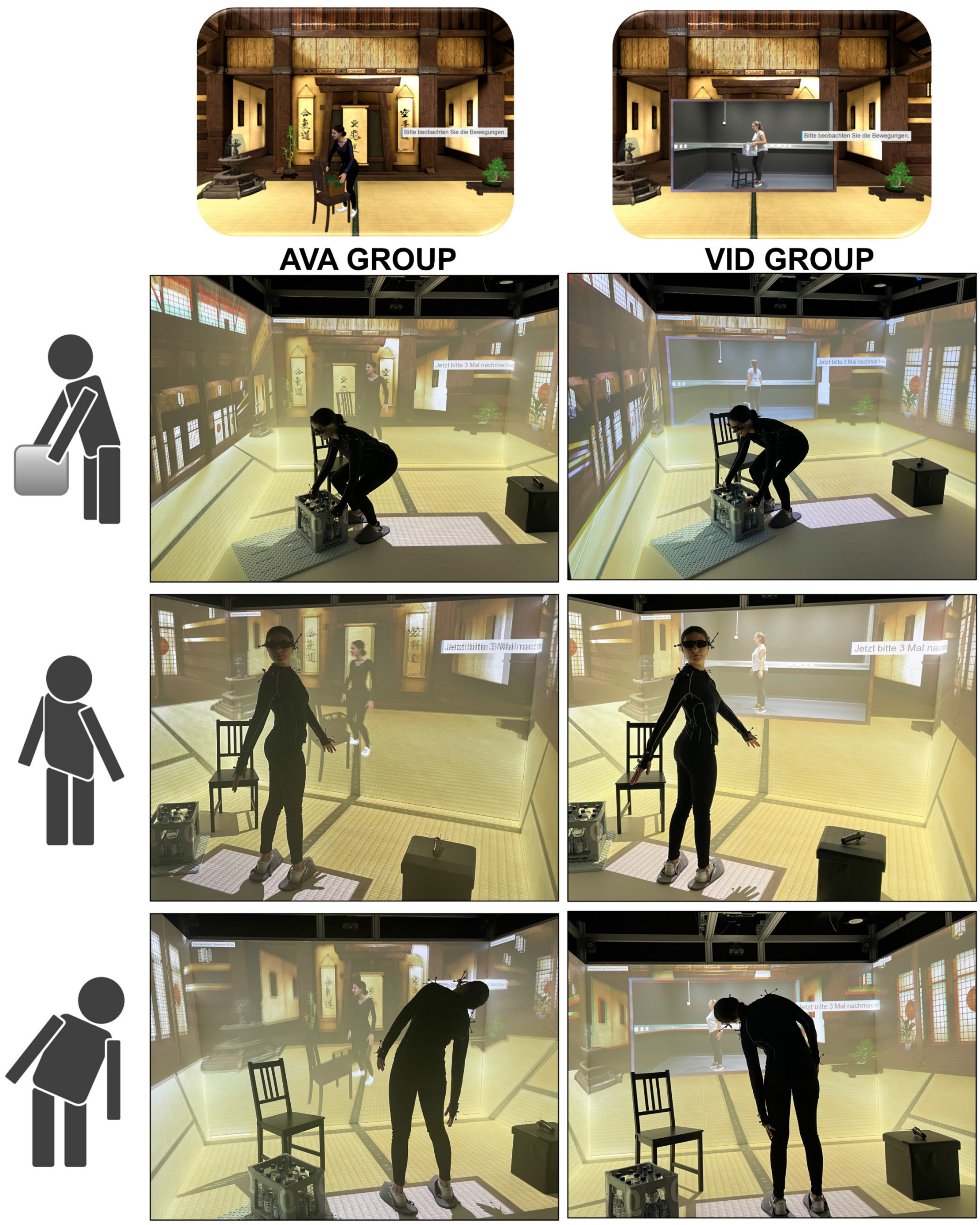

Figure 19. Study 2: Experimental setup (D) – re-staging of experiment.

Re-staging of experiment for VID (left column) and AVA (right column) for all movements: crate-moving (CM), rotation in horizontal plane (RH), and lateral flexion (bending sideward, BS).

4.3.6 Questionnaire Assessment

Participants answered questions at three time points during the experimental sessions: in the beginning, after the movements when still in the virtual environment, and after having left the virtual environment. At the beginning of every experimental session, participants completed the *FABQ* again, together with the first section of the Multidimensional Pain Inventory (*MPI1*), which comprises the scales regarding *pain intensity*, *interference*, *affective distress*, *social support* and *life control*. They also reported their *current pain level* on a discrete numeric rating scale (NRS) from 0 (“no pain at all”) to 10 (“most intense pain imaginable”), and to which extent they feared that the following three movement types would amplify their back pain, i.e., the *pain expectancy*, on a NRS from 0 (no pain expected) to 4 (full agreement with the statement that movements would lead to pain), cf. (Klinger, Kothe, et al., 2017; Schmitz et al., 2019).

When still immersed in the virtual environment, participants answered an “engagement” question on whether they *went to the limits* of their capacity during the experiment, referring to all three movements together with an NRS from 0 (complete disaffirmation) to 6 (complete affirmation). After the VR part, every session was concluded by three questions (Klinger, Kothe, et al., 2017; Schmitz et al., 2019) for each movement (BS, RH, CM). The participants’ own perception of their *ability* was assessed by asking them whether they could perform the movement with an NRS from 0 (not at all) to 3 (unrestricted yes). They were also asked how strongly they felt *limited* in the movement by their pain with an NRS from 0 (no limitation at all) and 10 (complete incapability), and they reported their *pain during the movement* on an NRS from 0 (no pain) to 10 (most intense pain imaginable). Participants’ self-reported ability to perform each movement was then pooled to gain a *functional capacity* score in percent (average over all three movements, converted into percent of the maximal score possible). *Movement limitation by pain* and *pain during the movements* were also each averaged over all three movements, resulting in a score between 0 and 10.

After the movement task but still immersed in the VR, participants answered questions on their perception of and identification with the model, using the *Autonomous Avatar Questionnaire* with the three scales “identification/ affiliation”, “perceived situational pleasantness for movement model” and “changes in body perception” (Kammler-Sücker et al., 2021). These showed high internal consistencies and were adapted by dropping single items to fit the experimental setup in this study (resulting in an AAQ-multimedia version, or AAQmm, see supplement section 8.2.6, starting from p. 187, for details). To assess the perception of the virtual environment (Slater & Usoh, 1993), the *Igroup Presence Questionnaire* (*IPQ*) was employed, which measures participants’ presence in the virtual environment by asking for their involvement, experienced realism of the VR, and how strongly they felt relocated into the virtual world (Schubert et al., 2001). Both the AAQmm scales and the IPQ subscales were used as predictors for the analysis of VR-related influences on ROM.

4.3.7 Motion Data

To capture movements of the back in standing position, optical markers attached to the upper back and shoulder region were measured with the optical motion capture system, which also tracked the 3d glasses for real-time rendering (see Figure 19). We conducted quantitative analyses of two movement types (BS and RH), defining a functional range of motion (ROM) based on the amplitude of the respective oscillatory movement of the upper back/shoulders (Kammler-Sücker et al., 2021): the maximal rotations/deflections of the upper torso to both sides during the movement define a movement range in degrees for the current movement repetition. We treated each repetition as a separate data point, hence with maximally nine data points per session and movement. Sessions with poor overall tracking quality for the respective movement (less than three trackable ROM values) were excluded (11 sessions for BS, 0 for RH). We also checked the motion data for within-subject outliers and manually inspected the respective motion trajectories (4 outlier data points removed for BS, 3 for RH). Data of subjects with only one remaining session were excluded as a whole (3 for BS, 0 for RH). The final data sets consisted of 853 observations in 33 subjects for RH, and of 657 observations in 30 subjects for BS (due to tracking-related missing values). The software *Matlab 2019* (*MathWorks*, Natick, MA) was used for post-processing of motion data and cleaning of tracking artefacts.

4.3.8 Power Analysis

In planning the experiment, we conducted a power analysis for a repeated measures design with an analysis of variance (ANOVA). Although we would later employ linear mixed effects (LME) modeling, we used this approach for a ballpark estimate. We used the statistical software *G*Power* (Faul et al., 2007) to estimate required sample size for a repeated measures design with between-factors, in our case with two groups (experimental or control). We assumed medium effect size (0.5) for the group effect, an α error level of 0.05, and an intended power of 0.8. Defining ROMs as target outcomes for group effects, the number of repeated measurements was set to 27 repeated measurements (nine movement repetitions over three sessions). For correlations among repeated measures, we assumed a value of 0.9, based on within-session intra-class correlations for ROMs in a previous movement study (Kammler-Sücker et al., 2021). The resulting target sample size was 32.

4.3.9 Statistical Analysis

We used multilevel modeling to analyze both motion and self-report data based on linear mixed effects models (LMEMs), an extension of multiple regression for data sets with grouped structure. LMEMs allow for group-specific deviations (*random effects*) from grand-sample regression coefficients and intercepts (*fixed effects*), thus resulting in additional group-wise *random slope* and *random intercept* estimates. In our analyses, we allowed for a full covariance matrix of random effects and only included random intercepts. We employed the *restricted maximum likelihood method* (*REML*) to estimate model coefficients, except for analyses involving model comparisons via likelihood ratio tests, in which case the *maximum likelihood* (*ML*) method was used. Error estimation of t and $p(t)$ values for fixed effects coefficients relied on the Kenward-Roger approximation method (Kenward & Roger, 1997). Analyses of variance

(ANOVAs) of the fixed effects in the LME models was also conducted with the Kenward-Roger method, as implemented in the *R* package *lmerTest* (Kuznetsova et al., 2017). If interactions were analyzed, a separate model including the interaction term(s) was analyzed in addition. If the latter revealed significant interactions, post-hoc contrast analyses of marginal means were applied, testing for differences between the levels of one variable with the other factor level held constant, and vice versa. Effect sizes were estimated by standardized regression weights β_z (Hox et al., 2018, p. 18). For all LME analyses, the *R* package *afex* (Singmann et al., 2020) was used, which builds on the *lme4* package (Bates et al., 2015a), and model-based estimates for expected mean values (*simple* or *marginal* effects) were calculated with the package *emmeans* (Lenth, 2020). In pairwise testing of group differences in interactions, correction for multiple testing used the false-discovery rate (FDR) correction (Benjamini & Hochberg, 1995), as implemented in the *multcomp* package (Hothorn et al., 2008), applied separately for each direction of marginalization.

For analyses of *motion capture* data, the *basic LME models* for both ROM_{BS} and ROM_{RH} were fitted separately, with the only predictors being *treatment group* (either AVA or VID) and *session*. The latter was modelled as a factor variable to account for varying inter-session intervals. This basic model was then extended by an interaction term between group and session. If the mixed-model ANOVA revealed this interaction to be significant, it was further analyzed by post-hoc comparisons of the estimated marginal means. In addition, we also analyzed *extended models* for ROMs to assess influences of other predictors and to check the validity of our results. We assumed that ROMs would be decreased by pain current pain state and pain expectancy, stimulated by identification with a model perceived to be comfortable in its movements, increased by immersion and presence, and influenced by demographic characteristics. Thus, the additional predictors were the MPI scale on pain intensity (interference scale had a correlation of 0.72 with this scale and was thus not added), pain expectancy (with a correlation of 0.41 with the FABQ physical activity score, so the latter was not included), AAQmm1 (identification) and AAQmm2 (situational pleasantness; AAQmm3 on changed body perception not included due to boundary effects towards zero), IPQ presence (total score, as suggested by high correlations of 0.43 to 0.56 between IPQ subscales), age in years, and gender. In general, these extended models did not change the outcomes of the basic models. *Self-report measures* were analyzed with similar models. The influence of our experimental manipulation on *prior pain expectancy* was modeled with a basic model involving session and experimental groups, as well as their interaction. Models for *posterior self-reports* included group, session and three additional predictors. These were pain expectancy, to detect effects of prior expectations, and the averaged ROMs for BS and RH, to assess potential correlations between motion capture and self-report. Relevant self-report outcomes regarded motor engagement (based on the NRS item on *how far participants had gone to their limits*), *functional capacity*, *limitation of movements by pain*, and *pain during the movements.*

In *post-hoc moderation analyses*, we extended the basic models for ROMs and self-reported pain after the movements by adding a binary *level of pain expectancy* as a potential moderator. The level of pain expectancy for a session was defined as “low” for pain expectancy ratings of 0 or 1, and “high” for ratings of 2-4. To assess potential moderator effects of pain expectancy level on group effects, LME models with two-way interactions were analyzed. As moderation could also affect session-dependent group effects, three-way interactions between pain expectancy level, group and session were also included.

Table 7. Study 2: Descriptive statistics of behavioral outcome variables.

		AVA		VID	
Variable	**type**	**mean (sd)**	**median (IQR)**	**mean (sd)**	**median (IQR)**
Pain Expectancy pre	single item	1.55 (1.19)	1.00 (2.00)	1.19 (0.93)	1.00 (1.00)
1st session		1.00 (0.82)	1.00 (0.25)	1.25 (0.77)	1.00 (1.00)
2nd session		1.75 (1.13)	1.00 (2.00)	1.13 (0.96)	1.00 (0.50)
3rd session		1.88 (1.41)	1.00 (2.00)	1.19 (1.12)	1.00 (2.00)
ROM_{BS}	degrees	90.06 (14.60)	88.54 (16.17)	93.65 (27.09)	88.53 (18.88)
1st session		93.34 (17.41)	92.86 (19.41)	94.45 (23.76)	90.63 (16.75)
2nd session		89.48 (13.17)	87.43 (13.40)	95.13 (30.05)	83.77 (22.66)
3rd session		87.35 (12.03)	87.79 (15.42)	91.52 (27.11)	89.23 (16.59)
ROM_{RH}	degrees	205.58 (27.20)	206.89 (42.39)	193.26 (23.27)	190.08 (36.90)
1st session		207.61 (29.94)	205.41 (38.30)	194.08 (22.87)	194.09 (38.12)
2nd session		207.03 (25.44)	208.72 (42.14)	192.17 (23.18)	188.40 (39.24)
3rd session		202.19 (26.08)	207.52 (41.02)	193.61 (23.89)	189.07 (31.35)
Engagement ("went to my limits")	single item	3.75 (1.89)	4.00 (3.00)	2.46 (1.95)	2.00 (3.00)
1st session		3.65 (1.87)	4.00 (2.00)	2.75 (1.84)	2.50 (3.25)
2nd session		3.65 (2.09)	4.00 (3.00)	2.19 (2.04)	1.50 (4.00)
3rd session		3.94 (1.78)	4.00 (2.00)	2.44 (2.03)	2.00 (3.25)
Functional Capacity for Movements	percent score	80.17 (18.63)	77.78 (33.33)	85.19 (23.30)	88.89 (22.22)
1st session		81.70 (16.17)	77.78 (33.33)	84.03 (28.10)	94.44 (13.89)
2nd session		76.47 (23.20)	77.78 (33.33)	88.89 (14.05)	94.44 (22.22)
3rd session		82.35 (16.23)	77.78 (33.33)	82.64 (26.28)	88.89 (22.22)
Limitation of Movements by Pain	sum score	2.47 (2.09)	2.17 (3.17)	1.90 (2.09)	1.17 (2.00)
1st session		2.67 (2.02)	2.33 (3.00)	1.71 (1.83)	1.00 (1.83)
2nd session		2.51 (2.21)	2.00 (3.50)	2.25 (2.37)	1.50 (2.00)
3rd session		2.23 (2.15)	2.17 (2.58)	1.71 (2.10)	1.00 (2.00)
Pain during Movements	sum score	2.49 (1.65)	2.17 (1.75)	1.92 (1.84)	1.33 (1.83)
1st session		2.57 (1.13)	2.67 (2.00)	1.87 (1.57)	1.67 (1.50)
2nd session		2.40 (1.76)	2.00 (1.83)	2.08 (2.29)	1.00 (1.83)
3rd session		2.48 (2.05)	2.17 (2.50)	1.80 (1.66)	1.33 (1.83)

Variables are listed in the order of assessment during the experimental sessions. The values are reported per group, first pooled over sessions and then broken down by session. Ranges of motion were assessed with optical motion capture, all other measures by participants' self-reports.

Abbreviations: ROM – range of motion; BS – bending sideward; RH – rotation in horizontal plane; AVA – experimental group (avatar, N=17); VID – control group (videotaped model, N=16); sd – standard deviation; med. – median; IQR – interquartile range.

4.4 Results

Descriptive statistics for all outcome variables can be found in Table 7. The raw data distributions after preprocessing for both lateral flexion (BS) and rotation in the horizontal plane (RH) are shown in supplement section 8.2.1, starting from p. 179.

4.4.1 Range of Motion

Parameter estimates of the LME models for ROMs (both for BS and RH) are reported in Table 8. For bending sideward (BS), there was no significant effect of treatment group on ROM_{BS}, $F_{(1,27.00)} = 0.30$, $p = 0.59$, $\beta_z = -0.11$. However, there was a significant effect of session, $F_{(2,625.28)} = 26.15$, $p < 10^{-10}$, which was driven by a significant decline in ROM between the first and third session ($\beta_z = -0.11$). There were no significant interactions between group and session, $F_{(2,623.29)} = 0.17$, $p = 0.84$.

In the basic model for ROM_{RH}, the effect of AVA versus VID group had a positive sign, but did not reach significance, $F_{(1,31.00)} = 2.26$, $p = 0.14$, $\beta_z = 0.23$. Again, session had a significant effect, $F_{(2,818.14)} = 7.57$, $p < 0.001$, driven by a significant decline in ROM between first and third session ($\beta_z = 0.08$). In contrast to BS, there was a significant interaction between group and session, $F_{(2,816.14)} = 6.28$, $p < 0.01$. Post-hoc contrast analyses (see Figure 20, detailed results in supplements, Table 13) showed no significant effect of session in the VID group. In the AVA group, in contrast, there was a decline between session 2 and session 3. With respect to contrasts between groups, the consistently positive difference in marginal means between AVA and VID was not significant for any session.

Table 8. Study 2: Coefficients of basic model for ranges of motion (ROM).

Model	Predictor	*β*	Std. Error	df	*t*	*p*(*t*)	β_z
ROM_{BS}							
	intercept	93.65	4.32	27.94	21.70	< 0.001 ***	---
	group: AVA – VID	-2.37	4.32	27.94	-0.55	0.59	-0.11
	1st sess. – 3rd sess.	2.62	0.41	625.17	6.36	< 0.001 ***	0.12
	2nd sess. – 3rd sess.	-0.14	0.42	625.28	-0.34	0.7338	-0.01
ROM_{RH}							
	intercept	200.10	4.01	31.00	49.96	< 0.001 ***	---
	group: AVA – VID	6.02	4.01	31.00	1.50	0.14	0.23
	1st sess. – 3rd sess.	2.15	0.60	818.10	3.56	< 0.001 ***	0.08
	2nd sess. – 3rd sess.	-0.24	0.59	818.21	-0.41	0.68	-0.01

The table reports fixed effect estimates of the linear mixed effects (LME) models for ranges of motion (ROM) as outcome variables, both for *bending sideward* (BS) and *rotation in the horizontal plane* (RH). Both LME models found that ROM strongly depended on participants, as indicated by the standard deviations (SD) of random effects (ROM_{BS}: *SD* = 23.58; ROM_{RH}: *SD* = 22.87).

Regression weights *β* are reported with standard error (Std. Error). Group effect is reported as contrast between experimental (avatar: AVA) and control (videotaped model: VID) group. Session (sess.) was modeled as a categorical variable, resulting in two contrasts of first and second session with the last session. The Kenward-Roger method was used to estimate degrees of freedom (df), the *t* value and the according *p*(*t*) value (Kenward & Roger, 1997). Standardized regression weights β_z are normalized to the standard deviations of ROM_{BS} and the respective predictor, following (Hox et al., 2018, p. 18).

The extended models for both RH and BS confirmed the main effects found in the basic models (see supplement section 8.2.3, starting from p. 183, for complete ANOVAs and model coefficients). Although with small effect size, pain expectancy was a significant predictor for both BS, $F_{(1,621.21)} = 29.07$, $p < 0.001$, $\beta_z = -0.09$, and RH, $F_{(1,822.58)} = 4.10$, $p = 0.04$, $\beta_z = -0.04$. Besides this, the only other significant effect was exerted by AAQmm2 (situational pleasantness) on ROM_{RH}, again with small effect size, $F_{(1,822.58)} = 4.10$, $p = 0.04$, $\beta_z = -0.04$. Pain state (MPI1 pain intensity), identification (AAQmm1), and presence (IPQ) did not show significant effects. Demographic characteristics showed a marginally significant effect in two cases, namely gender for ROM_{BS}, $F_{(1,25.99)} = 3.79$, $p = 0.06$, $\beta_z = -0.78$, and age for ROM_{RH}, $F_{(1,29.36)} = 3.05$, $p = 0.09$, $\beta_z = -0.27$.

4.4.2 Pain Expectancy

For pain expectancy, there was no significant main effect of treatment group, $F_{(1,30.81)} = 1.67$, $p = 0.21$, $\beta_z = 0.17$. The effect of session did not reach significance, $F_{(2,60.57)} = 2.16$, $p = 0.12$. However, there was a significant interaction effect between group and session, $F_{(2,60.57)} = 3.33$, $p = 0.04$. Post-hoc contrast analyses of estimated marginal means (see Figure 21, detailed results in supplements, Table 14) revealed no significant effect of session in the VID group. In contrast, the AVA group showed a significant increase in pain expectancy between session 1 and session 2 ($p = 0.03$). The higher marginal means for group AVA compared to VID in the second and third session did not reach marginal significance ($p = 0.13$ for both sessions).

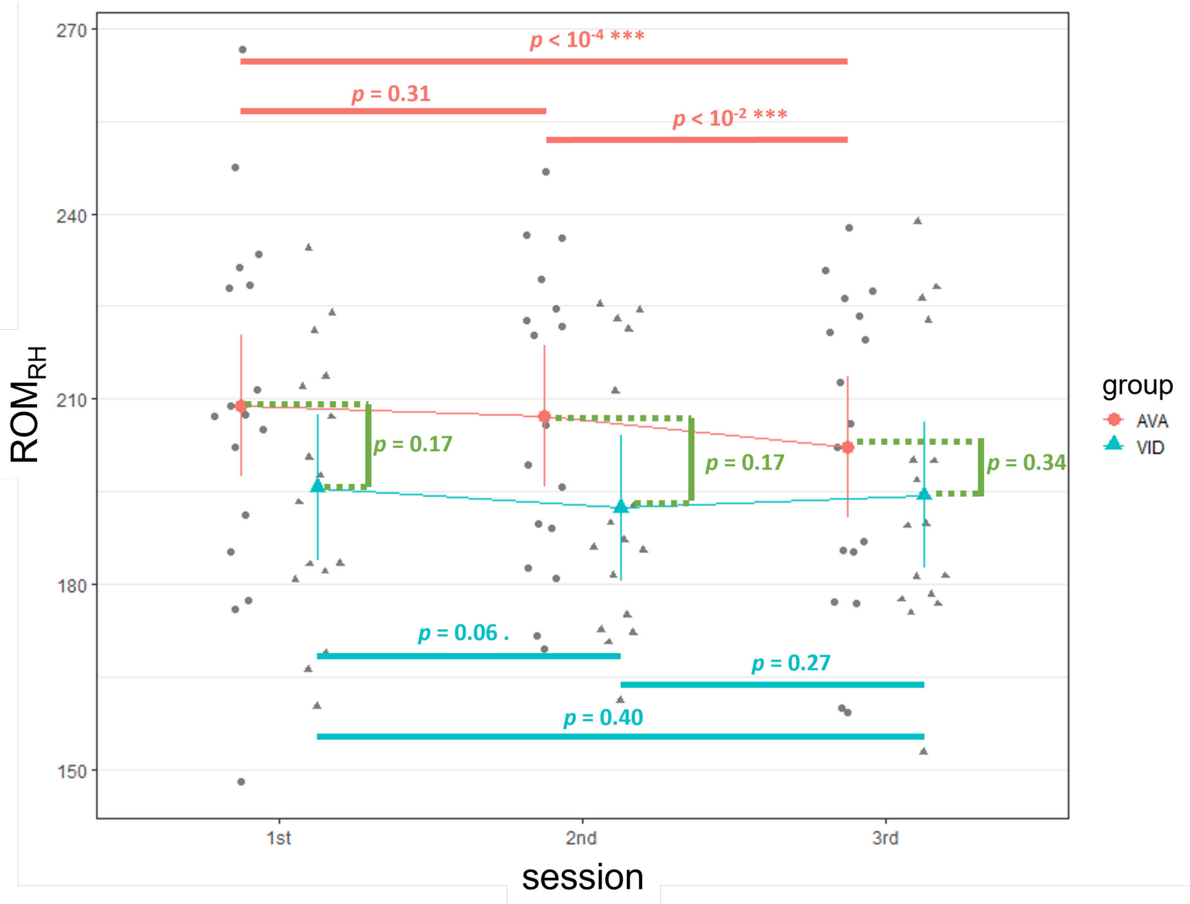

Figure 20. Study 2: Results of post-hoc contrast analysis for basic model for ROM_{RH}.

Raw data (subject-specific averages) are shown in grey and broken down by session, with AVA group indicated by spheres and VID by triangles. Model estimates for marginal means by group and session are shown in red (AVA) and blue (VID). Pairwise contrasts are depicted with respective p values as estimated with Kenward-Roger approximation and FDR correction (Benjamini & Hochberg, 1995; Kenward & Roger, 1997), with session-wise group comparisons in green and comparisons between sessions in red (AVA) and blue (VID). Note the decrease for AVA between second and third session, while the constantly lower values for VID do not change except for a marginally significant decline between first and third session. The quantitative values are reported in the supplements, Table 13, p. 183.

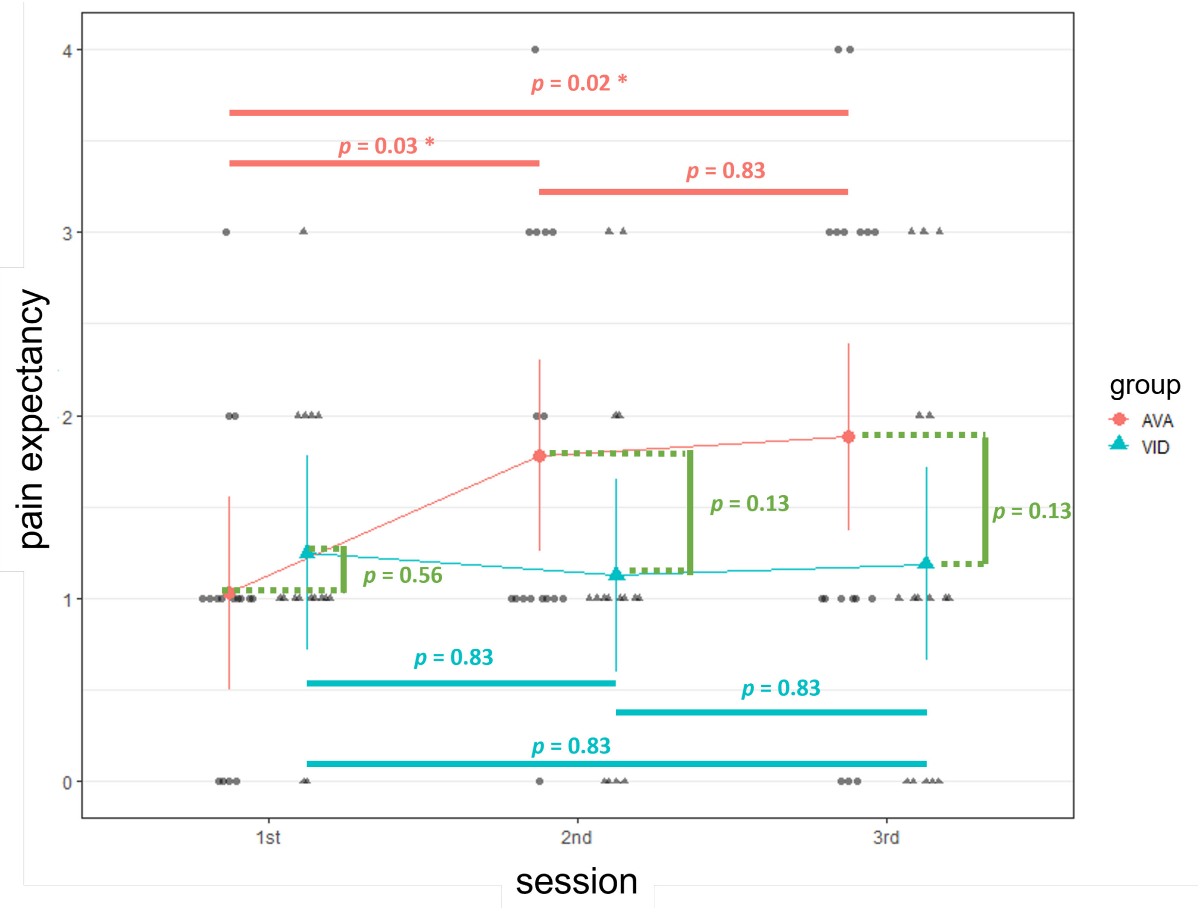

Figure 21. Study 2: Results of post-hoc contrast analysis for basic model for pain expectancy.

Raw data (subject-specific averages) are shown in grey and broken down by session, with AVA group indicated by spheres and VID by triangles. Model estimates for marginal means by group and session are shown in red (AVA) and blue (VID). Pairwise contrasts are depicted with respective p values as estimated with Kenward-Roger approximation and FDR correction (Benjamini & Hochberg, 1995; Kenward & Roger, 1997), with session-wise group comparisons in green and comparisons between sessions in red (AVA) and blue (VID). Note the decrease for AVA between second and third session, while the constantly lower values for VID do not change except for a marginally significant decline between first and third session. The quantitative values are reported in the supplements, Table 14, p. 183.

4.4.3 Engagement, Pain and Function

The LME analyses for participants' self-reports after the movements revealed a similar pattern for all four variables, i.e., the engagement question on whether participants had *gone to their limits*, the *functional capacity* score, the average *limitation of the movements by pain*, and the average *pain during the movements*. Descriptive statistics per group and session for all these measures are shown in Table 7.

The intervention group had a marginally significant effect on the engagement item, $F_{(1,26.97)} = 3.22$, $p = 0.08$. Here, the AVA group tended to report higher levels than the VID group, with a medium effect size $\beta_z = 0.30$. With respect to pain during movement and functional capacity, there were no significant effects of intervention group (functional capacity: $F_{(1,24.77)} = 0.32$, $p = 0.58$; limitation: $F_{(1,25.68)} = 1.09$, $p = 0.31$; pain: $F_{(1,25.91)} = 0.27$, $p = 0.61$).

Session did not show significant effects on any self-report after the movements, neither for engagement ($F_{(2,53.68)} = 1.03$, $p = 0.36$), nor for function (functional capacity: $F_{(2,55.80)} = 0.31$, $p = 0.74$, limitation: $F_{(2,50.63)} = 2.19$, $p = 0.12$) or pain ($F_{(2,50.31)} = 1.16$, $p = 0.32$). Motor behavior as assessed with ROM (for movements BS and RH separately, averaged by session) did also not have any significant effects on self-report measures. This held for engagement (predictor ROM_{BS}: $F_{(1,37.93)} = 0.43$, $p = 0.52$; predictor ROM_{RH}: $F_{(1,55.54)} = 0.006$, $p = 0.94$), functional capacity (ROM_{BS}: $F_{(1,28.76)} = 0.07$, $p = 0.80$; RH: $F_{(1,31.96)} = 0.69$, $p = 0.41$), limitation (ROM_{BS}: $F_{(1,30.82)} = 0.84$, $p = 0.37$; RH: $F_{(1,38.45)} = 2.53$, $p = 0.12$), and pain (ROM_{BS}: $F_{(1,31.87)} = 0.86$, $p = 0.36$; RH: $F_{(1,40.83)} = 0.28$, $p = 0.60$). Note that even when self-reports on pain and function were analyzed separately for each movement, ROMs did not show any significant effects (data not shown).

Prior pain expectancy, in contrast, was a significant predictor for all self-reports on pain and function (functional capacity: $F_{(1,66.63)} = 8.75$, $p < 0.01$, $\beta_z = -0.25$; limitation: $F_{(1,72.48)} = 10.78$, $p < 0.01$, $\beta_z = 0.25$; pain: $F_{(1,71.56)} = 10.49$, $p < 0.001$, $\beta_z = 0.28$).

Similarly, there was a significant effect of prior pain expectancy on self-reported engagement, $F_{(1,73.50)} = 3.22$, $p = 0.03$, $\beta_z = 0.17$.

4.4.4 Moderation Analysis: Group, Pain Expectancy and Session

In the moderation analysis for the outcome variable ROM_{BS} (complete ANOVA tables in the supplements, Table 18), all interactions with pain expectancy level were significant (group × pain expectancy level: $F_{(1,615.55)} = 6.39$, $p = 0.01$; session × pain expectancy level: $F_{(2,614.15)} = 7.95$, $p < 0.001$; group × session × pain expectancy level: $F_{(2,614.15)} = 3.85$, $p = 0.02$). Post-hoc contrast analyses of the three-way interaction (Figure 22) revealed the following pattern. In the AVA group, there was a mild decline in ROM_{BS} for both levels of pain expectancy (low: significant decline between first and third session; high: significant decline between second and third session), and for none of the sessions was the difference in ROM_{BS} between low and high pain expectancy levels significant. In contrast, the VID group showed a continuous decline of ROM_{BS} between sessions (at least $p < 0.01$ for all pairwise comparisons) for measurements with high levels of prior pain expectancy, whereas the marginal means did not show any decline for low pain expectancy. Consistently, a difference in marginal means for ROM_{BS} developed in the second and third session (for both sessions at least $p < 0.01$), which had not been present in the first session. Contrasting AVA and VID group did not reveal any significant differences for any combination of session and pain expectancy level.

For ROM_{RH}, all interactions involving pain expectancy level turned out as at least marginally significant (group × pain expectancy level: $F_{(1,813.80)} = 4.16$, $p = 0.04$; session × pain expectancy level: $F_{(2,802.19)} = 2.73$, $p = 0.07$; group × session × pain expectancy level: $F_{(2,802.19)} = 2.41$, $p = 0.09$). Post-hoc contrast analyses of the latter three-way interaction revealed a pattern similar to that found in BS (Figure 23): the AVA group shows a continuous decline for both low and high pain expectancy (for low expectancy, at least marginally significant for both pairwise comparisons; for high expectancy, a marginally significant decline between first and third session), with no differences between expectancy levels for any session. In contrast, the VID group showed distinctly different patterns dependent on pain expectancy: in the former case of low expectancy, a marginally significant drop in ROM_{RH} between first and second session was followed by a significant increase in the third session compared to the second session, thus arriving at a level comparable to the first session. In case of high pain expectancy in the VID group, however, the marginal means show a weak decline over sessions (marginally significant for first versus third session). Consistently, after the first two sessions without differences between pain expectancy levels, the third session then shows a highly significant difference in marginal means for ROM_{RH} between low and high levels of pain expectancy. Contrasting AVA and VID group did not reveal any significant differences for any combination of session and pain expectancy level.

For self-report, the three-way interaction models with predictors group, session, and pain expectancy level did not reveal significant interactions (detailed results in supplements, Table 18), except for pain during the movements. For this variable, the two-way interaction group × pain expectancy level was significant, $F_{(1,76.30)} = 6.99$, $p < 0.01$, and was hence further analyzed with post-hoc contrasts. The interaction of session and expectancy level was marginally significant, $F_{(2,62.87)} = 3.02$, $p = 0.06$. The three-way interaction of these variables, however, was not significant, $F_{(2,61.87)} = 1.49$, $p = 0.23$.

The post-hoc contrasts for the interaction of intervention group and pain expectancy level (Figure 24) showed a significant prediction of pain during movement by prior pain expectancy in the VID group. In contrast, no such relationship between pain expectancy level and subsequently reported pain was present in the AVA group.

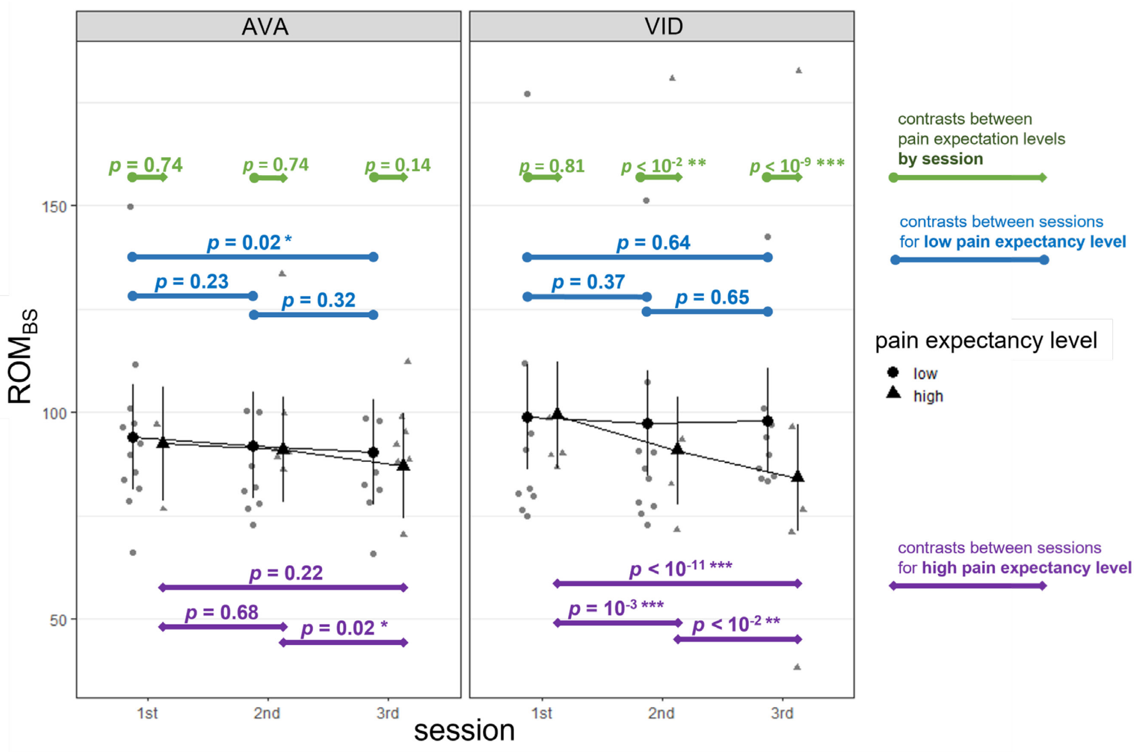

Figure 22. Study 2: Results of post-hoc contrast analysis for interaction model for ROM_{BS}.

Raw data (subject-specific averages) are shown in grey and broken down by session and group (experimental group AVA, and control group VID). Model estimates for marginal means are indicated for low and high pain expectancy levels. Pairwise contrasts are depicted with respective *p* values as estimated with Kenward-Roger approximation and FDR correction (Benjamini & Hochberg, 1995; Kenward & Roger, 1997), with session-wise comparisons in green and comparisons between sessions in blue (low pain expectancy) and violet (high pain expectancy). Note the decrease in ROM for high but not for low pain expectancy levels in the VID group; the AVA group in contrast, does not show differences between pain expectancy levels.

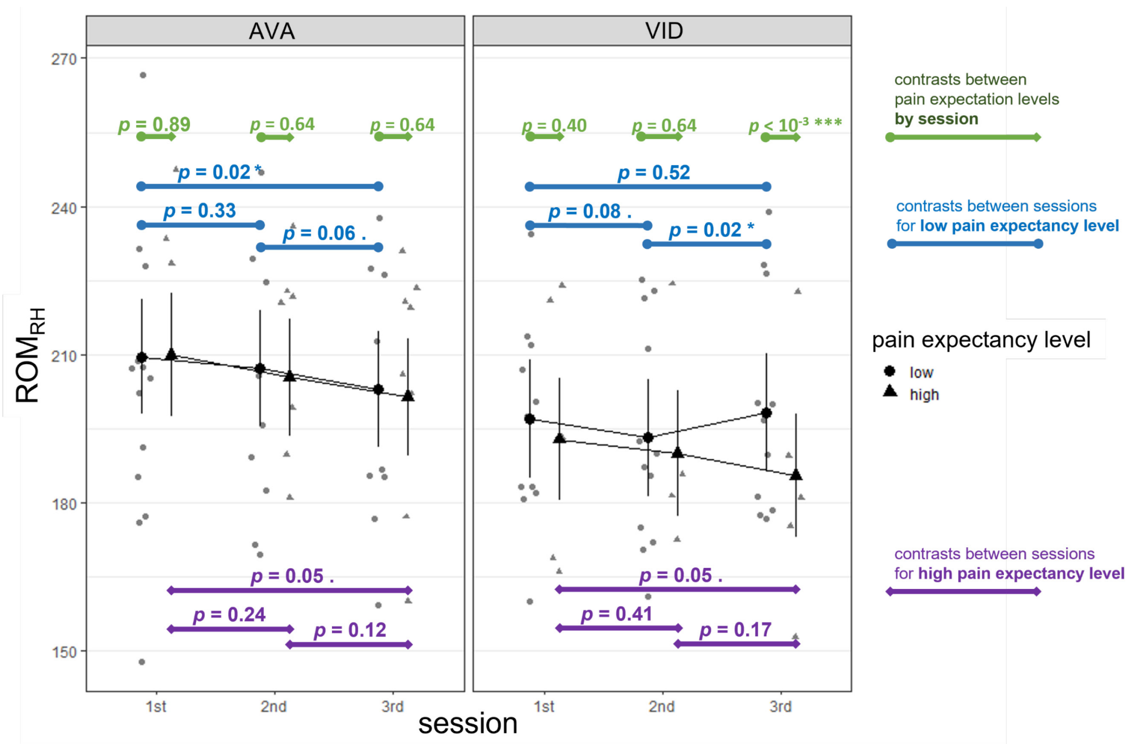

Figure 23. Study 2: Results of post-hoc contrast analysis for interaction model for ROM_{RH}.

Raw data (subject-specific averages) are shown in grey and broken down by session and group (experimental group AVA, and control group VID). Model estimates for marginal means are indicated for low and high pain expectancy levels. Pairwise contrasts are depicted with respective *p* values as estimated with Kenward-Roger approximation and FDR correction (Benjamini & Hochberg, 1995; Kenward & Roger, 1997), with session-wise comparisons in green and comparisons between sessions in blue (low pain expectancy) and violet (high pain expectancy). Note the decrease in ROM for high but not for low pain expectancy levels in the VID group; the AVA group in contrast, does not show differences between pain expectancy levels but only a generic weak overall decline over sessions.

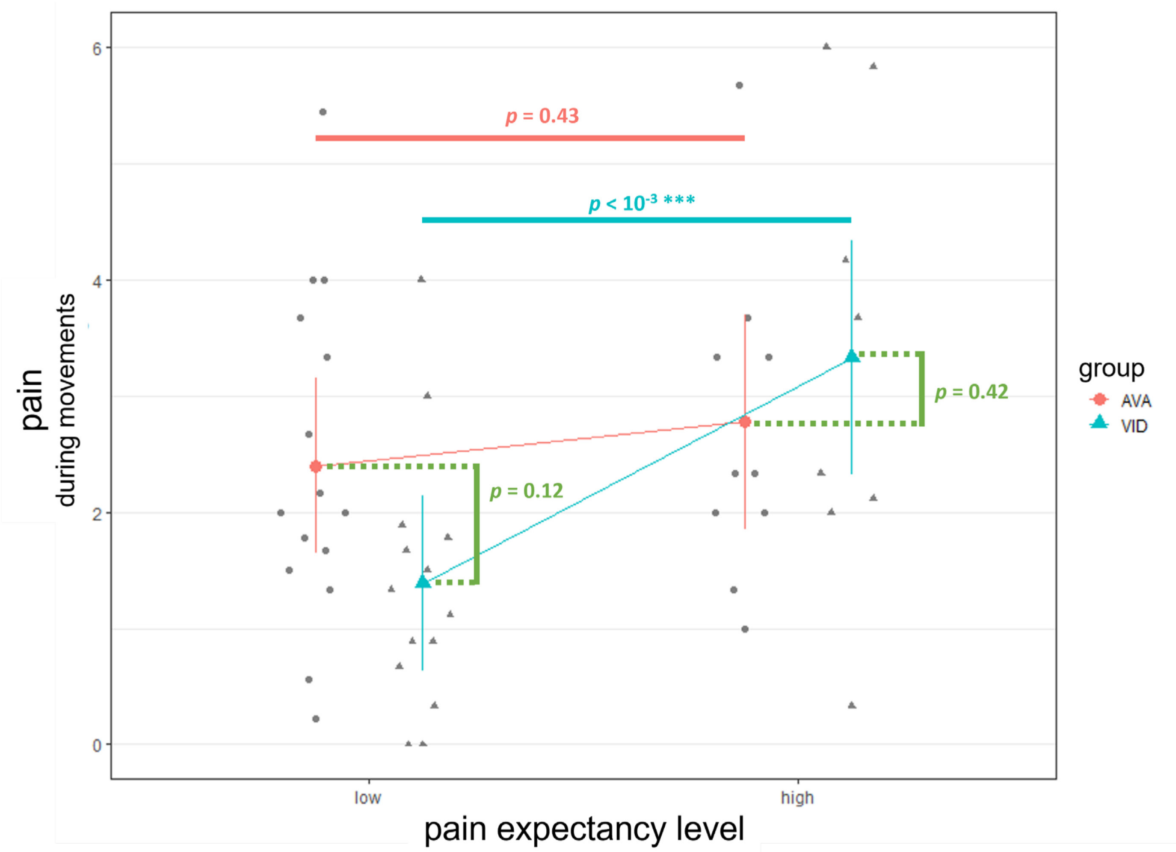

Figure 24. Study 2: Results of post-hoc contrast analysis for interaction model for pain during movements.

Raw data (subject-specific averages) are shown in grey and broken down by group (experimental group AVA, and control group VID) and pain expectancy level. Model estimates for marginal means are indicated by dots (AVA) and triangles (VID). Pairwise contrasts are depicted with respective *p* values as estimated with Kenward-Roger approximation and FDR correction (Benjamini & Hochberg, 1995; Kenward & Roger, 1997), with group comparisons in green and comparisons between expectancy levels in red (AVA group) and blue (VID group). Note how treatment group acts as a moderator of the relationship between level of prior pain expectancy and pain during movements.

4.5 Discussion

4.5.1 Effects of Model Personalization

The aim of this study was the exploration of model personalization and its effects on motor performance and engagement, pain expectancy, pain and function. With respect to motor performance as measured by range of motion (ROM), no significant group differences were found, although for rotation in the horizontal plane (RH), there was a trend approaching marginal significance. The small effect size ($\beta_z = 0.23$) suggests that larger sample sizes may be necessary to detect a significant effect here. For the other movement, bending sideward (BS), there was no significant group effect or trend. The same held for self-reports on pain and function after the movements. Thus, our data could not confirm a group effect on ROM, pain and function as hypothesized.

Participants' self-perceived engagement, in contrast, showed a marginally significant effect of group, with the AVA group reporting higher levels on the question of how far they had gone to their limits. The weak but significant effect of pain expectancy ($\beta_z = 0.17$) on self-reported engagement probably reflects a specificity of this item: as it was formulated relative to the subjects' perceived limitations, subjects probably scaled their response to their perceived limits of ability and pain tolerance: thereby, participants with generally higher pain levels, reflected in higher pain expectancies, would report higher "relative engagement" for a specific level of activity if they sustained it despite of adverse effects.

For pain expectancy itself, our findings were contrary to our initial hypothesis: starting from the same level of pain expectancy as the VID group, the AVA group expressed a significantly *increased* pain expectancy in the second and equally the third session. In contrast, the VID group did not show changes in pain expectancy. Moderation analyses could cast some light on these seemingly ambiguous results. They revealed that the AVA group showed a "*decoupling*" of pain expectancy from its effects on motor performance (ROM_{BS} and ROM_{RH}) and self-reported pain (pooled for BS, RH, and crate-moving) as they were observed in the control group: in the VID group, high pain expectancy predicted higher experimental pain, and over the sessions, motor performance levels diverged for high versus low pain expectancy, such that the difference in ROM levels became significant in the last session. This can be interpreted as an example of avoidance elicited by pain expectancy. In the AVA group, in contrast, these patterns were not observed, with prior pain expectancy level lacking any significant effect on reported pain and motor performance over sessions, arguably reflecting a decoupling of avoidance behavior from pain expectancy.

4.5.2 Potential Mechanisms and Future Research

Intervention with doppelganger models decoupled motor behavior and pain from prior pain expectancy. The effect was accompanied by a seemingly conflicting increase in pain expectancy over sessions. This could be a consequence of muscle ache after the first session, which would have confirmed and reinforced prior expectations if participants had engaged strongly *despite* high pain expectancy (as also indicated by anecdotal remarks of participants). This would also match the marginally significant effect of higher self-reported engagement in the AVA compared to the VID group. It is noteworthy that the decoupling effect in the AVA group nevertheless lasted over all three sessions. This can be interpreted as a stimulation of *pain tolerance* and task *persistence* despite pain, i.e., a positive effect on participants' ability to ignore and disregard concurrent nociception during movements, and to persevere in performing the task.

Several potential mechanisms may be at work here. Increased imitative tendencies, as shown in real-world and virtual chameleon and imitation effects (Chartrand & Bargh, 1999; Kammler-Sücker et al., 2021), might have counteracted motor avoidance; however, this explanation is not supported by our extended models, which did not find effects of AAQmm1 identification score on motor behavior. Alternatively, an attention-grabbing doppelganger might have stimulated motivation. However, the lack of gamification elements and the ROM inhibition by experienced realism would rather weigh against this explanation. In both movements, a small decline in ROM over sessions was significant. This suggests an overall trend of declining motivation during repeated sessions in our setup.

An observational placebo effect that generalized over sessions is also not supported by our data, as it would have been accompanied by a decrease in pain expectancy. However, a short-term within-session placebo overridden by between-session muscle ache would be consistent with the results. Theoretically, placebo effects may also have occurred independently of explicit expectancies, as has been shown for classical placebo effects (Bąbel, 2019). However, whether effects of vicarious experience, such as observational placebo (Colloca et al., 2013; Schenk et al., 2017) are possible without cognitive processing is a matter of some debate on the neural underpinnings of imitation (Bandura, 1986; Duffy & Chartrand, 2015; Greer et al., 2006; Hamilton, 2015; Tomasello, 2016; Zentall, 2006).

Alternatively, observation of moving doppelgangers could have decreased harm expectancy (Crombez et al., 1999), in the sense of expectation of detrimental effects from the movements. Our data support this hypothesis as the apparent wellbeing of the movement model, assessed with the AAQmm2 “situational pleasantness” scale, had a significant positive effect on ROM_{RH} (and a marginally significant effect on ROM_{BS}). Observing the doppelgangers may also have increased self-efficacy expectations, which are distinct from control beliefs (Bandura, 1977) and can facilitate pain tolerance on their own (Litt, 1988). In our experiment, they might have increased task persistence despite limited control of pain. Self-efficacy is amenable to vicarious experience (Bandura, 1977, 1998) and regularly addressed in CBT interventions (cf. Flor & Turk, 2011). The closely related construct of pain resilience (Slepian et al., 2016) has been found to decouple motor performance from fear-avoidance beliefs in in CBP (Palit et al., 2020). Further research on “doppelganger facilitation” could investigate these possible links between task persistence, self-efficacy, and pain resilience.

Decoupling fear from avoidance has been suggested as a specific leverage point for exposure treatments in chronic pain (Gatzounis et al., 2021), hence circumventing pain expectations which can be more persistent than avoidance (Janssens et al., 2019) or harm expectations (Riecke et al., 2020). Making use of current advancements in accessible avatar personalization (Bartl et al., 2021; Wenninger et al., 2020), virtual doppelgangers may thus provide a viable tool to address the vicious cycle of fear and avoidance.

4.5.3 Limitations

One limitation of this movement study is the lack of reward, which probably would have amplified effect sizes. However, rewards were deliberately left out for the purpose of isolating the effect of model personalization. Future investigations of virtual doppelgangers in chronic pain might extend this with gamification techniques.

Another potential limitation of our sample is adverse selection, as persons with high fear of movement or general anxiety might have been hesitant to participate in a movement study under pandemic conditions. All participants ranged above the threshold (70%) for clinically relevant disability on the FFbH (Kohlmann & Raspe, 1996). This is in line with the rather low GCPS pain grades in our sample, which had median values between 1.5 and 2 (see Table 6). This ranges between the GCPS categorization (Von Korff et al., 2020) of “mild chronic pain” (1) and “bothersome chronic pain” (2), in contrast to “high impact chronic pain” (3). Based on the current proof-of-principle study, future studies of similar design should aim at recruiting more severely impaired participant samples.

Another limitation of our study relates to possible demand characteristics, as participants of the AVA group noticed the effort that was put into avatar generation. However, we tried to minimize this effect with an equally detailed virtual environment for the VID group and by not revealing the other condition until completion of the experiment.

In addition, the pandemic-related high variation in inter-session intervals with partially considerably longer durations than the originally intended two-week margin adds a further limitation to the results of this study. It probably decreased the power to detect any effects on clinical pain variables. Future studies should organize sessions within strict schedules of inter-session intervals of maximally one week to intensify treatment effects and potentially allow for transfer to daily-life activities.

Based on our discussion above, future research might profit from including more severely impaired samples and by administering questions on harm expectancies to differentiate these from pain expectancies. Implicit physiological markers of pain could clarify the role of momentary placebo effects. For example, cortical hemodynamic activity might be measured by functional near-infrared spectroscopy during painful movements (Öztürk et al., 2021).

4.6 Conclusion

Virtual doppelgangers as movement models might provide an additional tool to current cognitive-behavioral treatments in chronic back pain and could potentially be included in future exposure setups. In virtually duplicating the observer’s body, they may create a learning situation in between first-person and vicarious third-person experience, facilitating task persistence and decoupling movement avoidance and experienced pain from prior expectancies. Future research should address replicability of these findings and investigate underlying mechanisms in this new type of virtual stimuli.

4.7 Acknowledgements

We want to express our gratitude to Iris Reinhard and Dieter Kleinböhl for their valuable advice on statistical matters. Our thanks for valuable assistance go to Melissa Mohr, who also re-staged the experiment, and Anna Staib, Isabelle Neumann, and Jerusha Devendraraj. We also want to thank all participants, especially those who have agreed to the use of their doppelganger image. This work was funded by a Reinhart Koselleck award of the Deutsche Forschungsgemeinschaft to HF (FL 156/41-1).

5 GENERAL DISCUSSION

5.1 Summary of Findings

In both experiments described above, we assessed the influence of model personalization on behavior in the form of functional ranges of motion (ROM) and self-reports in healthy participants (Study 1) and participants with chronic back pain(Study 2). Empirical findings could partially support, and be explained by, the previously assumed mechanisms. However, they also indicated effects beyond prior assumptions and partially in contrast to the latter.

Study 1 could support the prior hypothesis of a *chameleon effect* of enhanced motor imitation. We found that increased identification with virtual doppelgangers did indeed stimulate *imitative tendencies* in healthy participants (see Figure 25 for a schematic illustration). This is in line with the hypothesis that motor imitation would be *enhanced by maximized model-observer similarity*, which had been manipulated by different virtual characters of varying realism and personalization.

Study 2, in contrast, did not confirm its main prior predictions, which had been that virtual doppelgangers should decrease pain expectancy and avoidance, increase motor engagement, and reduce pain. In our sample of participants with chronic back pain, all these effects were absent and/ or not significant. However, we found that *self-reported engagement showed a marginally significantly higher level* in the experiment group which had observed their doppelganger avatars (AVA), compared to the control group watching videotaped models (VID). Besides this, there was no general increase in behavioral motor engagement, measured in ROM. Similarly, post-hoc reports on pain and functional ability during the experiment were not different for the AVA compared to the VID group. The *absence of group differences in ROMs and post-hoc reports* was rather accompanied by an *increase in pain expectancy* over sessions for the AVA condition, compared to no such rise in VID. This contradicted the expected decrease in pain expectancy for the AVA group.

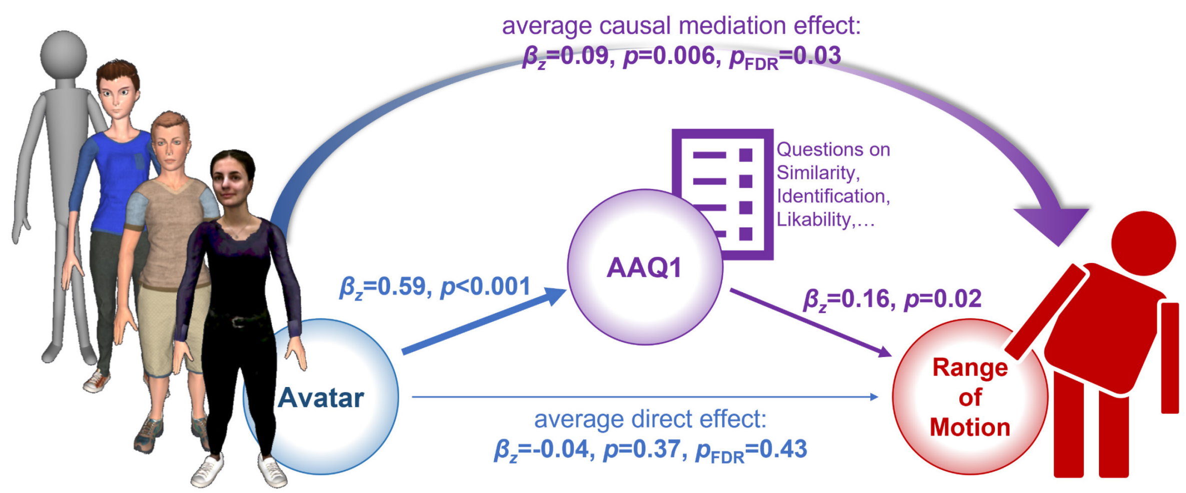

Figure 25. Schematic illustration of findings from Study 1.

Study 1 with healthy participants found that self-reported identification with the movement model (*AAQ1* ratings) mediated an effect of avatar level on range of motion for the movement *bending sideward*. Standardized regression weights, as obtained from linear mixed effects models, are reported as β_z. The *p* values are based on parametric bootstrapping. Corrections for false discovery rate are indicated (FDR).

Going beyond prior predictions, a *moderation effect of doppelgangers* was found instead (Figure 26): these induced a *decoupling of motor engagement and pain from prior pain expectancy*. This effect was consistently present for ROMs of both quantitatively analyzed movements (bending sideward, BS, and rotation in horizontal plane, RH). The same decoupling was found in participants' self-reports on their pain during the movements, which had also included the challenging crate-moving task (CM). This was distinct from what was observed in the VID group: the latter showed the expected correlation of prior pain expectancy with enhanced avoidance behavior and pain experience.

In the light of these findings, the *pain-specific mechanisms assumed beforehand* could mostly not be confirmed. The increase in pain expectancy over sessions contradicts a hypothesized *extinction of conditioned fear* (**mechanism 2** in Section 1.4). The same holds for *fear reduction by vicarious experience* (**mechanism 3**). In contrast, the fourth hypothesized mechanism, an *observational placebo effect* (**mechanism 4**) might well have played into decoupling behavior from prior pain expectancy, at least as a

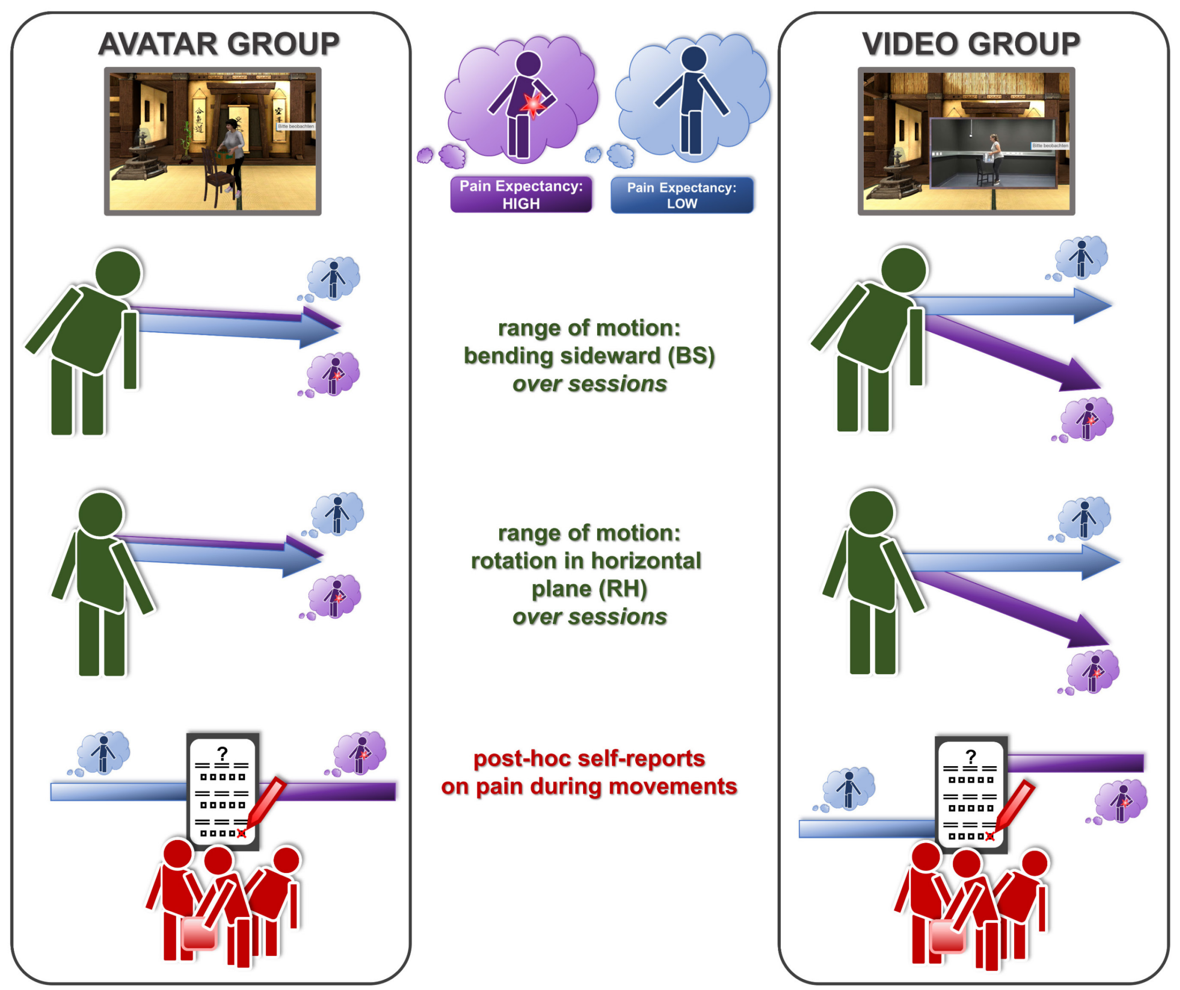

Figure 26. Schematic illustration of findings from Study 2.

Study 2 investigated the effects of virtual doppelganger avatars (AVA) as movement models in participants with chronic back pain, with the control group watching videotaped models. While most prior hypotheses were not confirmed exactly, the experiment did reveal an interaction effect of doppelganger avatars with prior pain expectancy. In the VID group, ranges of motion (ROMs) declined over sessions with high prior pain expectancy, whereas low-expectancy sessions had roughly constant ROMs. In addition, post-hoc pain reports were significantly higher for high versus low prior pain expectancy. In the AVA group, in contrast, none of these effects of prior pain expectancy level was present: ROMs showed a slight decline over sessions for both levels (not bringing them under the VID levels, though), and post-hoc pain reports were not significantly different for high versus low prior pain expectancy levels. These moderation effects indicate that virtual doppelgangers as movement models may decouple behavioral avoidance and experienced pain from prior pain expectancy.

momentary short-term effect within single sessions. However, it appears to be insufficient to explain the stability of decoupling over sessions. Arguably, there was an additional effect of *increased pain tolerance and intensified task persistence*, which will be discussed in the following section on possible interpretations of these findings.

5.2 Interpretation of Findings

As described in Chapter 1, the theoretical underpinnings of both experiments were drawn from the psychology and neuroscience of behavioral plasticity. Virtual doppelgangers were assumed to be perceived as so similar to the observers themselves that the latter would show enhanced behavioral reactions in form of observational modeling (Greer et al., 2006). Regarding participants with back pain, it was assumed that the observation of painless movements of their “alter-ego” body would come as close to firsthand experience as possible for a visual third-person perspective. Firsthand learning and observational modeling share common behavioral and neural bases (Carcea & Froemke, 2019; Ramsey et al., 2021), as most prominently illustrated by the physiological activity of so-called mirror neurons in both circumstances (Gallese et al., 1996; Rizzolatti & Craighero, 2004; Rizzolatti et al., 1996). In our studies, it was hypothesized that this would potentially place the doppelganger observation at the boundary between “firsthand” experience with behavioral modification on the one hand and learning from vicarious experience on the other hand.

Our experiments could indeed support this assumption. They established two doppelganger effects, which both are best explained by observational modeling that is intensified by high identification and model-observer similarity. Interpretations of both effects are discussed below.

5.2.1 Doppelganger Chameleon Effects

Study 1 supports the hypothesis of a *doppelganger-stimulated chameleon effect* that leads to implicit enhancement of voluntary motor imitation. It showed that increased identification (AAQ1 score) mediates a stimulating effect of virtual doppelgangers on motor behavior. However, this effect was only detected for one of three movements analyzed quantitatively (lateral flexion/ bending sideward, BS). For the other two movements (bending backward, BB, and rotation in the horizontal plane, RH), the number of previous movement cycles already performed was the only significant predictor. This probably reflects tiring and stretching. Self-reported model-observer similarity, identification and affiliation were aligned along a common *dimension of “identification” (AAQ1)*. The doppelganger avatar loaded highest on this dimension, compared to the other three virtual characters. Participants were not necessarily aware of this dimension as a stimulator of imitation engagement. This is indicated by their answers on the question that asked how far they had gone to their limits: the respective ratings loaded only weakly on the identification dimension. This suggests that participants’ conscious perception of their engagement was not influenced by identification. This dissociation suggests that the behavioral effect may have been outside of *participants’ awareness*.

The small effect size of differential motor enhancement, together with its relative independence of explicitly self-reported engagement, speak in favor of the assumed *chameleon effect*, which is in general rather subtle (Bailenson & Yee, 2005b). Chameleon effects comprise phenomena of implicit imitative tendencies, which are mutually dependent with interpersonal affiliation. Imitative tendencies are stimulated by a desire to bond with the observed model on the one hand, and increase mutual likability and affiliation in model and imitator on the other hand (Chartrand & Bargh, 1999; Lakin et al., 2003). The facilitating role of model-observer similarity in observational modeling (Braaksma, 2002; Bussey & Bandura, 1984; Rosekrans, 1967; Stotland et al., 1961) renders this interpretation most plausible. In this respect, our experiment could establish a doppelganger version of the *digital chameleon effect* for computer-generated models (Bailenson & Yee, 2005a, 2005b; Bailenson et al., 2008).

5.2.2 Doppelgangers Decouple Avoidance and Pain from Expectancy

Study 2 found that *pain expectancy increases over sessions* in the AVA group but not in the VID group. Viewed from the perspective of our initial hypotheses, this was unexpected. However, there were *no significant group differences in motor behavior (ROM) and post-hoc reports on pain and function*, except for a marginally significantly higher level of self-reported motor engagement. This absence of group differences is interesting because overt behavior and experienced pain are often found to be influenced by expectancies (e.g., Council et al., 1988; Janssens et al., 2019; Schmitz et al., 2019).

This was analyzed further in a moderation analysis. The latter revealed a doppelganger-stimulated *decoupling of pain expectancy from motor avoidance and pain experience*. This decoupling appeared most prominently in the *different trajectories of performance over sessions*, as assessed by the three-way interaction between group, pain expectancy, and time. In general, the AVA group showed similar trajectories for high and low pain expectancy levels, in contrast to diverging trajectories in VID.

As noted above, this suggests that *non-vicarious fear extinction and vicarious fear reduction*, the hypothesized mechanisms, were not relevant in this study. Based on these mechanisms, one would have expected a decrease in pain expectancy and an increase of motor performance over sessions. In contrast, we observed an increase in pain expectancy. There was even a decrease in ROM for the AVA group, although it was not deep enough to fall under the VID level, which also decreased over sessions. In principle, a general increase in pain expectancy over sessions could have been temporarily suspended by a within-session decrease of pain expectancy. In favor of this, it has been found that persons with chronic back pain can quickly adapt their pain expectancies if movements turn out to be painless, in contrast to their prior expectations (Crombez et al., 1996). In our case, however, the movements seem to have been linked to real pain in the form of post-session muscle ache in the days after. At least this is indicated by the pain expectancy increase over sessions. Therefore, it appears unlikely that pain expectancies, underpinned by first-hand experiences of muscle ache, could have been changed quickly by observing a doppelganger within one session (only to be reversed by following after-session muscle ache again). Recognizing a body in 3PP as one's own requires a computationally complex integration of several processing streams, with the prerequisite of a biographically and culturally acquired body image. First-person pain experience, in contrast, provides a strong and direct reinforcement signal. Therefore, post-experimental muscle ache, as reflected by higher pain expectancy in later sessions, would probably have prevented any short-term fear extinction effects of observing a painless doppelganger. If movements have indeed been paired with real pain, the acquired pain expectations are quite resistant to extinction, even if the respective avoidance behavior is extinguished, which has recently been shown for pain-free participants (Janssens et al., 2019).

A short-term *observational placebo* effect (Colloca & Benedetti, 2009) could have played a role within a session. This would match the observation that post-hoc reports on experimental pain were decoupled from prior pain expectancy in the AVA group. This mechanism, eliciting short-term within-session effects, could in principle suffice to explain the observed pattern of decoupling behavior and experience from prior expectations. However, the combination with a distinctively increased pain expectancy in later sessions raises the question of additional mechanisms which could have sustained the decoupling effect. Modifications in expectancies in general, and fear in particular, are main contributors to observational placebo effects (cf. the models by Bajcar & Bąbel, 2018; Schenk et al., 2017), as to placebo analgesia in general (Colloca et al., 2013). Therefore, it appears that a strong short-term decoupling without any effects on pain expectancy in the next session, only some days to weeks later, exceeds the explanatory power of observational placebo effects. Thus, the *increase* in pain expectancy accompanied by a *concurrent, sustained and almost complete decoupling* from avoidance and post-hoc pain report calls for additional explanations.

A possible mechanism relies on *pain tolerance* and *task persistence*. Observation of a doppelganger performing potentially painful movements could have stimulated *pain tolerance*, which other research has found to be an important predictor for self-perceived musculoskeletal flexibility (Marshall & Siegler, 2014). This would increase *task persistence* during the movements, and thereby decrease pain report afterwards. Such a mechanism would arguably be more effective in those sessions which found their participants especially vulnerable to experimental pain, as in these sessions a mechanism counteracting the behavioral effects of pain would be more relevant. Such a hypothetical vulnerability could have been due to the psychological and/ or physical state of participants simply depending on the day, or on priming effects of the VR experiment and painful experiences in earlier sessions. In both cases, it would have been reflected (and via nocebo effects also been increased by) higher pain expectancy levels. Only in these sessions would pain tolerance and task persistence (despite expected or experienced adverse effects) have had considerable effects on performance: when there is no pain to tolerate and to persist against, the effects would be less notable . This would exactly match the pattern of avatar personalization as a *moderator* of the effects of pain expectancy.

Such an increase in pain tolerance and task persistence could have been elicited by at least two mechanisms. *Self-efficacy beliefs* have been shown to positively affect both of these features (Litt, 1988). They play an important role in functional ability in chronic back pain (Council et al., 1988), and in coping with pain in general (Nicholas, 2007). Self-efficacy beliefs are amenable to generalization from vicarious experience of an observed model (Bandura, 1977), an effect enhanced by high model observer similarity. This links our experiments to the trait of *pain resilience*, which is closely related to self-efficacy beliefs (Slepian et al., 2016) and influences motor behavior in chronic pain (Palit et al., 2020). Our findings suggest that virtual doppelgangers might function as “models of pain resilience”, which could be explored further in future experiments.

In addition, observing a life-sized alter-ego version of oneself, effortlessly performing feared movements, might have worked as kind of an *imagination technique*: “VR-supported imagery” of being fully able to do these movements might have stimulated the transfer of imagery to action. These processes may have interacted with imitative tendencies, as found in Study 1, and with short-term observational placebo effects and vicarious extinction *in virtuo* to bring about the decoupling effect observed in Study 2. Virtual doppelgangers could hence provide an interesting tool to further explore the *motor imagery* and *action observation* in pain rehabilitation, which is a promising field that requires more high-quality evidence for clinical application (cf. the recent meta-analysis by Suso-Martí et al., 2020).

5.3 Methodological Contributions

There are three main methodological contributions achieved in the course of this thesis project. Firstly, the reported studies could validate the usability of the *avatar personalization method* that was developed. In the experiments, the main input variable under control was model personalization. A virtual doppelganger avatar was compared to three other virtual characters as movement models (Study 1), and to a videotaped real-world model (Study 2). Participants' self-reports, scored along the *Autonomous Avatar Questionnaire (multi-media)*, which were developed in the course of these studies, showed higher loads of the virtual doppelganger on the identification dimension. Therefore, the experimental manipulation appears to have been successful. Thus, the *techniques of creating virtual doppelgangers* that was developed for these studies can be used to reliably manipulate identificatory characteristics of virtual counterparts.

Secondly, the studies above also established the usability and safety of using an *immersive CAVE for movement experiments in chronic back pain* with *mixed reality* elements in form of real-world objects to interact with. In general, participants of all ages and levels of VR experience tolerated the experiment well and even reported enjoyment afterwards.

The third main methodological contribution is the development of a contact-free method to determine *functional ranges of motion* (ROMs) for movements of clinical relevance in chronic back pain. The developed method is based on motion trajectories of end effectors for these movements, which can be tracked with *optical motion capture*. This measures another aspect than joint-specific ROM definitions (Ryf & Weymann, 1995) and methods to assess motility and muscle stiffness by applying physical counterforce (Marshall & Siegler, 2014). Therefore, the method of functional ROMs for unhindered, freely performed whole-trunk movements might become a useful additional tool in clinical practice.

5.4 Limitations

There are several limitations to our studies, besides the design differences complicating comparability between both experiments discussed above.

The most prominent limitation with respect to clinical applications is the *absence of any reward elements* in both experiments. This was a deliberate choice to allow for an isolated investigation of doppelganger effects. Nevertheless, effect sizes were small in general, and ROMs declined over sessions in Study 2 for both groups. Thus, to be sustained over time, doppelganger effects may profit from gamification elements (such as in-game rewards or virtual competitors), which is widely used to increase physical activity and other outcomes (cf. the reviews by Johnson et al., 2016; Koivisto & Hamari, 2019; Mouatt et al., 2020). This would be an especially promising line of future research, as virtual doppelganger avatars might very well find their intuitive embedding in so-called serious games for back pain rehabilitation (France & Thomas, 2018; Jansen-Kosterink et al., 2013; Stamm et al., 2020).

A second limitation is the *lack of physiological measurements* alongside the behavioral motion tracking and questionnaire assessment applied in these studies. These could be, for example, skin conductance responses as measures of physiological stress levels (e.g., Thieme et al., 2015), heart rate as a measure of valence (e.g., Fusaro et al., 2016), and hemodynamic responses in cortical regions related to pain, measured by functional near infrared spectroscopy (e.g., Gentile et al., 2020). Future research should aim at including such methods to better differentiate underlying mechanisms of behavioral outcomes in these experiments. Similarly, gaps in understanding the between-sessions trajectories of pain and pain expectancies in Study 2 could be filled by *ecological momentary assessment* (EMA) in future studies of similar design (May et al., 2018). Smartphone applications with daily reminders to fill out a brief pain questionnaire and other questions on current emotional state would be a valuable tool to shed further light on mechanisms such as extinction or consolidation and generalization of experimental short-term experiences in everyday life.

A third limitation is specific for Study 2, which is our sample of *relatively unimpaired participants with back pain*. Future replication studies should certainly aim at recruiting larger and more severely impaired samples of pain patients. If potential benefits could be confirmed in this subgroup as well, this would establish their clinical relevance. For now, the observed effects are limited to the samples investigated in both experiments: in healthy (pain-free) participants and in participants with rather small functional impairments despite their chronic back pain. The proof of principle provided by our experiments has arguably laid the ground to extend these applications to more severely impared patient groups in an ethically responsible way.

5.5 Outlook

5.5.1 Future Experiments in Chronic Back Pain

Our approach of personalized movement models as stimulators of imitation in chronic pain could be extended in two directions: Firstly, *morphing techniques* to gradually change bodily features have already been applied to avatars derived from 3d scans (Mölbert et al., 2018). They could be used to incrementally manipulate similarity of virtual models to their real-world observer in observational settings. This would allow for a more fine-grained investigation of behavioral effects of model-observer similarity. Secondly, *manipulations of identificatory characteristics* of virtual models without personalizing them would create the possibility to better differentiate effects of affiliation, model- observer similarity and their interactions. Different approaches to this are currently under development in psychological research employing virtual characters. For example, in *narrative self-introductions* of virtual characters, those who told stories in 1PP appear more trustworthy than those telling stories about others in 3PP (Gilani et al., 2016). Another way to change trustworthiness and likability are adaptations to *facial expressions* of characters, suggesting different interpersonal stances towards the observer, e.g., by letting them keep eye contact or smile (Galinsky et al., 2020). A more implicit approach are *manipulations in facial features*, following empirically derived markers of seeming trustworthiness, which have been found to influence perceived dominance and likability (Oosterhof & Todorov, 2008; Todorov et al., 2008; Todorov et al., 2009).

Future experiments should also focus on trait and state measures of pain resilience and experimental manipulation of self-efficacy beliefs. For example, *competence of movement models* could be varied from “highly proficient” to “obviously amateurish”: observational modeling is influenced by the apparent discrepancy in competencies between model and observer. Models “too competent” and therefore not relatable enough can be less effective in stimulating modeling (c.f., for vicarious fear reduction, Kazdin, 1974). In addition, measurements of *physiological markers of arousal*, such as *skin conductance responses*, could help to determine the current physiological stress levels during the movements as indicators of pain (Thieme et al., 2015; Zidda et al., 2018). An interesting starting point here is a full-body illusion experiment with a virtual avatar, seen in 3PP and stroked synchronously and asynchronously with tactile stimulation of participants (Romano et al., 2014). In this case, higher self-identification in synchronous visuotactile stimulation was correlated with lower skin-conductance responses to painful stimuli and accordingly lower pain ratings, giving physiological evidence of visually induced analgesia in virtuo. In addition to responses in skin conductance, *heart rate* as a measure of valence has been influenced by vicariously experienced painful and pleasant touch of virtual characters, viewed in 3PP and 1PP (Fusaro et al., 2021; Fusaro et al., 2016), and could thus be an interesting measure in doppelganger studies. Recording these measures during encounters with virtual doppelgangers could help differentiating mechanisms of observational placebo in the narrow sense and other effects that reduce more general stress phenomena.

Another physiological marker could be cortical hemodynamic activity, measured by *functional near-infrared spectroscopy* (fNIRS, for a review in the pain field, c.f. Karunakaran et al., 2021), during painful movements (Gentile et al., 2020; Öztürk et al., 2021). Complementing these, *fMRI* measurements during passive watching of personalized movement models could help differentiate the potential effects at play (although display of these would be limited to small screens suitable to be used in an MRI scanner): pain tolerance stimulated by self-efficacy beliefs, possibly accompanied by strong prefrontal activity; motivational factors increasing task persistence, potentially reflected by activation of meso-corticolimbic reward systems; placebo effects diminishing pain itself as reflected by decreased activity of networks of sensory and affective pain processing (Zunhammer et al., 2021); and finally extinction effects of fear itself, potentially reflected in decreased activity of brain regions involved in fear processing, such as the amygdala (Whittle et al., 2021) or increased activation in frontal controls regions (Burgos-Robles et al., 2007; Milad & Quirk, 2002). Extensions of fMRI research in pain towards analyses of global cortical activation patterns (Reddan & Wager, 2018) could shed further light on interacting streams of cortical brain processing. Virtual doppelgangers could also be used for an innovative form of fMRI *neurofeedback* in pain (Sorger et al., 2018), as their vicarious real-time modification (e.g., in color or size) could provide a highly intuitive and intrinsically rewarding way to display visual feedback on successful self-regulation of pain-related fMRI activity.

On a *behavioral level*, feedback on maladaptive and healthy movement patterns could also be displayed in 3PP on personalized doppelgangers. This would require a kinematic model of *healthy movement behavior* in backpain-related movements, from which target features in movement trajectories and healthy parameter ranges for these measures could be derived (cf. the approach by van Dieën et al., 2017). Based on this model, a real-time implementation of VR-based feedback on virtual doppelgangers would be a promising way to combine 1PP training of healthy movements with 3PP observational modeling, as it was explored in our studies.

To investigate underlying mechanisms of our findings in Study 2, it would be promising to *assess between-session pain and muscle ache* in future experiments of similar design. This could allow for an investigation of the reasons of increased pain expectancy, which has been observed in experiments on VR-based exposure schedules as well (Hennessy et al., 2020). Using *electronic pain diaries* could be an interesting tool to this purpose (Jamison et al., 2001; Marceau et al., 2007; Morren et al., 2009).

5.5.2 Applications in Treatments of Chronic Pain

Our experiments with virtual doppelgangers may kick off an additional research strain on applications of VR in pain. As shortly described in Section 1.3.2., current developments have already moved beyond distraction, which nevertheless will not lose its important role in VR analgesia. Today's approaches focus mainly on gamification to increase motivation by rewards and on changing body perception by virtual embodiment (Matamala-Gomez, Donegan, et al., 2019). Beneficial effects of the later are related to *visually analgesia*, which is known from non-VR settings in stationary (Löffler et al., 2017; Longo et al., 2009) and movement-related settings (Wand et al., 2012). It can also be invoked by seeing an embodied virtual arm (Nierula et al., 2017), and be further increased if embodied limbs are manipulated in size, transparency or other features (Matamala-Gomez, Diaz Gonzalez, et al., 2019; Ronchi et al., 2017). For musculoskeletal pain such as CBP, a closely related mechanism is especially relevant: reduction of *pain-related distortions in body image and maladaptive body perception*, along with accompanying beliefs about its functional motor abilities (for CBP, cf. Alemanno et al., 2019). Shifting the focus even more towards functional ability, *VR-based graded exposure or extinction therapy* to extinguish fear of movements and avoidance behaviors and to increase adaptive behaviors comes into focus (Gupta et al., 2018; for CBP, cf. Hennessy et al., 2020). In accordance with these considerations, the recent reviews on VR in CBP by Tack (2021) and Bordeleau et al. (2022) also identified these three mechanisms (distraction, changed body perception, and exposure with gamification) as main tools for VR interventions.[8]

Based on our experiments, use of *virtual vicarious models* can join right into this rank of treatment approaches, promising beneficial interactions with the ones already established. Virtual doppelgangers as movement models appear to decouple

[8] Note that the former conceptualizes changes in body perception as "neuromodulation", and the latter add a fourth mechanism of "accelerated time perception" by engaging working memory, which might be rather a consequence of distraction and gamification combined.

movement avoidance from pain expectancy, at least in our sample. This opens the toolbox of well-known influencing factors on observational modeling for VR-based pain rehabilitation. In our case, this was used in the form of manipulating model-observer similarity. Although our findings do not support fear extinction and vicarious fear reduction as contributors to this effect, our results offer the possibility to decouple fear from avoidance by other mechanisms. Exploring the latter should start with observational placebo effects, vicariously boosted self-efficacy beliefs and stimulated imagination as facilitators of task persistence and pain tolerance.

In any case, the decoupling effect itself can become a valuable tool to intensify *exposure treatments* aiming at fear extinction (Vlaeyen et al., 2012) and operant extinction of avoidance and the increase of healthy behavior (Flor & Turk, 2011). The *connection between pain expectancy and avoidance is complex*: avoidance can return after successful fear extinction (Gatzounis & Meulders, 2020) or outlast it unchanged (Vervliet & Indekeu, 2015), especially for conditions of outcome uncertainty (Glogan et al., 2021). Similarly, explicit pain expectancies can persist despite successful extinction of avoidance behavior (Janssens et al., 2019). Some current approaches to operant treatments of pain target exactly this *“breaking point” in the vicious cycle of chronic pain, fear and avoidance* to decrease interference with daily activities and enhance functional abilities (Flor & Turk, 2011; Gatzounis et al., 2021; Gatzounis et al., 2012). Here, the use of virtual doppelgangers as observational models in combination with game-typical rewards could add a powerful additional tool to already existing VR-based exposure (Hennessy et al., 2020).

This would facilitate an advanced type of serious VR games for chronic back pain and other chronic pain conditions, a type of *doppelganger trainer exergames*, i.e., games designed to motivate bodily movement exercise or other healthy behaviors. A movement game with personalized virtual avatars would combine the principles of distraction and reward-based gamification in exergames (France & Thomas, 2018; Jansen-Kosterink et al., 2013; Stamm et al., 2020) with exposure techniques and the observational effects on pain perception, tolerance and task persistence observed in our experiments. Recent advances towards accessible, medium-cost avatar personalization (Gorisse et al., 2019; Wenninger et al., 2020) could lay the ground for a broader application of such techniques, although cost-efficient high-fidelity personalized avatars that are easy to create are still some way down the road of technological development (Bartl et al., 2021). Of high importance in this respect is our exploratory finding in Study 2 that *experienced realism* of the VR as an aspect of presence in fact *decreased motor engagement*, although with small effect size. While this raises some serious questions for VR research itself, it nevertheless is promising for affordability and accessibility of potential doppelganger exergames. This could mean that these do not need highly realistic appearance in effortfully designed virtual environments. If this is confirmed by future research, this would decrease development costs considerably and lead to higher adoption of this principle on the market of health-related computer games. In addition, experienced realism is usually increased by highly immersive technology. If the latter is indeed not necessary for effective doppelganger models, rehabilitation applications could also rely on *medium-to-high immersion technology*, such as large-screen presentations of virtual doppelganger training sessions. These could in principle be *set up at home*, i.e., by using video projectors for home use, which would probably increase compliance with rehabilitation exercise schedules remarkably. Motion tracking could then complement the gaming experience by visual feedback on own movements, as already implemented in gaming products as for example the *Wii* (*Nintendo*, Kyoto) or *Xbox* (*Microsoft*, Redmond, WA). Advances in cable-free HMDs will soon render highly immersive technology a viable candidate for home-based movement games as well, if the weight of these “VR helmets” does not turn out to be a problem in this respect. The successful integration of real-world objects into our mixed reality setup could also pave the way for *augmented reality* applications, which could display doppelgangers performing the movements in participants’ familiar environments. This could be accomplished by using tablet computers or smart glasses that overlay virtual content on real-world vision.

Besides distraction, gamification and exposure, virtual doppelgangers may also add value to *research on changes in body perception and body image in pain*. In VR research, these areas of research mostly focus on 1PP embodiment of avatars or limbs

(Matamala-Gomez, Donegan, et al., 2019). However, effects of doppelgangers have been seen in 3PP in other areas of VR research (Gorisse et al., 2019). Starting from our demonstration of behavioral doppelgangers effects in CBP, the link between body image and self-related expectancies, such as self-efficacy beliefs, and flexibility in mental imagery with respect to own movements should be further investigated. Although the ratings on the subscale AAQ(mm)3 on altered body perception were generally low in both of our experiments, the behavioral effects suggest a further exploration of doppelgangers on body perception. Influences of virtual doppelgangers on explicit and implicit body representations would probably require *prolonged exposition* over more experimental sessions to show relevant effects. In addition, our experiments did not assess *gradual manipulation of virtual body appearance*. Applying morphing techniques to modify model-observer similarity in body shape and appearance gradually could make it possible to explore the differential effects of “alter-ego” versus “virtual-other” perception of the movement models. However, note that this would require a technologically very challenging and potentially high-cost generation of more regularly meshed 3d avatar objects than achieved by our low-cost solution. Here the abovementioned future developments in standardized avatar design would also come in handy for easier experimental manipulation.

This leads to potential applications beyond pain research, as virtual doppelgangers and the techniques developed in our experiments can also benefit other clinical research areas in which bodily, cognitive, and affective aspects of the self are interacting with each other.

5.5.3 Applications in Clinical Research

Potential clinical applications of the mechanisms explored in our experiments go beyond the field of chronic back pain. Body perception and perception of one’s own motor abilities and limitations are interrelated, which is reflected in the complex relationship between different levels of conscious body image and motor-related implicit body schemata (Blanke et al., 2015; Longo, 2015). VR has shown impressive *potential to change body perception*, which inspired Jaron Lanier’s theory of "homuncular flexibility" (Won et al., 2015). Nevertheless, the embodiment of virtual limbs can be limited by damaged physiological control of their real-world counterparts, as it has been shown for spinal cord injury decreasing ownership of a virtual leg, while leaving the possibility to evoke full body illusions intact (Ronchi et al., 2017). It is important to better understand changes in body perception and the factors they are limited by. To a certain degree, distorted body representations appear to be a generic phenomenon in humans (Longo, 2021). However, they become particularly clinically relevant when taking the form of maladaptive changes, which have been found not only in pain syndromes (Flor et al., 1997; Lewis et al., 2007; Lotze & Moseley, 2007; Moseley, 2008; Moseley & Flor, 2012) but also in other clinical conditions as well (Moseley et al., 2012).

For example, *eating disorders* and the accompanying changes in body representation (Ziser et al., 2018) are promising targets for the inherently embodied technology of VR (Riva et al., 2019). By creating bodily and visual experiences which would otherwise be difficult or impossible to elicit, virtual characters and avatars (in 1PP and 3PP) allow for investigating different aspects of body image. A promising example is the study by Mölbert et al. (2018) in participants with anorexia nervosa. In contrast to current theories, the authors did not find distorted body image when participants had to estimate the correct size of a personalized avatar retrieved from 3d scans. However, there was a maladaptive distortion in participants' ideal body size, despite of patients' efforts to adjust their body ideal in compliance with treatment. Autonomously moving doppelgangers, potentially morphed in model-observer similarity and/ or body weight, could shed light on the interaction between social learning from models and how this relates to identification and body ideal. It would be interesting to assess whether motor imitation is maximized for a doppelganger model with seemingly "ideal" weight. In the other direction, a voluntary effort to imitate movements of a non-underweight doppelganger avatar could shift body ideal towards its size via the chameleon effect of increased identification with models mirrored by (or conversely mirroring) the observer. This would extend VR treatment approaches in eating disorders (Paslakis et al., 2017; Serino et al., 2019), which often focus on exposure to virtual food stimuli or body shape

(Clus et al., 2018), with recent developments aiming at exposure to virtually increased body weights (Döllinger et al., 2019).

Basic research on autonomous doppelgangers influencing body ideal could be applied in *body integrity dysphoria*, a condition coming with a strong desire for amputation of an intact but seemingly alien limb. Here, augmented reality has been used to temporarily create the impression of apparent wish fulfillment, with the possibility to assess the psychological and physiological effects of this experience (Turbyne et al., 2021). Supporting imagery of one's own changed appearance by seeing virtual doppelgangers after fictional amputation could offer an interesting tool to investigate the still unclear etiology of this condition, although this tool should be applied with the highest caution for ethical reasons.

Besides body representations in the broad sense, psychotherapy research has explored a broad range of applications for VR as a therapeutic tool (Freeman et al., 2017). An especially interesting application is a *self-counselling* study by Slater et al. (2019), who let participants meet their virtual doppelganger in 3PP while embodying a pop-cultural symbol of counselling (an avatar in the image of Sigmund Freud) in 1PP. From this perspective, they gave their own doppelgangers friendly advice, to which they could later listen themselves when put into the position of the doppelganger. Similarly, the moving doppelgangers from our studies could be used in setups in which participants teach their own doppelgangers how to move in a less maladaptive way, potentially consolidating behavioral change in themselves.

The field of *anxiety disorders* is one of the earliest application areas for VR in psychotherapy research and it could profit as well from personalized models. Confrontation and *exposure therapy* has been implemented in virtual environments, as it has been studied in *post-traumatic stress disorder* (Rizzo et al., 2011) and in different *phobias* (Botella et al., 2017; Strickland et al., 1997). VR setups with virtual characters may also provide a training tool for social interactions. For example, experimentally induced social anxiety has shown a tendency to be increased by embodiment of an avatar highly similar to participants (as seen in a virtual mirror) than in the dissimilar condition (Aymerich-Franch et al., 2014). The doppelganger effect we established in Study 2, decoupling behavioral avoidance from fear, would be an impactful tool for these contexts as well. Given the *roots of fear-avoidance models of pain in research on anxiety disorders* (Crombez et al., 2012), this potential generalization of treatment mechanisms appears worth investigating. Virtual doppelgangers that deal fearlessly with situations and objects eliciting anxiety in patients might evoke vicarious strengthening of self-efficacy beliefs and stimulate imagery of one's own successful dealing with them (cf. the early imagery study by Kazdin, 1974). This might provide a different type of VR treatment in a "*vicarious alter-ego exposure*". With respect to our study, it would be interesting whether in anxiety disorders a vicarious reduction of fear would be observed. In contrast to our study in pain, such an effect might be far stronger in anxiety disorders and hence be easier to detect. This would be an innovative test of the controversial conception that pain-related fears of movement are highly similar to phobic symptoms, as the often-used term of "kinesiophobia" suggests. In any case, a successful application of *virtual doppelgangers as "courage models"* would be a nice form of "payback" from pain to anxiety research.

5.5.4 Applications in Media Psychology

Beyond clinical applications, our experiments also have some implications for basic research. We will focus on media and social psychology in the following, with an outlook on embodiment research.

Virtual characters can be used for new lines of social psychology research, as for investigating psychosocial role expectancies by the behavioral *Proteus effect* (Yee et al., 2009): embodiment with an avatar of a specific gender, ethnicity or social class, may change behavior in line with established stereotypes, or conversely override the latter. This can affect both judgments about others, such as when it decreases or increases sexist beliefs held by the user depending on the degree of sexualization of their female avatar (Fox et al., 2013), and self-related expectancies, for example by increasing self-confidence in negotiations after embodying a tall avatar (Yee & Bailenson, 2007) or by reducing effects of stereotype threat in female participants when embodying a male avatar during a math test (Peck et al., 2018). The Proteus effect can be elicited quite reliably in immersive VR with 1PP embodiment designs, as highlighted by a recent meta-analysis (Ratan et al., 2020). However, it is not limited to these and has also been found for desktop computer games (Ash, 2015) with implications for attitudes and behavior towards real-world persons and social groups (Hawkins et al., 2021). A recent review by Praetorius and Görlich (2020) distinguished three dimensions of avatar identification which can facilitate behavioral changes due to the Proteus effect: *identification via self-similarity*, *wishful identification* with avatars perceived as superior (such as in attractiveness or height), and *embodied presence* in the strict sense of 1PP embodiment. These dimensions were also found in a large-scale online-survey on self-reported identification with computer-game characters by Downs et al. (2019). However, their polythetic model, based on a PCA of responses, also established additional dimensions: *value homophily* reflected in aligning psychosocial characteristics, *perspective-taking* with respect to the virtual character, and the interpersonal feeling of *liking*.

Note that in all these studies, the avatars are user-controlled to some extent, such that a sense of agency is usually accompanying said identification processes. Virtual doppelgangers which move autonomously could help to decouple these dimensions of identification and thus allow for a separate assessment of their behavioral relevance. For example, our own dimensional constructs in form of *Autonomous Avatar Questionnaires (multi-media)* align self-similarity, likability, and some items on perspective-taking along one dimension, distinct from changes in body perception and sense of agency (as typical for embodiment of avatars). An interesting next step would be the implementation of different degrees of user-control over the doppelgangers, e.g., by letting the latter start to mirror their observers' movements at some point. Thereby, the conditions under which these *dimensions of identification* align and when they run apart could be separated more exactly. More generally and independently of the degree of user control, experiments that put participants in 3PP on virtual characters could employ our AAQmm item sets. This would add a complementary tool to embodiment questionnaires (Peck & Gonzalez-Franco, 2021), although a substantial overlap in items is given by our inclusion of earlier embodiment and enfacement questionnaires (Gonzalez-Franco & Peck, 2018; Tajadura-Jiménez et al., 2012). Differentiating the role of visual perspective, embodiment and user control in identification would also shed some important light on a complex issue for which Proteus effects are an important potential mediator, namely the *interrelations between computer games and real-world behavior* and their positive or negative consequences (for reviews spanning the discoursive spectrum, cf. Burnay et al., 2022; Halbrook et al., 2019; Markey et al., 2015).

5.5.5 Exploratory Applications of Doppelgangers in Basic Research

Besides clinical research, virtual doppelgangers as explored in our studies might also be applied to questions of basic research. Two examples are shortly sketched in the following. The first application would put a theory from cultural anthropology to a test: virtual doppelgangers could be used as a lab model for René Girard's theory of "mimetic desire" between highly similar individuals as a source of conflict. This theory is highly influential in cultural studies and political sciences but is hard to test empirically. The second application would be the use of doppelgangers as a tool in research of avatar and tool embodiment. Integration of objects into body image and body schema is a widely discussed topic in cognitive sciences. Some perspectives on body perception emphasize the role of dynamic coupling between neuromotor systems with objects, while other accounts rather conceptualize it as a matter of neural representation and processing of information. Semi-autonomous virtual doppelgangers with varying degrees of model-observer similarity could be one study case for these different perspectives.

To start with, virtual doppelgangers could provide *social psychology* with a tool to test competing anthropological theories on imitation and observational modelling. In processes of social transmission of behavioral patterns, identificatory mechanisms play an important role, as analyzed in social learning theory (Bandura, 1986; Bandura & Walters, 1977). The human tendency to mirror, emulate and learn from behavior of conspecifics develops quite early ontogenetically, compared to other primates (Tomasello, 2016, 2020). Some perspectives from evolutionary anthropology see its sophisticated and complex forms as one distinctive feature of human sociality, which enables cultural evolution (Tomasello, 2019). Fittingly, the chameleon effect as the tendency of behavior mirroring has been described as "social glue" for human communities (Lakin et al., 2003). However, perspectives from cultural anthropology point to the potential for conflict in observational modeling (Garrels, 2005). They refer to René Girard's concept of *mimetic desire* (Girard, 1977). This theory states that humans tend to adopt objects of desire for the very reason that others are observed to desire them, which inevitably leads to conflict when these objects are limited and when modeling of aggressive behavior comes into play as well. According to Girard (1977), this is reflected in myths and legends about dangerously blurred identities between individuals and social groups, which he attributes to an intuitively felt threat of excessive mirroring leading to societal destruction in a "dog eats dog" style. One of Girard's examples is the fearful reaction by which identical twins are confronted in many cultures, as they implicitly embody this threat, according to his theory. Although this elaborate theory is difficult to test psychologically, it has found fruitful application in political science, for example, for analyses of religious (Imran & Zhai, 2021) and post-cold war political conflicts (Krastev & Holmes, 2019). In social cognitive theory, the ambiguous effects of observational modeling have early been acknowledged, as paramount in the famous "bobo doll" study by Bandura (1965) that showed the imitation of aggressive behavior by children. In this context, autonomous virtual doppelgangers could not only be used to enhance beneficial imitation in a collaborative setting, as it was the goal in our studies. Complementarily, they could also provide social psychology with a laboratory model for mimetic conflict by manipulating "*model-opponent similarity*" in competitive game situations in which participants play against doppelgangers. Using virtual doppelgangers as virtual "twins" (in the allegedly threatening sense) could thereby explore whether in some situations, high similarity of opponents can incite aggressiveness in conflict. If confirmed, this could also provide an interesting explanation for the *uncanny valley effect* (Mori et al., 2012), which describes the eeriness often felt by observers of virtual characters that are close-to-photorealistic. This effect appears not to be universal for perception of virtual humans (de Borst & de Gelder, 2015), and the correlation between model-observer similarity and likability in our Study 1 indicates that it was not relevant in our studies. However, virtual doppelgangers in aversive situations of conflict could show whether uncanny valley effects are not only dependent on the quality of character design, but also on especially uncomfortable or threatening contexts. In any case, encounters with autonomous virtual doppelgangers, potentially morphed in self-similarity, provide a new research tool to develop and test experimental hypotheses on observational modeling and the effects of model-observer similarity in this regard.

We conclude this outlook with a short description of how virtual doppelgangers can add some new perspectives on the *construction and malleability of the bodily self*. This links psychological and medical research on doppelgangers back to the origin of the concept itself: in literary fiction, from which the term “doppelganger” originated, these alter-ego doubles usually evoke awe, fascination and terror alike (Nilsen, 1998). Here they represent the potential for dissolution and redrafting of the self – which poses a threat as well as a temptation.[9] This relates to their role in VR, where they can induce unusual states of the bodily self, extending real-world body illusions. VR research has mostly employed the 1PP on embodied avatars in experiments, which has been shown to increase effects (Petkova et al., 2011). However, illusionary embodiment of bodies seen in 3PP (Pomes & Slater, 2013), similar to real-world full body illusions (Lenggenhager et al., 2007), and virtual “body swapping” (Petkova & Ehrsson, 2008) provide an especially powerful illustration of the flexibility of the perceived bodily self (Blanke & Metzinger, 2009). This matches with the phenomenal body perception and neural body representation, which are subject to a variety of possible distortions (Longo, 2021). This touches on open questions regarding the *emergence of bodily awareness*. Where *representationalist conceptions* draw it as an internal brain simulation based on inflow of external signals (Metzinger, 2009), approaches from the

[9] See for example the doppelganger encounters in the Romantic novels *The Double* (1846) by Fyodor Mikhailovich Dostoevsky, and *The Devil’s Elixirs* (1815) by E. T.A. Hoffmann. These doppelgangers act more disinhibited and boldly than their models (and are potentially violent), quite similarly to Mr Hyde in the *Strange Case of Dr Jekyll and Mr Hyde* (1886) by Robert Louis Stevenson.

framework of *embodied cognition (EC)* emphasize the role of dynamic interactions between brain and bodily processes (Gallagher, 2017). This results in different approaches to the functional principles underlying the embodiment of avatars and tool objects (Schettler et al., 2019).

VR as an embodied technology intensifies the “incorporation” (Calleja, 2007) of virtual environments and could help putting these approaches to a test. Virtual doppelgangers could be controlled by participants to disentangle sense of agency from other more cognitivist factors. A game in which a doppelganger is used as an embodied tool could test whether embodiment rather depends on successful dynamical coupling between one’s own and the avatar’s movements, or whether visual similarity and other sensory signals are dominant. While the former effect would rather support dynamic coupling theories based on EC, the latter mechanism would emphasize the importance of prior body knowledge and the suitability of new input to internal body simulations, as predicted by representationalist accounts. Doppelganger experiments could switch between avatar autonomy and user control, while at the same time varying the self-similarity by morphing. This would potentially elicit changes in bodily perception and body image while at the same time the virtual other could still be perceived as an agent of their own.

It should be emphasized that such experiments could certainly not decide far-reaching philosophical debates about bodily selfhood and the perception of virtual bodies and worlds as “real” or “fictional” (Chalmers, 2017; Metzinger et al., 2018). However, they could give some interesting empirical input to these debates. Feeding back into clinical research, this could inspire new treatment approaches of conditions in which body perception and motor control and coordination are impaired.

6 SUMMARY

The studies described in this thesis explored the application of virtual reality as an embodied technology virtual reality in the treatment of the complex bodily phenomenon of chronic back pain. Our approach used personalized virtual doppelgangers as movement models in an immersive virtual reality with real-world elements in a Cave Automatic Virtual Environment. Behavior was assessed with self-report questionnaires as well as analyses of movement trajectories recorded with motion capture. The theoretical framework behind this was drawn both from learning theories of chronic pain, such as operant conditioning and fear avoidance models of chronic pain, and from theoretical accounts of observational modeling, such as social cognitive theory.

Study 1 showed that increased identification with doppelgangers, as compared to other virtual characters, stimulated voluntary motor imitation in healthy participants. The randomized controlled Study 2 found an interaction effect between movement model and prior pain expectancy for behavioral outcomes. In the control group, watching videotaped movement models, prior pain expectancy was linked to the development of motor engagement over sessions, as well as to post-hoc self-reports on experienced pain during movements. In contrast, the experimental group, observing their personalized doppelgangers, did not show any of these effects. This suggests that virtual doppelgangers stimulate observational modeling by eliciting a chameleon effect of imitation enhanced by identification. In addition, for persons with chronic back pain, virtual doppelgangers appear to decouple pain expectancy and fear from behavioral avoidance and actually experienced pain. This offers a new possibility to cognitive-behavioral therapy in chronic pain, for example, by intensifying virtual exercise games with doppelgangers as virtual trainer models, possibly amplifying extinction of fear of movement and avoidance behavior.

Virtual doppelgangers offer the opportunity to use the malleability of the bodily self in clinical applications. Thus, VR may stimulate behavioral flexibility in chronic pain and thereby alter the pain experience itself. Virtual doppelgangers are intermediate beings that represent the twilight zone between “me” and “other” and are therefore particularly suited to stimulate perceptual and behavioral flexibility. This may not suffice to fully overcome the hard facts of bodily existence, as they intensify in severe pain. However, this special tool may help virtual reality as an embodied medium to fluidify the limits of bodily existence, both in chronic pain and beyond.

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8 APPENDIX

8.1 Supplements of Study 1

8.1.1 Exploratory Model Analysis

In our exploratory model selection, we proceeded as follows: We selected the model complexity, starting with an intercept-only LME model (i), by stepwise adding CN (ii), AN (iii), and person characteristics (iv) and assessing whether the extended model showed an increased deviance *D,* which can be explained by chance with a probability of less than p=0.2 (otherwise the selection process stops at the previous stage).

Our model selection procedure (Figure 27) starts with the simplest model (i) only containing a sample mean ROM (the so-called fixed intercept) and subject-dependent deviances from this mean (random intercepts). The next model in line (ii) includes only the additional control variable cycle-number. Then we add AN, our variable of interest (iii): adding it as the second candidate variable after the former control variable should make sure that AN did at least promise some increase in overall explanatory power before analyzing its influence in more detail. Finally, the trait variables may be added (iv). This step investigates a different level of possible influences: Whereas cycle-number and avatar number vary within each subjects' data points and allow for modeling random slopes (level-1 variables), the trait variables only vary between subjects and can have only effects on subjects' mean ROM (level-2 variables).

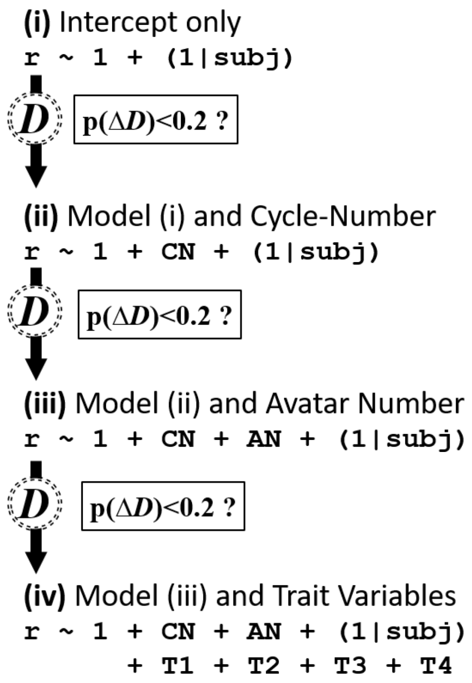

Figure 27. Supplements Study 1: Model selection.

Model selection for exploring personal traits as predictors of ROM. Models are indicated by their model number and short description (first line) and *R* pseudo-code (second line; conventions following the *R* package *lme4*). The stepwise model selection process starts from the "Intercept only" model, which only takes into account random effects per participant (indicated by "subj"). Each step follows the same selection method: if the next complex model decreases the deviance *D* (-2*log-likelihood) more than would be expected by chance with a probability *p* = 0.2 (likelihood ratio test for nested models, employing the Chi-square test), then the more complex model is selected. In the contrary case, the model selection process halts at the antecedent model.

Abbreviations: AN – avatar number; CN – cycle number; r – range of motion; subj – subject (participant ID); T – trait variable (personal characteristics per subject).

Level-2: Trait Variables

We expected that subjects' overall tendency to engage strongly in the reproduction of model movements would be influenced by several factors, ranging from trait properties (trait anxiety and empathy) over aspects of body image shaping expectations (such as body acceptance and perception of bodily complaints) to social factors influencing mirroring and collaboration in tasks (influenced by gender roles, for example). Therefore, we also included these aspects in our analyses. We retrieved trait measures based on established questionnaires: *empathy* (Interpersonal Reactivity Index [IRI; Davis, 1983]: sum score), *anxiety* (State-Trait Anxiety Inventory [STAI;

Spielberger, 1983]: trait score), *bodily complaints* (Gießen Subjective Complaints List 24 [GBB-24; Brähler et al., 2000]: total sum score), and *body acceptance* (Dresden Body Image Questionnaire [DKB-35; Pöhlmann et al., 2014]: acceptance score).

For *lateral flexion (BS)*, the personal characteristic variables were included in the model selection process (model iv). Although the more detailed analysis for BS in step (2) did then indicate substantial effect sizes for body acceptance (DKB, β_z=0.3157), trait empathy (IRI, β_z=0.3438) and gender (β_z=0.6015), none of these effects reached significance (all p_{SM} and p_{PB} values above 0.1, with the only exception of IRI with p_{SM}=0.0519 and p_{PB}=0.1001). This suggests that these variables (especially IRI, but also DKB and gender) may deserve a closer examination in setups with larger sample sizes and higher statistical power, whereas the role of trait anxiety may well be left aside in future analyses (STAI-trait, β_z=0.0679).

8.1.2 Detailed Results of Model Selection Processes

In case of *spinal extension (BB)* and *rotation in the horizontal plane (RH)*, the model selection process (1) arrived at model (iii), indicating that our set of personal characteristics was not significant in explaining inter-subject differences in ROM.

In the following, we report for each movement the model characteristics for all models, followed by a pairwise Model Comparison table: There we report the Chi-square test *p*-values for the respective decrease in deviance, *p*(ΔD).

Table 9. Supplements Study 1: Results of model selection.

Bend Backward (BB)				
Model Characteristics				
Model number	**(i)**	**(ii)**	**(iii)**	**(iv)**
df	3	6	10	14
logLik	-106.02	-93.46	-85.25	-82.45
deviance *D*	212.04	186.92	170.49	164.91
AIC	218.04	198.92	190.49	192.91
BIC	226.40	215.65	218.37	231.93
Pairwise Model Comparisons: p(ΔD)				
	(i)	**(ii)**	**(iii)**	**(iv)**
(i)	---	$< 10^{-4}$	$< 10^{-6}$	$< 10^{-5}$
(ii)	---	---	$< 10^{-2}$	$< 10^{-2}$
(iii)	---	---	---	0.23

Bend Sideward (BS)				
Model Characteristics				
Model number	**(i)**	**(ii)**	**(iii)**	**(iv)**
df	3	6	10	14
logLik	-94.00	-89.17	-84.20	-80.65
deviance *D*	188.00	178.34	168.40	161.30
AIC	194.00	190.34	188.40	189.30
BIC	201.93	206.20	214.84	226.32
Pairwise Model Comparisons: p(ΔD)				
	(i)	**(ii)**	**(iii)**	**(iv)**
(i)	---	0.02	$< 10^{-2}$	$< 10^{-2}$
(ii)	---	---	0.04	0.03
(iii)	---	---	---	0.13

Rotation in horizontal plane (RH)				
Model Characteristics				
Model number	**(i)**	**(ii)**	**(iii)**	**(iv)**
df	3	6	10	14
logLik	-94.40	-83.76	-79.99	-78.71
deviance *D*	188.80	167.52	159.97	157.41
AIC	194.80	179.52	179.97	185.41
BIC	203.16	196.25	207.85	224.44
Pairwise Model Comparisons: p(ΔD)				
	(i)	**(ii)**	**(iii)**	**(iv)**
(i)	---	$< 10^{-4}$	$< 10^{-3}$	$< 10^{-3}$
(ii)	---	---	0.11	0.26
(iii)	---	---	---	0.63

Results of model comparisons of linear mixed effects models for ranges of motion (ROM) for different movements. The models (i)-(iv) are nested and can thus be compared with likelihood ratio tests, employing Chi-square tests to determine the probability *p* that the decrease in deviance (*D*) by adding a predictor has occurred by chance ($p(\Delta D)$). The first sub-table lists different model characteristics for all models, whereas the second sub-table gives the $p(\Delta D)$ values of pairwise model comparisons, respectively. Model numbers indicate the predictors present in the respective model: (i) – Intercept only; (ii) – Intercept and cycle number (CN); (iii) – model (ii) and avatar number (AN); (iv) – model (iii) and trait variables.

In the stepwise model selection process, a model can only be selected if it performs better than *all* antecedent models (as decided by an unconservative *p* value of < 0.2). For *bending backward* (BB) and *rotation in the horizontal plane* (RH), the selected model was this model number (iii). For *bending sideward* (BS), the selected model was the most complex one, number (iv). However, analysis of fixed effects in model (iv) did not reveal any significant influences of personal characteristics ("trait variables") on ROM even for this movement, except for a marginally significant effect of the empathy measure of interpersonal reactivity index (IRI), with β_z=0.34, with a Satterthwaite *p* value estimate of p_{SM}=0.05 and a bootstrapped *p* value estimate of p_{PB}=0.10.

Abbreviations: AIC – Akaike information criterion; BIC – Bayesian information criterion; logLik – log-Likelihood; df – degrees of freedom for Chi-square test.

8.1.3 Items of Autonomous Avatar Questionnaire (AAQ) Scales 2 and 3

Table 10. Supplements Study 1: Items of Autonomous Avatar Questionnaire, Scale 2 (AAQ2).

Load	Source	Question
-0.5198		It was strange to watch the character.
0.5160		The movements were easy for the character.
0.4824		The character gave the impression to be fit for the performed movements.
0.4687	B2/5	I felt as if another person stood in front of me.
0.4381		The character gave the impression to be sporty.
0.4247		The character was comfortable with the movements.
-0.4137		The movements were uncomfortable for the character.
-0.3700		The character looks eerie.
-0.3699		The movements were exhausting for the character.
0.3584	B9	I felt as if the virtual body was moving by itself.
0.3516		The movements of the character appeared very natural.
-0.3430		The character appeared sad.
0.2783		It was comfortable to watch the character.
-0.2682		The character appeared bored.
-0.2667		The character was repugnant.
0.2416	B8	I felt as if the movements of the virtual character were influencing my own movements.
0.1330[a]		In my own movements, I went to the limits of my capacities.
-0.0879		Is the character taller or smaller than you?

English translation of the German questions. It was constructed via *varimax* rotation using the 2nd principal component of the correlation matrix for the character ratings as given by all subjects. Items from embodiment (B) (Gonzalez-Franco & Peck, 2018) and enfacement (F) (Tajadura-Jiménez et al., 2012) questionnaires are labeled with their index number there, all other items were defined anew. To get the sum scores for AAQ2, the respective ratings (ranging from 0 for *"(I do) not (agree) at all"* to 6 for *"(I) totally agree"*) on all items listed above are simply added up, with reverse weight for items with negative load.

[a]This item was ultimately excluded from the AAQ2 scale, due to its low load value.

Table 11. Supplements Study 1: Items of Autonomous Avatar Questionnaire, Scale 3 (AAQ3).

Load	Source	Question
0.4270	B14	I felt as if my body was located where I saw the virtual character.
0.4141	B3	It seemed as if I might have more than one body.
0.4125	B20	I felt like I was wearing different clothes from when I came to the laboratory.
0.3919	F5	It seemed as if I might have more than one face.
0.3721	F4	It felt as if my face were drifting towards the character's face.
0.3676	B17	It felt as if my real body were turning into a virtual body.
0.3549	B16a	I felt as if my own body were drifting towards the virtual character.
0.3455	F7	It appeared as if the character’s face were drifting towards my own face.
0.3433	B15	I felt out of my body.
0.3223	B7*	I felt as if I influenced the movements of the virtual body.
0.3140	B16b	I felt as if as if the virtual character were drifting towards my body.

English translation of the German questions. It was constructed via *varimax* rotation using the 3rd principal component of the correlation matrix for the character ratings as given by all subjects. Items from embodiment (B) (Gonzalez-Franco & Peck, 2018) and enfacement (F) (Tajadura-Jiménez et al., 2012) questionnaires are labeled with their index number there, all other items were defined anew. To get the sum scores for AAQ3, the respective ratings (ranging from 0 for *“(I do) not (agree) at all”* to 6 for *“(I) totally agree”*) on all items listed above are simply added up.

8.1.4 Behavioral Data over Cycle Number

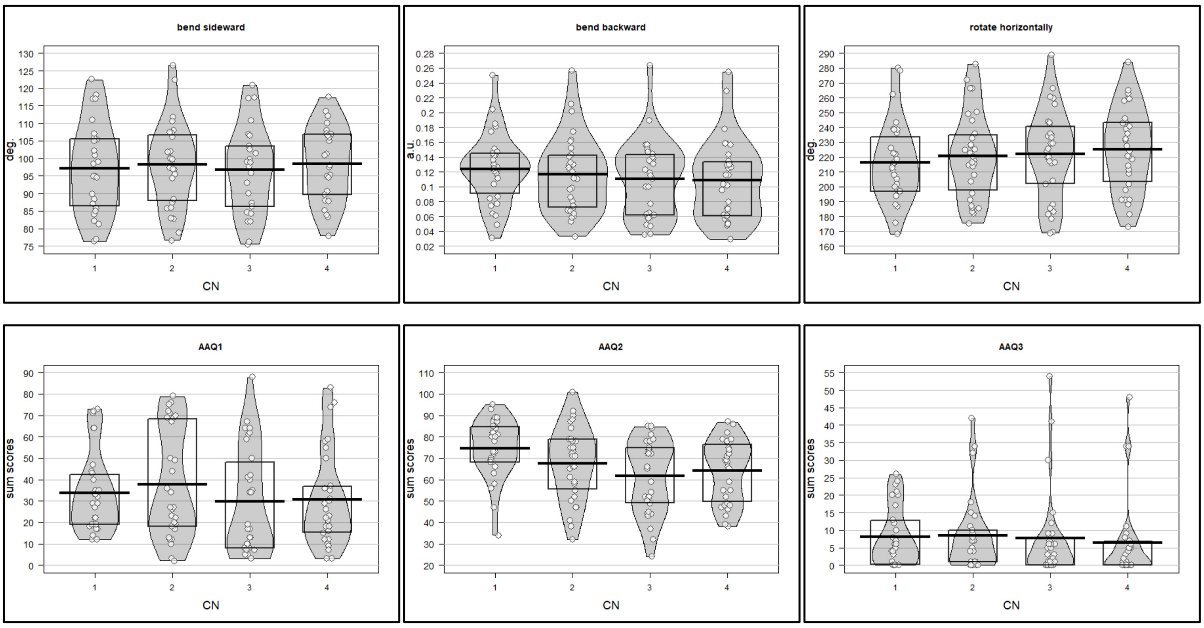

Figure 28. Supplements Study 1: Behavioral data over cycle number.

Ranges of Motion (ROM) in top row and sum scores for the Autonomous Avatar Questionnaire (AAQ) in the bottom row, per cycle number (CN). Graphical conventions follow Figure 14 (p. 64).

8.1.5 Detailed Descriptive Statistics of Behavioral Measures

Table 12. Supplements Study 1: Detailed descriptive statistics of behavioral measures.

Variable[a]	Descr. [b]	Cond.[c]	Mean	SD[d]	Median	Min	Max	ICC[e]
BS	ROM [deg.]	Pooled	97.6532	12.0770	98.2964	75.5187	126.5552	0.9248
		AN = 1	96.9837	13.6377	98.5134	75.5187	120.9533	---
		AN = 2	97.2534	12.2657	97.2844	76.5374	122.5203	---
		AN = 3	97.9695	12.6905	99.8545	76.8908	126.5552	---
		AN = 4	98.4440	10.0516	98.1962	82.9134	122.3629	---
BB	ROM [a.u.]	Pooled	0.1148	0.0511	0.1203	0.0289	0.2634	0.9508
		AN = 1	0.1036	0.0516	0.1052	0.0310	0.2563	---
		AN = 2	0.1208	0.0493	0.1246	0.0330	0.2634	---
		AN = 3	0.1177	0.0509	0.1195	0.0476	0.2547	---
		AN = 4	0.1173	0.0533	0.1221	0.0289	0.2504	---
RH	ROM [deg.]	Pooled	221.0679	28.4249	220.2689	168.2170	288.6591	0.9435
		AN = 1	221.4831	29.6486	219.9199	168.6939	288.6591	---
		AN = 2	223.1871	28.2585	222.9614	175.1017	278.0764	---
		AN = 3	218.5042	28.4407	218.3178	173.0698	284.0956	---
		AN = 4	221.0973	28.5905	221.9489	168.2170	282.8016	---
AAQ1	Sum score	Pooled	33.0417	22.7992	27	2	88	0.0668
	of 15 items,	AN = 1	13.5000	9.9853	11	2	40	---
	range 0-90	AN = 2	27.8333	15.4498	27	7	72	---
		AN = 3	25.7667	10.8204	24	9	50	---
		AN = 4	65.0667	11.7765	66	33	88	---
AAQ2	Sum score	Pooled	67.0167	16.3208	71	24	101	0.3128
	of 17 items,	AN = 1	57.7333	18.6786	51	24	93	---
	range 0-102	AN = 2	69.0333	16.2215	72	32	95	---
		AN = 3	68.9000	14.7048	72	39	101	---
		AN = 4	72.4000	11.7374	74	47	92	---
AAQ3	Sum score	Pooled	7.6667	10.8297	5	0	54	0.5276
	of 11 items,	AN = 1	4.7333	5.8718	4	0	24	---
	range 0-66	AN = 2	6.2000	9.8590	3	0	41	---
		AN = 3	5.1000	7.2747	2	0	30	---
		AN = 4	14.6333	15.1167	9	0	54	---

ROMs (Ranges of Motion) for the three movements analyzed, and sum scores for the ratings on the Autonomous Avatar Questionnaires (AAQ1-3). For the ROM definitions, see Figure 13. Rotational ROMs (bending sideward, BS, and rotating horizontally, RH) are measured in degrees [°]; in contrast, translational ROMs (bending backward, BB) are in arbitrary units [a.u.], as the maximal distance of the respective end effector is normalized by dividing the trajectory amplitude in meters by the subjects' view height in meters. Note the high intraclass correlation values for all movements, indicating the intra-subject variation was considerably smaller than inter-subject variation. Autonomous Avatar Questionnaires were constructed as sum scores, based on the first three principal components of the correlation matrix for all subjects' ratings of the characters (*varimax* rotation was used for scale definition). These character ratings were retrieved during the experiment, with integer response levels from 0 to 6. The pool of questions was a compilation from embodiment (Gonzalez-Franco & Peck, 2018) and enfacement (Tajadura-Jiménez et al., 2012) questionnaires and new items defined specifically for this experiment. A possible post-hoc interpretation of AAQ1 is that it represents avatar naturalism, likability and similarity to the subject (cf. the item list in Table 1); AAQ2 mainly contains items related to the pleasantness of the situation for both the virtual character and the subjects themselves; items on AAQ3 mainly indicate actual changes in subjects' body perception (for AAQ2 and AAQ3, see the item lists in Table 10 and Table 11). Note the low intraclass correlation for AAQ1, which suggests that subject-specific biases in general rating behavior were not as important for this scale as for the others.

[a]BB = bending backward, RH = rotation in the horizontal plane, BS = bending sideward, AAQ = Autonomous Avatar Questionnaire. [b]Description of the respective variable: ROM = Range of Motion, deg. = degrees, a.u. = arbitrary units (in this case: ROM [meters] divided by view-height of subjects [meters]). [c]Within-Subject Condition: Pooled = "All data pooled", AN = Avatar Number. [d]Standard deviation. [e]Intraclass correlation coefficient (conditional), which can take values of 0 (no inter-class variation) and 1 (no intra-class variation); defined only for data pooled over all conditions.

8.1.6 Graphical Depiction of Experimental Flow

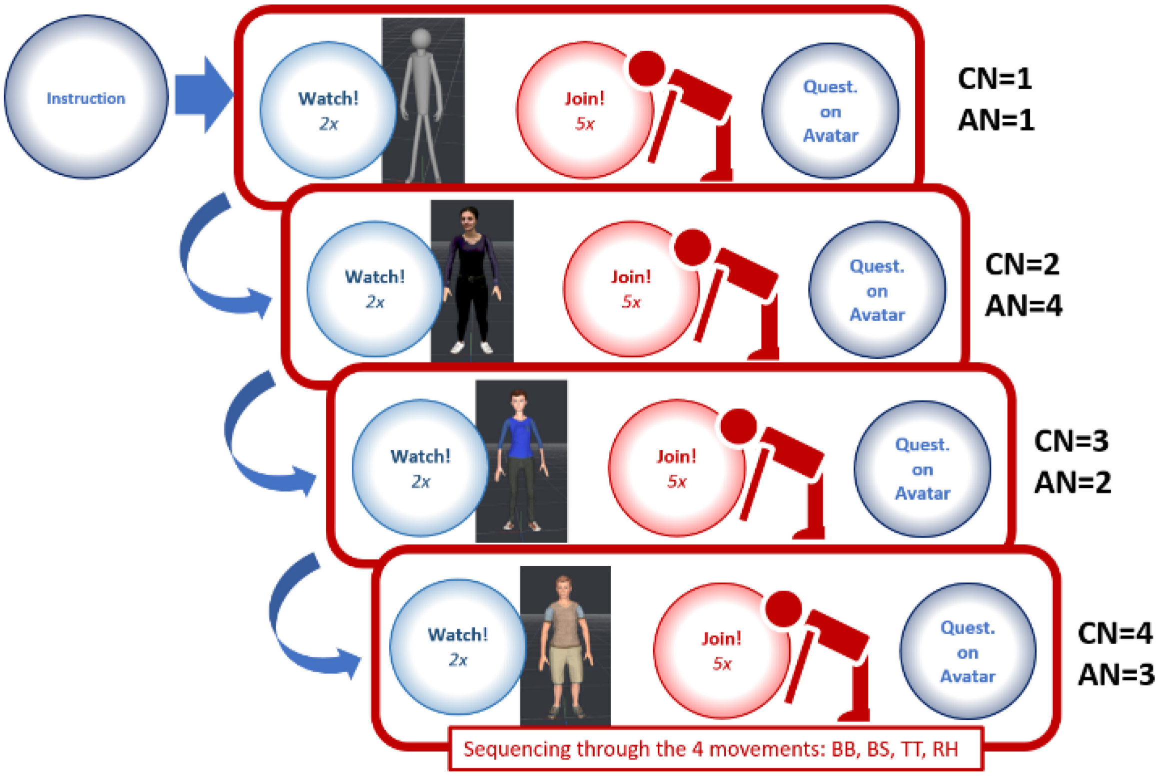

Figure 29. Supplements Study 1: Experimental flow of experiment.

After initial instruction, the subject watched a character perform a movement (2 repetitions), then joined the movement (5 repetitions). This happened for all four movements (BB: bend backward, BS: bend sideward, TT: touch toes, RH: rotate horizontally), the sequence then being closed by the subject rating the virtual character (using a remote control). The movement cycle was repeated (with cycle number CN indicating the round) for the other characters. The latter are indexed with avatar number (AN), their order was randomized between subjects.

8.2 Supplements of Study 2

8.2.1 Raw Data: Ranges of Motion (ROM)

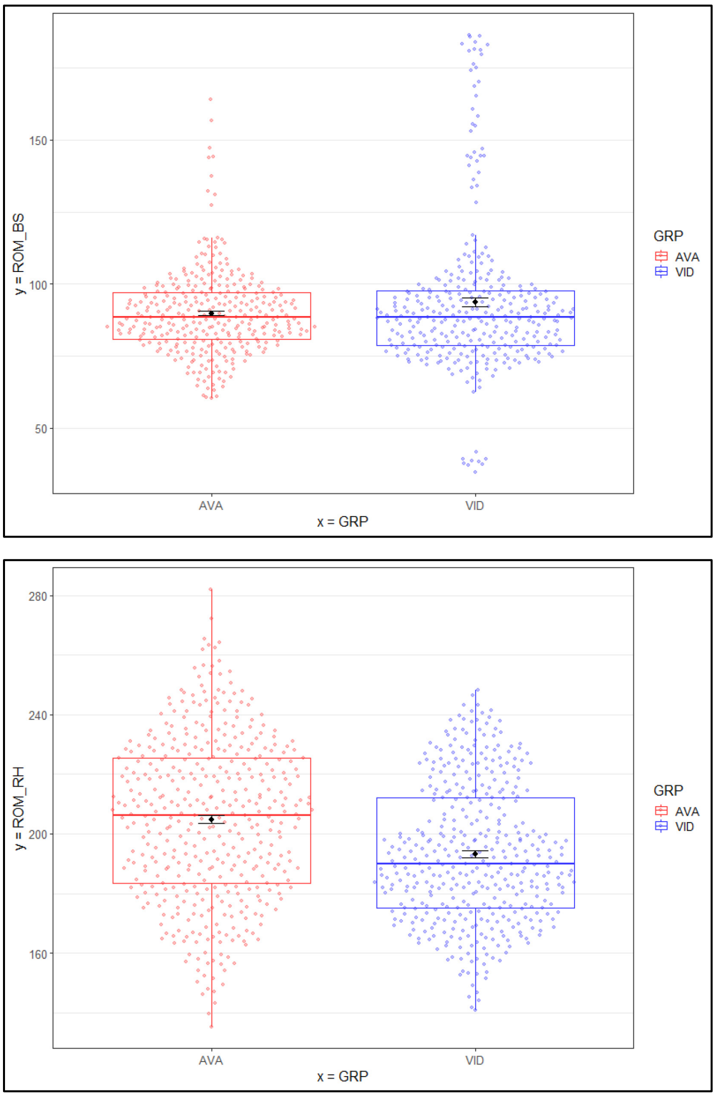

Figure 30. Supplements Study 2: Raw ranges of motion.

Raw data distributions for ROM_{BS} (upper panel) and ROM_{RH} (lower panel). Data are pooled over all sessions and participants but broken down by group. Depicted are single ROM measurements (dots), box-and-whisker plots indicating median, lower and upper quartile (colored lines), and grand mean and standard deviation (black lines). For RH, the raw data approximate a bimodal distribution, roughly. To check for other causes than subject-specific grouping (up to 27 data points per subject), we performed an exploratory search for any criterion (such as age, gender, GCPS pain grade) or set of pain-related scores (in a k-means cluster analysis based on baseline assessment scores) that could successfully discriminate the data into two unimodal distributions. However, we did not find any such criterion.

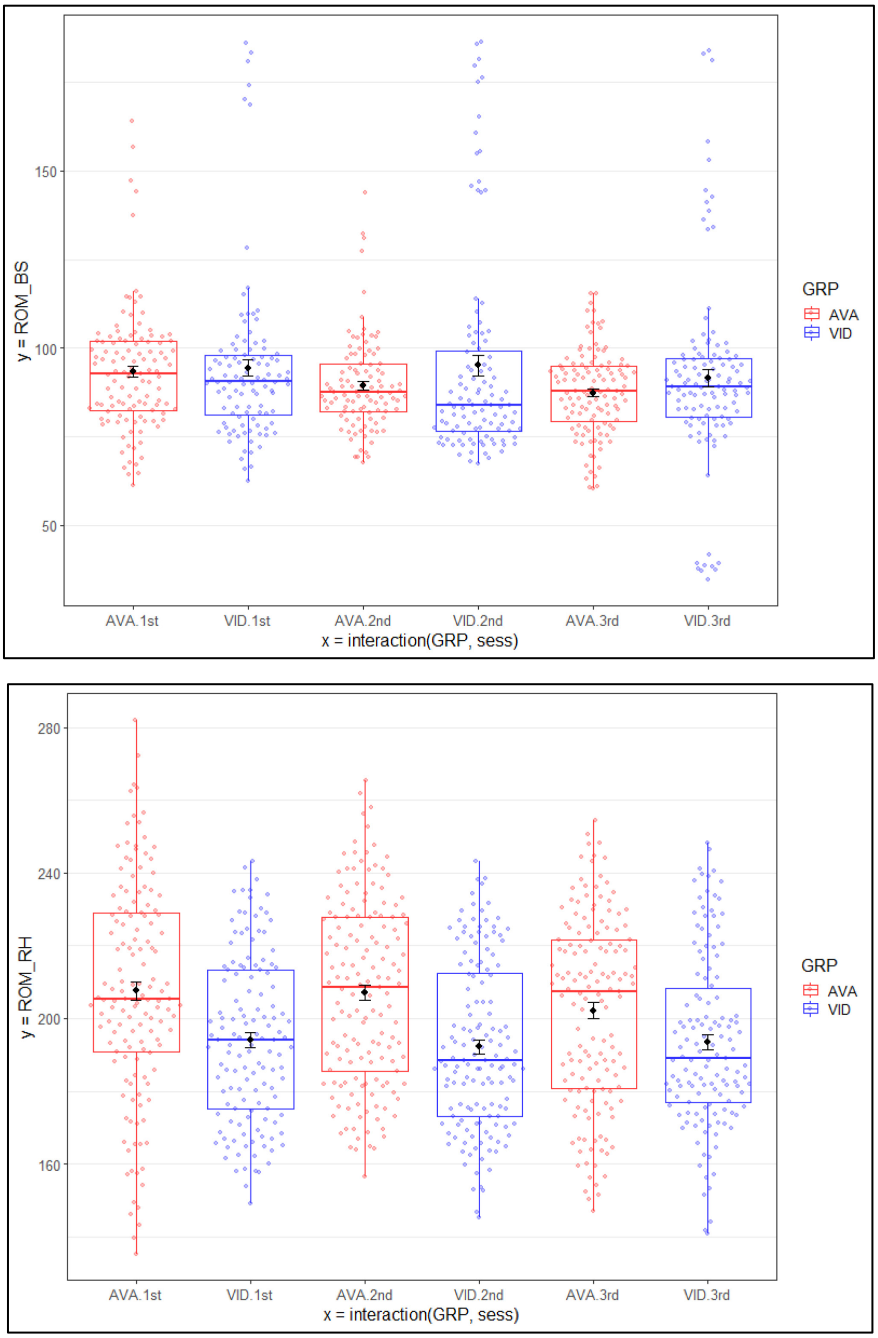

Figure 31. Supplements Study 2: Raw ranges of motion, pooled by session.

Raw data distributions for ROM_{BS} (upper panel) and ROM_{RH} (lower panel). Data are pooled over participants but broken down by group and sessions. Depicted are single ROM measurements (dots), box-and-whisker plots indicating median, lower and upper quartile (colored lines), and grand mean and standard deviation (black lines).

8.2.2 Post-hoc Contrasts of Basic Interaction Models (ROM_{RH} and Pain Expectancy)

Table 13. Supplements Study 2: Results of post-hoc contrast analyses of basic model for ROM_{RH}.

	contrast	Estimate	Std. Error	df	*t*	*p*(*t*)
By group:						
group = AVA	sess. 1 – sess. 2	1.626	1.431	816	1.136	0.31
	sess. 1 – sess. 3	6.587	1.44	816	4.573	< 0.001 ***
	sess. 2 – sess. 3	4.96	1.407	816	3.526	< 0.001 ***
group = VID	sess. 1 – sess. 2	3.233	1.477	816	2.188	0.06 .
	sess. 1 – sess. 3	1.253	1.499	816	0.836	0.40
	sess. 2 – sess. 3	-1.98	1.477	816	-1.341	0.27
By session:						
sess. 1	group: AVA – VID	13.236	8.109	32.5	1.632	0.17
sess. 2	group: AVA – VID	14.842	8.097	32.3	1.833	0.17
sess. 3	group: AVA – VID	7.902	8.105	32.4	0.975	0.34

Degrees of freedom (df), *t* value and according *p*(*t*) values estimated with Kenward-Roger method (Kenward & Roger, 1997), the latter corrected for false discovery rate (Benjamini & Hochberg, 1995) within each marginalization dimension (by group and by session, respectively).

Table 14. Supplements Study 2: Results of post-hoc contrast analyses of basic model for pain expectancy.

	contrast	Estimate	Std. Error	df	*t*	*p*(*t*)
By group:						
group = AVA	sess. 1 – sess. 2	-0.75	0.28	60.10	-2.64	0.03 *
	sess. 1 – sess. 3	-0.85	0.28	61.40	-3.03	0.02 *
	sess. 2 – sess. 3	-0.10	0.28	61.40	-0.36	0.83
group = VID	sess. 1 – sess. 2	0.13	0.28	60.10	0.44	0.83
	sess. 1 – sess. 3	0.06	0.28	60.10	0.22	0.83
	sess. 2 – sess. 3	-0.06	0.28	60.10	-0.22	0.83
By session:						
sess. 1	group: AVA – VID	-0.22	0.37	68.30	-0.59	0.56
sess. 2	group: AVA – VID	0.66	0.37	68.30	1.75	0.13
sess. 3	group: AVA – VID	0.70	0.37	67.20	1.88	0.13

Degrees of freedom (df), *t* value and according *p*(*t*) values estimated with Kenward-Roger method (Kenward & Roger, 1997), the latter corrected for false discovery rate (Benjamini & Hochberg, 1995) within each marginalization dimension (by group and by session, respectively).

8.2.3 Extended Models for ROMs: ANOVAs and Model Coefficients

Table 15. Supplements Study 2: ANOVAs of extended linear mixed effects models for ranges of motion.

model	Predictor	df num	df den	*F*	*p*
ROM_{BS}					
	group (AVA or VID)	1	28.33	0.56	0.46
	session	2	615.81	13.52	< 0.001 ***
	MPI pain intensity	1	631.32	2.07	0.15
	pain expectancy	1	621.21	29.07	< 0.001 ***
	AAQmm1	1	631.01	0.24	0.63
	AAQmm2	1	632.65	2.97	0.09 .
	IPQ score	1	639.00	1.98	0.16
	age	1	26.20	0.04	0.85
	gender	1	25.93	3.79	0.06 .
ROM_{RH}					
	group (AVA or VID)	1	35.82	2.37	0.13
	session	2	804.32	9.42	< 0.001 ***
	MPI1 pain intensity	1	810.01	0.44	0.51
	pain expectancy	1	822.58	4.10	0.04 *
	AAQmm1	1	823.92	1.20	0.27
	AAQmm2	1	818.43	5.62	0.02 *
	IPQ score	1	730.64	0.00	1.00
	age	1	29.36	3.05	0.09 .
	gender	1	28.93	2.78	0.11

Reported are analyses of variance for extended linear mixed effects models. Ranges of motion (ROM) were modeled as outcome variables both for *bending sideward* and *rotation in the horizontal plane*. Kenward-Roger method was used to estimate degrees of freedom, *F* and *p* values, as implemented in the *R* package *lmerTest* (Kuznetsova et al., 2017).

Notes: engagement – item "*went to limits*".

Abbreviations in variables: group – experimental group (avatar: AVA) / control group (videotaped model: VID); MPI1 – West Haven-Yale Multidimensional Pain Inventory, part 1; AAQmm – Autonomous Avatar Questionnaire (multimedia), scales 1 & 2; IPQ – Igroup Presence Questionnaire; gender – male (m) / female (f).

Table 16. Supplements Study 2: Coefficients of extended models for ranges of motion (ROM).

Model	Predictor	β	Std. Error	df	t	$p(t)$	β_z
ROM_{BS}							
	intercept	99.34	15.50	32.11	6.41	< 0.001 ***	---
	group: AVA – VID	-3.31	4.43	28.27	-0.75	0.46	-0.15
	1st sess. – 3rd sess.	2.09	0.48	615.41	4.40	< 0.001 ***	0.10
	2nd sess. – 3rd sess.	0.24	0.42	615.06	0.56	0.58	0.01
	MPI1 pain intensity	0.99	0.69	631.30	1.44	0.15	0.05
	pain expectancy	-2.38	0.44	621.18	-5.40	< 0.001 ***	-0.09
	AAQmm1	0.04	0.08	631.00	0.49	0.63	0.03
	AAQmm2	0.13	0.07	632.63	1.73	0.08 .	0.06
	IPQ score	-0.08	0.06	639.00	-1.41	0.16	-0.06
	age	-0.05	0.27	26.15	-0.19	0.85	-0.04
	gender: m – f	-17.10	8.78	25.88	-1.95	0.06 .	-0.78
ROM_{RH}							
	Intercept	220.32	13.80	48.48	15.97	< 0.001 ***	---
	group: AVA – VID	6.41	4.16	35.34	1.54	0.13	0.25
	1st sess. – 3rd sess.	2.91	0.69	805.11	4.19	< 0.001 ***	0.11
	2nd sess. – 3rd sess.	-0.51	0.60	800.74	-0.84	0.40	-0.02
	MPI1 pain intensity	-0.69	1.03	809.78	-0.67	0.50	-0.03
	pain expectancy	-1.34	0.66	822.53	-2.03	0.04 *	-0.04
	AAQmm1	-0.13	0.12	823.89	-1.10	0.27	-0.07
	AAQmm2	0.26	0.11	818.33	2.38	0.02 *	0.11
	IPQ score	< 0.001	0.08	729.44	0.00	1.00	0.00
	age	-0.40	0.23	28.96	-1.75	0.09 .	-0.27
	gender: m – f	-13.59	8.16	28.53	-1.67	0.11	-0.52

The table reports the fixed effects estimates of the linear mixed effects (LME) models for ranges of motion (ROM) as outcome variable, both for *bending sideward* (BS) and *rotation in the horizontal plane* (RH). Both LME models found that ROM strongly depended on participants, as indicated by the standard deviations (SD) of random effects (ROM_{BS}: *SD* = 23.25; ROM_{RH}: *SD* = 21.89).

Given are regression weights β with standard error (Std. Error). Group effect is reported as contrast between experimental (avatar: AVA) and control (videotaped model: VID) group. Session (sess.) was modeled as a categorical variable, resulting in two contrasts of first and second sessions with the last session. The Kenward-Roger method was used to estimate degrees of freedom (df), t value and the according $p(t)$ value (Kenward & Roger, 1997). Standardized regression weights β_z are normalized to the standard deviations of ROM_{BS} and the respective predictor, following (Hox et al., 2018, p. 18).

Abbreviations in variables: MPI – West Haven-Yale Multidimensional Pain Inventory, AAQmm – Autonomous Avatar Questionnaire (multimedia), scales 1 & 2; IPQ – Igroup Presence Questionnaire; gender – male (m) / female (f).

8.2.4 Basic Models for Self-reports: Model Coefficients

Table 17. Supplements Study 2: Model coefficients for post-hoc self-reports on functional ability and pain during movements.

	Estimate	Std. Error	df	*t*	*p*(*t*)	β_z		Estimate	Std. Error	df	*t*	*p*(*t*)	β_z
Engagement							**Limitation of Movements by Pain**						
sd rand. eff.	1.51						sd rand. eff.	1.97					
intercept	3.07	2.19	56.03	1.40	0.17	---	intercept	5.99	2.25	38.91	2.66	0.01 *	---
group: AVA - VID	0.57	0.32	27.50	1.80	0.08 .	0.30	group: AVA - VID	0.31	0.30	25.14	1.05	0.31	0.13
1st session - 3rd session	0.28	0.20	55.14	1.39	0.17	0.14	1st session - 3rd session	0.32	0.26	51.33	1.21	0.23	0.13
2nd session - 3rd session	-0.19	0.19	52.27	-1.02	0.31	-0.10	2nd session - 3rd session	0.23	0.26	48.17	0.90	0.37	0.10
pain expectancy	0.40	0.17	73.63	2.28	0.03 *	0.17	pain expectancy	0.74	0.22	72.46	3.36	< 0.01 **	0.25
<ROM_{BS}>	-0.01	0.01	38.51	-0.66	0.51	-0.10	<ROM_{BS}>	-0.01	0.01	30.25	-0.93	0.36	-0.11
<ROM_{RH}>	0.00	0.01	56.01	0.08	0.94	0.01	<ROM_{RH}>	-0.02	0.01	37.91	-1.62	0.11	-0.21
Functional Capacity for Movements							**Pain during Movements**						
sd rand. eff.	4.69						sd rand. eff.	1.12					
intercept	73.05	19.81	32.35	3.69	0.00	---	intercept	3.47	1.98	40.62	1.75	0.09 .	---
group: AVA - VID	-1.40	2.45	25.67	-0.57	0.57	-0.07	group: AVA - VID	0.14	0.26	24.72	0.52	0.61	0.08
1st session - 3rd session	-2.46	3.14	57.62	-0.78	0.44	-0.12	1st session - 3rd session	0.26	0.22	50.37	1.21	0.23	0.15
2nd session - 3rd session	1.16	3.08	54.81	0.38	0.71	0.06	2nd session - 3rd session	0.05	0.21	47.16	0.21	0.83	0.02
pain expectancy	-6.54	2.15	67.13	-3.04	0.00	-0.25	pain expectancy	0.62	0.19	71.45	3.31	< 0.01 **	0.28
<ROM_{BS}>	0.03	0.10	29.72	0.26	0.79	0.03	<ROM_{BS}>	-0.01	0.01	30.58	-0.94	0.36	-0.13
<ROM_{RH}>	0.09	0.10	32.95	0.84	0.41	0.11	<ROM_{RH}>	-0.01	0.01	39.52	-0.54	0.59	-0.08

The table reports the fixed effects estimates of the linear mixed effects (LME) models for posterior self-reports as outcome variable. All LME models found that outcomes strongly depended on participants, as indicated by the standard deviations of the random effects.

Given are regression weights *β* with standard error (Std. Error). Group effect is reported as contrast between experimental (avatar: AVA) and control (videotaped model: VID) group. Session (sess.) was modeled as a categorical variable, resulting in two contrasts of first and second sessions with the last session. The Kenward-Roger method was used to estimate degrees of freedom (df), *t* value and the according *p*(*t*) value (Kenward & Roger, 1997). Standardized regression weights β_z are normalized to the standard deviations of ROM_{BS} and the respective predictor, following (Hox et al., 2018, p. 18).

Abbreviations: sd – standard deviation; Std. Error – standard error; rand. eff. – random effects; <…> – within-session average; ROM – range of motion; BS – bending sideward; RH – rotation in the horizontal plane.

8.2.5 Moderation Analysis for Self-report Measures: ANOVAs of Interaction Models

Table 18. Supplements Study 2: ANOVAs of LME interaction models for post-hoc reports.

	Engagement	**Functional capacity**
group	$F_{(1,33.01)} = 3.13$, $p = 0.09$.	$F_{(1,33.93)} = 0.07$, $p = 0.80$
sess.	$F_{(2,56.41)} = 0.16$, $p = 0.85$	$F_{(2,59.83)} = 0.002$, $p > 0.99$
Pain Exp. Level	$F_{(1,76.02)} = 3.79$, $p = 0.06$.	$F_{(1,81.51)} = 5.63$, $p = 0.02$ *
group × Pain Exp. Level	$F_{(1,76.02)} = 1.40$, $p = 0.24$	$F_{(1,81.51)} = 0.04$, $p = 0.84$
sess. × Pain Exp. Level	$F_{(2,62.19)} = 0.63$, $p = 0.53$	$F_{(2,73.37)} = 0.26$, $p = 0.77$
group × sess.	$F_{(2,56.41)} = 0.54$, $p = 0.58$	$F_{(2,59.83)} = 0.54$, $p = 0.58$
group × sess. × Pain Exp. Level	$F_{(2,62.19)} = 0.20$, $p = 0.82$	$F_{(2,73.37)} = 1.55$, $p = 0.22$

	Limitation by pain	**Pain during movements**
group	$F_{(1,33.74)} = 0.20$, $p = 0.66$	$F_{(1,33.68)} = 0.05$, $p = 0.82$
sess.	$F_{(2,54.26)} = 1.83$, $p = 0.17$	$F_{(2,54.07)} = 1.03$, $p = 0.36$
Pain Exp. Level	$F_{(1,76.96)} = 12.06$, $p < 0.001$ ***	$F_{(1,76.30)} = 12.60$, $p < 0.001$ ***
group × Pain Exp. Level	$F_{(1,76.96)} = 2.38$, $p = 0.13$	$F_{(1,76.30)} = 6.99$, $p < 0.01$ **
sess. × Pain Exp. Level	$F_{(2,62.39)} = 2.14$, $p = 0.13$	$F_{(2,61.87)} = 3.02$, $p = 0.07$.
group × sess.	$F_{(2,54.26)} = 1.75$, $p = 0.18$	$F_{(2,54.07)} = 1.03$, $p = 0.36$
group × sess. × Pain Exp. Level	$F_{(2,62.39)} = 1.70$, $p = 0.19$	$F_{(2,61.87)} = 1.49$, $p = 0.23$

Reported are the three-way interaction models for measures of engagement, experimental pain and function. Kenward-Roger method was used to estimate degrees of freedom, *F* and *p* values, as implemented in the *R* package *lmerTest* (Kuznetsova et al., 2017).

Notes: sess. – session; pain exp. level – level of prior pain expectancy; engagement – item "*went to limits*".

8.2.6 Autonomous Avatar Questionnaire – multimedia

The newly introduced *Autonomous Avatar Questionnaire* (Kammler-Sücker et al., 2021) was answered by participants after the movement sessions, while still immersed in VR. Their context of origin was a within-subject design with virtual characters of different levels of personalization and realism. In the current study, which adds videotaped real-life models, we expected some items to change their mutual correlation, as for example those assessing realism and model-observer similarity. Therefore, we first determined internal consistency by calculating Cronbach's alpha for the original scales Autonomous Avatar Questionnaire scales 1-3, which assess the dimensions of identification/ affiliation, situational pleasantness, and changed body perception. These scales displayed already acceptable to high consistencies in our sample (α_{AAQ1} = 0.82, α_{AAQ2} = 0.70, α_{AAQ3} = 0.80). We then excluded items if they had either an item-rest correlation below 0.3 (indicating low correlation with the other items) and/ or if their exclusion increased the scale's overall alpha value. This was the case for three out of 15 (AAQ1), six out of 16 (AAQ2), and two out of eleven items (AA3), respectively. The modified scales are referred to as *AAQ-multimedia* (*AAQmm*) in the following and have consistently high values of internal consistency (α_{AAQmm1} = 0.87, α_{AAQmm2} = 0.80, α_{AAQmm3} = 0.85; item lists in Table 19, Table 20, and Table 21).

Table 19. Supplements Study 2: Items of AAQ1 and AAQmm1.

Item	Cronbach's α without item α^*	Item-rest correlation r^*
The character was likable.	0.81	0.47
The character appeared real like a genuine person.	*0.86*	*-0.45*
The character was the spitting image of myself.	0.79	0.70
At some point it felt that the virtual character resembled my own body in terms of shape, skin tone or other visual features.	0.79	0.71
How well could you put yourself in the character's shoes?	0.81	0.51
The character appeared cheerful.	*0.82*	*0.29*
I could empathize with the character quite well.	0.81	0.43
I identified myself with the character.	0.79	0.65
The character was attractive.	0.81	0.40
The character was well-dressed.	0.81	0.43
Did the character appear as rather male or female?[a]	0.81	0.43
I felt as if the character's face were my face.	0.79	0.70
The character's face began to resemble my own face, in terms of shape, skin tone, or some other visual feature.	0.80	0.56
I felt as if the virtual character were myself.	0.80	0.59
At some point it felt as if my real body was starting to take on the posture or shape of the virtual body that I saw.	*0.82*	*0.25*

Items of Autonomous Avatar Questionnaire scale AAQ1 (Kammler-Sücker et al., 2021) and of its multi-media modification AAQmm1, developed in the current study. Items in *italics* have been excluded in AAQmm, either due to an item-rest correlations $r^* < 0.3$, or due to an increase in internal consistency if the item was dropped, indicated by a Cronbach's $\alpha^* > 0.82$ (α for the AAQ scale in the current data). The resulting AAQmm1, indicating affiliation and identification, has an internal consistency of $\alpha = 0.87$ in the current sample.

Notes: [a]Item weighted according to participant's gender (gender-match variable).

Table 20. Supplements Study 2: Items of AAQ2 and AAQmm2.

Item	Cronbach's α without item α^*	Item-rest correlation r^*
The movements of the character appeared very natural.	0.67	0.48
The character gave the impression to be sporty.	0.68	0.41
The character gave the impression to be fit for the performed movements.	0.67	0.56
The character was comfortable with the movements.	0.66	0.62
The movements were exhausting for the character.[a]	0.69	0.32
The movements were easy for the character.	0.69	0.33
The character appeared sad.[a]	0.67	0.49
The character appeared bored.[a]	*0.70*	*0.22*
The movements were uncomfortable for the character.	0.67	0.53
It was comfortable to watch the character.	0.67	0.48
It was strange to watch the character.[a]	0.68	0.40
The character was repugnant.[a]	0.69	0.36
The character looks eerie.[a]	*0.71*	*0.11*
Is the character taller or smaller than you?[a]	*0.73*	*-0.14*
I felt as if another person stood in front of me.	*0.72*	*0.10*
I felt as if the movements of the virtual character were influencing my own movements.	*0.73*	*0.002*
I felt as if the virtual body was moving by itself.	*0.70*	*0.21*

Items of Autonomous Avatar Questionnaire scale AAQ2 (Kammler-Sücker et al., 2021), and of its multi-media modification AAQmm2, developed in the current study. Items in *italics* have been excluded in AAQmm, either due to an item-rest correlation of $r^* < 0.3$, or due to an increase in internal consistency if the item was dropped, indicated by a Cronbach's $\alpha^* > 0.7$ (α for the AAQ scale in the current data). The resulting AAQmm2, indicating situational pleasantness has an internal consistency of $\alpha = 0.8$ in the current sample.

Notes: [a]Reverse weight of item.

Table 21. Supplements Study 2: Items of AAQ3 and AAQmm3.

Item	Cronbach's α without item α^*	Item-rest correlation r^*
It felt as if my face were drifting towards the character's face.	0.79	0.49
It seemed as if I might have more than one face.	0.79	0.41
It appeared as if the character's face were drifting towards my own face.	0.79	0.61
It seemed as if I might have more than one body.	0.76	0.70
I felt as if I influenced the movements of the virtual body.	*0.81*	*0.26*
I felt as if my body was located where I saw the virtual character.	0.79	0.43
I felt out of my body.	0.78	0.63
I felt as if my own body were drifting towards the virtual character.	0.78	0.63
I felt as if as if the virtual character were drifting towards my body.	0.78	0.73
It felt as if my real body were turning into a virtual body.	0.78	0.63
I felt like I was wearing different clothes from when I came to the laboratory.	*0.83*	*0.45*

Items of Autonomous Avatar Questionnaire scale AAQ3 (Kammler-Sücker et al., 2021) and of its multi-media modification AAQmm3, developed in the current study. Items in *italics* have been excluded in AAQmm, either due to an item-rest correlation of $r^* < 0.3$, or due to an increase in internal consistency if the item was dropped, indicated by a Cronbach's $\alpha^* > 0.8$ (α for the AAQ scale in the current data). The resulting AAQmm3, indicating changes in body perception, has an internal consistency of $\alpha = 0.85$ in the current sample.

9 CURRICULUM VITAE

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PUBLICATIONS

Kammler-Sücker, K. I., Löffler, A., Kleinböhl, D., & Flor, H. (2021). Exploring Virtual Doppelgangers as Movement Models to Enhance Voluntary Imitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 29, 2173-2182.
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