Exploring Virtual Doppelgangers as Movement Models to Enhance Voluntary Imitation

Kornelius I. Kammler-Sücker, *Member, IEEE*, Annette Löffler, Dieter Kleinböhl, and Herta Flor

***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 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.**

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I. 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" [1], [2]. 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 [3]. Given these preconditions, VR can stimulate a sense of co-presence in interactions with virtual characters, whether they are controlled by other humans [4] or by algorithmically controlled virtual agents [5]. This allows for the creation of "virtual sociality". Besides this, perception of the bodily self can also be modified in VR [6]. 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 [7] and a mannequin body [8]. These illusions can be replicated in VR when subjects embody virtual body parts such as an arm [9] or even whole virtual bodies [10], 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 [11]. Further, one crucial factor for embodiment of a virtual body is the visual first-person perspective (1PP) of the virtual body [12], [11], which can suffice for virtual touch illusions [13] and illusory agency for virtual walking [14]. 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 [15], [16], [17]. Together, the senses of ownership, agency and self-location compose the sense of embodiment [18]. Embodiment of virtual bodies can alter bodily self-perception, both of one's own limb movements [19] and body shape [20], without the subject's awareness. Similarly, the sense of enfacement emerges when users 'embody' virtual faces viewed in 3PP or in a virtual mirror [21], an effect amplified by realism in facial animations [22].

In addition to interaction with virtual characters as "others" and embodiment of avatars as "virtual selves", VR facilitates situations that subvert this distinction [23], 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 [24], controlled by the user's actions [17], or move ‘autonomously’ [25]. Users may even swap in and out of the doppelganger, switching between 1PP embodiment and a 3PP doppelganger encounter [26].

This facilitates VR research on the interaction between model and observer characteristics in the complex phenomenon of imitation [27], which is a distinct form of modeling behavior [28] alongside other forms such as observational learning [29]. Imitative tendencies are closely linked to these other forms of modeling and social learning, both functionally [30] and on a neural level [31]. Imitation may be expressed automatically, such as in mimicry of facial expressions, motor and verbal patterns [32] 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 [33]. A desire to create rapport enhances mimicry [34], and a positive first impression increases walking synchronization with a stranger [35]. It has been argued that the mutually facilitating influences between social affiliation and behavior matching played an important evolutionary role as “social glue” [36]. This fits with the influence of perceived model-observer similarity on imitative behavior in many settings [37]–[39]. Model-observer similarity is often established by similar sociodemographic traits, such as gender [39] or social background [38], and seems to enhance identification with the model [37]. 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 [40] and can be further enhanced by employing attention and imagery [41]. An indirect effect of imitative tendencies on the perceptual-motor level is motor interference [42], 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 [43], but rather on similarity in motion kinematics and joint configuration [44].

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 [45]. 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 [46] and will thus plausibly stimulate the tendency to imitate movements. Among others, this opens up new possibilities for rehabilitation research: both observational modeling mechanisms [47] and (maladaptive) motor behaviors [48] 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 [49] and enfacement [50] 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 [51]. As these movements are also influenced by physiological short-time effects such as tiring or stretching [52], 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 [53] and human movements [54]. 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.

II. Materials and Methods

A. 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 (Fig. 1). 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

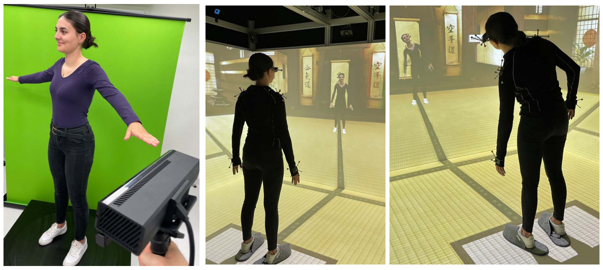

Fig. 1. Experimental procedure: In a preparatory session, 3d photographs of the participants were taken with a hand-held Kinect sensor, for which they were standing on a rotating plate (left panel); head scans were taken separately with subjects seated stationarily (not shown). During the experiment in the four-sided CAVE, participants watched a virtual character (middle panel) and then joined the movement of the latter (right panel).

software packages, in case of personalized avatars based on 3d photographs acquired with a Kinect Sensor (Microsoft™, 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) “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.

B. 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 (Fig. 2): 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 (see Table I). 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).

C. 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

Fig. 2. 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).

TABLE I
ITEMS OF AUTONOMOUS AVATAR 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.

Items of the Autonomous Avatar Questionnaire, Scale 1 (AAQ1, 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) [49] and enfacement (F) [50] 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.

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 (Fig. 3): For BS and RH, the ROM uses the connecting line between the shoulder

TABLE II
DESCRIPTIVE STATISTICS OF BEHAVIORAL MEASURES

Vaiable[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

Descriptive statistics of behavioral measures: 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 Fig. 4 For detailed statistics per avatar condition, see supplements. For the ROM definitions, see Fig. 3. 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 [49] and enfacement [50] questionnaires and new items defined for this experiment. Possible post-hoc interpretations are AAQ1 indicating *positive avatar characteristics* (cf. Table I), 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* [55].

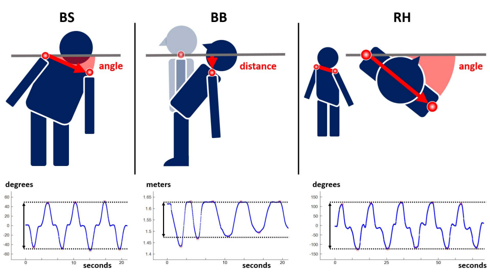

Fig. 3. Trajectories of end effectors for the three movements analyzed: Lateral flexion (BS: bending sideward, left panel), spinal extension (BB: bending backward, middle), rotation in the horizontal plane (RH, right). Rigid-body motion-capture markers placed on the shoulders are shown as red dots. The 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).

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 II (raw data in Fig. 4). The high values of conditional intraclass correlation coefficients [55] indicate that intra-subject variation was considerably smaller than inter-subject variation.

D. Principal Component Analysis of Avatar Questionnaires

The questions asked after each cycle were compiled from questionnaires on embodiment [49] and enfacement [50], 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 I (AAQ2 and AAQ3 in the supplement). Our post-hoc interpretation of AAQ1 is that it represents avatar naturalism, likability and similarity to the

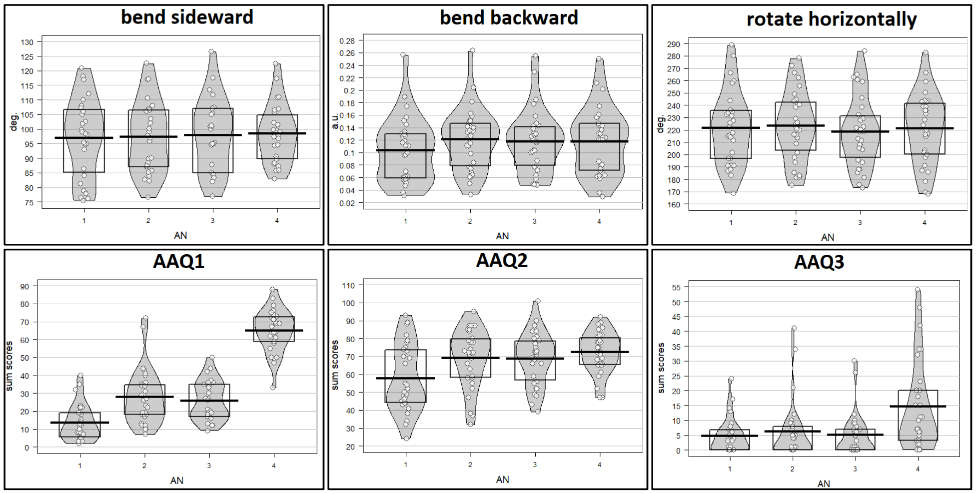

Fig. 4. Ranges of motion (ROM) in top row and sum scores for the autonomous avatar questionnaire (AAQ) in the bottom row, per avatar number (AN). The graphs combine scatter plots for the raw data, box plots describing the median (center bar) and the interquartile range (box ends), and smoothed density curves of the respective data distributions; for further descriptive statistics of the data, refer to Table I. 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 Fig. 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 III). 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 IV, 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.

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.[1] 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 virtual "other" than as a virtual mirror situation. A descriptive overview of sum scores on the AAQ scales can be found in Table II, raw data are shown in Fig. 4.

E. 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 [56], [57]. For all our fits, we used the *R* package *lme4* function *lmer* to fit the LME models [58], 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 [59]. 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 [59].

We modeled ROM as a dependent variable in three steps (for each movement separately, see Fig. 5). (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 [58]).[2] (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.[3] (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

[1]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 *II.E*.

[2]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 [60], but in our case was less so than p_{PB}.

[3]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.

TABLE III
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 Rate 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 Rate 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.

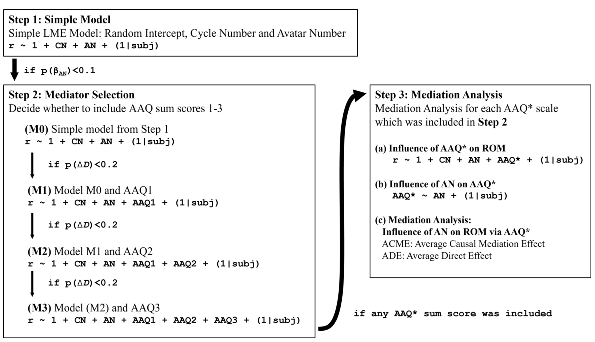

Fig. 5. Model analyses of range of motion (ROM) data. In step 1, a simple linear mixed effects model with predictors CN (cycle number) and AN (avatar number) is fitted to the ROM as the dependent variable. *R* pseudo-code is given (r = ROM; subj = subject ID; CN = cycle number; AN = avatar number). Step 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).

(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 [61] (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) [62] 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, 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).

III. 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 III). This indicated a linear trend in ROM with growing AN (see Figure 4), 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 IV and V): 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 IV
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 Fig. 5) 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 III.

TABLE V
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 Fig.4) for the influence of AN via AAQ1 on fROM (for movement BS), based on the LME models in Table IV. Treatment level is set to AN=4, control level on AN=3. Most abbreviations follow those in Table III and Table IV.
[a]ACME = Average Causal Mediation Effect, ADE = Average Direct Effect.

Table III) 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).

IV. DISCUSSION

A. 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.

B. 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 [29] and theoretic accounts of the chameleon effect [36]. 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.

C. Virtual Characters as Movement Models

Behavioral modeling arises in observational situations of various forms [29]: from intentional learning by observation [28] to nonconscious mimicry [33] and motor interference between one's own and others' coincident movements [42]. 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.

D. 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 [29], [31], 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 [63]. A study with virtual (facial) doppelgangers experiencing weight-loss after exercise found that observers' own exercise behavior was facilitated by identification with the models [25]. 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 [64], over analgesic effects of seeing one's virtual body [65], to actively changing the appearance of embodied virtual limbs to address chronic pain [66]. Especially the latter approach is a promising tool in novel treatments of changes in body representation in chronic pain [66]. Further expanding the increasingly differentiated approaches to VR treatment [67], 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 [68], and avoidance behaviors with respect to everyday movements [48]. Here as well as in general, non-vicarious (operant and respondent) conditioning [69], [70] and observational learning from vicarious experience [47] contribute to the multi-faceted complex of chronic pain [71]. This is mirrored by observational placebo effects, i.e. analgesic effects from placebo treatments previously observed to succeed in others [72], a phenomenon closely linked to modeling and social learning [73]. Effects of vicarious experience on pain and motor behavior have also been found with virtual models in 3PP, both in healthy participants [74] and in chronic back pain [75]. 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 [76], [77]. 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 [29], offering a promising line of future research with further enhanced identification with characters in immersive VR.

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