**Mind over matter: Perceived phantom/prosthesis co-location
contributes to prosthesis embodiment in lower limb amputees**

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Abstract

Prosthesis embodiment (PEmb) – the cognitive integration of a prosthesis into an amputees' body representation – has been identified as key feature of prosthetic rehabilitation. However, the underlying mechanisms remain unclear. There is reason to assume that phantom limbs that are experienced as part of the bodily self (phantom self-consciousness, PSC) can affect PEmb, but only if the phantom and the prosthesis can be brought into perceived co-location (phantom prosthesis tolerance, PPT). In the present study, phantom-prosthesis interactions were examined in lower limb amputees, and a PPT component was psychometrically extracted. Mediation analysis revealed an indirect-only effect, where the relationship between PSC and PEmb was mediated by PPT, indicating that phantom limbs can transfer their immanent vividness to the artificial limb. Subsequent analyses suggested that this effect can compensate for negative consequences that arise from phantom limb awareness. These results shape theoretical considerations about the cognitive processes contributing to the bodily self.

Keywords: bodily self; amputation; prosthesis; embodiment; phantom limb

1 Introduction

Prosthesis embodiment, that is, the cognitive integration of a prosthesis into an amputees' body representation (Makin, de Vignemont, & Faisal, 2017), has been identified as key feature of prosthetic rehabilitation, both by the users themselves (Murray, 2004) as well as experts providing prosthetic services (Schaffalitzky, Gallagher, MacLachlan, & Wegener, 2012). Prosthesis embodiment has been related to several beneficial outcomes of prosthesis use, such as a more stabilized body posture (Imaizumi, Asai, & Koyama, 2016), a better representation of the nearby space of action (Gouzien et al., 2017), higher prosthesis satisfaction (Bekrater-Bodmann, 2021), or less severe phantom limb pain (Bekrater-Bodmann, Reinhard, Diers, Fuchs, & Flor, 2021; Kern, Busch, Rockland, Kohl, & Birklein, 2009). The majority of amputees report prosthesis embodiment, albeit the inter-individual variability is high (Bekrater-Bodmann, 2020; Fritsch, Lenggenhager, & Bekrater-Bodmann, 2021). Recent studies identified several predictors of prosthesis embodiment, which can be summarized in terms of corporeal-structural characteristics of the user (e.g., the level of amputation), sensorimotor experiences and capabilities (e.g., time since amputation and prosthesis use frequency), and properties of the prosthetic device (Bekrater-Bodmann, 2021; Bekrater-Bodmann et al., 2021). However, the definite cognitive mechanisms underlying prosthesis embodiment are still poorly understood.

After the amputation of a limb, amputees often report phantom limb awareness (PLA) (Jensen & Rasmussen, 1994), that is, the persistent perception of the body part that has been removed. PLA can either be diffuse, described in terms of blurred painful or non-painful somatosensory perceptions located outside the physical body, or rather concrete with a vivid proprioceptive image of the amputated body part, the latter which allowing for a clear spatial differentiation of distinct body areas (Giummarra et al., 2010; Mayer, Kudar, Bretz, & Tihanyi, 2008). PLA can be validly assessed by questionnaires (e.g., Winter et al., 2001), amputees' drawings of the phantom limb (Schott, 2014), or behavioral pointing tasks for spatial mapping of the phantom limb (Longo, Long, & Haggard, 2012), the latter which indicating that a phantom limb can phenomenologically occupy a discrete spatial volume outside the physical body. Amputees

often retain a certain degree of controllability over the phantom limb (Kern et al., 2009), and own unpublished data indicate that the phantom limb is often perceived as integral part of the amputee's body, suggesting that the phantom, despite its unphysical nature, is an inherent part of the amputee's bodily self-consciousness (cf., Blanke, 2012; Serino et al., 2013). Moreover, there are substantial inter-individual differences in the course of PLA, with the phantom limb either vanishing shortly after amputation or remaining for decades (Jensen & Rasmussen, 1994), with or without changes in its perceived anatomical characteristics in terms of shape, size, or length (Giummarra et al., 2010). While some participants report perpetual PLA, it is an intermittent phenomenon in others (Giummarra et al., 2010). Taken together, PLA is characterized by high intra- as well as inter-individual variability.

Preliminary results suggest that PLA might affect the perception of the prosthesis. Using qualitative interview data, Bouffard, Vincent, Boulianne, Lajoie, and Mercier (2005) found that PLA can both positively or negatively interact with prosthesis use in upper limb amputees: for example, one amputee (positive phantom-prosthesis interaction) stated that controlling a myoelectric prosthesis, compared to a body-powered one, *'is more natural [...] because it uses my [phantom] hand'* (p. 29), while another amputee (negative phantom-prosthesis interaction) reported that the *'[phantom limb sensations] interfered with the control of my myoelectric prosthesis because I was trying to control the opening and closing of the myoelectric hand as if I was opening and closing my phantom hand'*, which *'induced something in my [phantom] hand, it was opening and closing, but I wasn't able to control my myoelectric prosthesis if I tried to control it like my phantom limb'* (p. 29). Analysis of qualitative data obtained from prosthesis-using upper or lower limb amputees (Giummarra et al., 2010) further revealed that some amputees with PLA describe their phantom limb as perceptually merging with the prosthesis (*'it all feels like one... like it's in a shoe when I put the prosthesis on'*, *'the phantom limb and prosthesis become one and the same'*; p. 801, 802). Others, however, characterize their phantom sensations as *'completely independent of the prosthesis as it doesn't fit into the prosthesis'* or that *'the phantom feels smothered because the prosthesis isn't long enough for the phantom limb'* (p. 802).

112 These reports suggest that amputees differ in the degree in which they are able to perceptually
113 unite their phantom limb with the prosthesis, arousing associations to another phenomenon
114 originally described several decades ago. In a thorough, albeit unsystematic, observation of
115 PLA in limb amputees¹, it has been examined, among other things, how the phantom limb
116 behaves if the residual limb is pointed towards a solid structure like a wall. Some amputees
117 reported that the phantom limb entered the obstacle, so that the phantom was perceived as
118 being located inside the wall. Other amputees, however, reported that the phantom limb
119 avoided entering the obstacle by evading to the side or into the residual limb, as if it had been
120 forced side- or backwards, respectively. Jalavisto (1950) took up this topic in a more systematic
121 way and proposed that amputees with PLA can be almost evenly assigned to one of two
122 groups, based on their phantom responses when pointing the stump to a solid object: members
123 of the 'obstacle shunning' group predominantly state that their phantom limb would either
124 disappear or retract into the stump before it comes into 'contact' with the wall; and members
125 of the 'obstacle tolerance' (Saetta et al., 2018) group state that their phantom limb would
126 perceptually occupy a place inside the wall. Other observations (Poeck, 1964; 1969)
127 essentially confirmed the presence of both perceptual phenomena. Given that the phantom
128 limb is often part of the amputee's bodily self-consciousness, the different phantom limb
129 responses might give insight into how the brain deals with the self-related physical law of
130 impenetrability (Saetta et al., 2018) that essentially forbid the concurrent spatial co-existence
131 of one's own body parts with an external solid object.

¹ Reference: Henderson, W. R., & Smyth, G. E. (1948). Phantom limbs. *Journal of Neurology, Neurosurgery & Psychiatry*, 11(2), 88-112.

This study was conducted in German prisoner-of-war hospitals and camps in the war years 1940-1945. Although the authors emphasized 'the men's co-operation in describing their impressions' (p. 89), the setting is not compatible with modern ethical standards. Thus, for reasons of scientific integrity and in consultation with the ethics commissioner of the Institute of Cognitive and Clinical Neuroscience, Central Institute of Mental Health, the author of the present study decided to cite this article in a footnote, while refusing to 'honor' the work by listing it in the bibliography.

Saetta et al. (2018) re-introduced the topic in an elegant study implementing a motion perception paradigm from cognitive neuroscience: in the apparent motion illusion (Shiffrar & Freyd, 1990), non-amputated participants report the perception of a movement trajectory when two static pictures of a body, differing only in the position of a limb, are presented in quick succession. If one picture shows the limb on the left side and the other picture on the right side (or vice versa) of a solid object, then participants report the perception of the limb moving around or through the object, depending on the stimulus onset asynchrony of the two images: short stimulus onset asynchrony triggers the perception of implausible movement trajectories *through* the solid object, while long stimulus onset asynchrony is accompanied by the perception of plausible movement trajectories *around* the object. Saetta et al. (2018) used this paradigm in two groups of unilateral lower limb amputees with PLA who were matched for their phantom responses in everyday life (i.e., whether the phantom limb shows obstacle shunning or obstacle tolerance; $n = 6$ subject each). Since it is known that the phenomenon of apparent motion perception relies on representational own-body constraints (e.g., Stevens, Fonlupt, Shiffrar, & Decety, 2000), Saetta et al. (2018) expected that those who report obstacle shunning might have such a vivid representation of their phantom limb that it adheres to the law of impenetrability, which should be reflected in a bias to perceive the presented leg to move around the solid objects in the apparent motion paradigm. Obstacle tolerance, on the other hand, was expected to be associated with a bias to perceive the legs to move through the solid objects, due to a hypothesized less vivid representation of the phantom limb and thus a lack of validity for the law of impenetrability. Interestingly, their results showed the opposite effect: while amputees with obstacle shunning perceived the limb to move through the solid object, amputees with obstacle tolerance had a bias to perceive the limb to move around it. This surprising finding suggests that the representation of the phantom limb in amputees reporting obstacle tolerance is not less, but actually more vivid, so that physical constraints in terms of body-object interactions are realistically processed by this group. In other words, representational vividness might constitute a necessary condition for a phantom limb to perceptually 'survive' the collision with a solid object.

Saetta et al. (2018) already recognized the importance of this finding for prosthesis use, by concluding that amputees perceiving obstacle tolerance (here: phantom prosthesis tolerance, PPT) may be able to better incorporate a prosthetic device compared to those who show obstacle shunning (here: phantom prosthesis shunning, PPS). Thus, PPT, rather than PPS, might contribute to the embodiment of a prosthesis (see Figure 1 A-C for an illustration; for a review introducing the underlying idea, see Giummarra, Gibson, Georgiou-Karistianis, & Bradshaw, 2007). Since PPT, in turn, might at least partly be contingent on the level of phantom vividness (cf., Saetta et al., 2018), it can be hypothesized that a phantom limb might ‘transfer’ its level of self-consciousness to a prosthesis. Figuratively speaking, the phantom limb might ‘animate’ the prosthesis, but only if the phantom limb ‘survives’ co-location with the prosthetic device. Following this conclusion, PPT as perceptual trait could mediate the relationship between phantom self-consciousness (PSC) and prosthesis embodiment (for the proposed mediation model see Figure 1 D).

insert Figure 1 about here

In the present work, data regarding PSC, phantom-prosthesis interactions in terms of PPT and PPS, and prosthesis embodiment of a large sample of unilateral lower limb amputees using a prosthesis were analyzed. Since there is evidence that phantom-prosthesis interactions might represent a dimensional rather than a categorical phenomenon (cf., Saetta et al., 2018), PPT and PPS were dimensionally assessed by using a theoretically- and empirically-driven set of items. Crucially, a mediation analysis on the relationship between PSC and prosthesis embodiment through PPT was performed. In concluding exploratory analyses, the potentially beneficial role of phantom-prosthesis interactions was evaluated.

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189 **2 Methods**

190 **2.1 Initial sample description and setting**

191 Data of $N = 148$ prosthesis-using individuals with unilateral major lower limb amputation were
192 collected. The group had a mean (M) age of 57.24 years, with a standard deviation (SD) of
193 11.26; there were 70.9% male and 29.1% female participants (no non-binary or gender-diverse
194 participants). The participants have already been included in a previous report on prosthesis
195 embodiment (Bekrater-Bodmann, 2021) and served as initial sample to identify individuals with
196 (PLA group) or without phantom limb awareness (noPLA group) (see below).

197 All participants had sufficient comprehension of the German language and took part in a
198 survey, which for the majority was implemented in an online questionnaire battery
199 (implemented in Gorilla™; <https://gorilla.sc/>); $n = 10$ participants, however, received a printed
200 version by mail, due to not having access to the internet. The battery (online or print version)
201 included questionnaires on demographics, amputation- and prosthesis-related information,
202 prosthesis embodiment, and phantom phenomena. The online version further included
203 branches which allowed for certain paths through the questionnaire, depending on individual
204 responses. For the present study purposes, data on phantom self-consciousness (PSC),
205 phantom-prosthesis interactions, and prosthesis embodiment were essential (see below). The
206 study was approved by the ethics review board of the Medical Faculty Mannheim, Heidelberg
207 University, and adhered to the Declaration of Helsinki in its current form. All participants gave
208 their written informed consent prior to study participation.

209

210 **2.2 Questionnaire**

211 **2.2.1 General amputation- and prosthesis-related information**

212 Participants were asked to indicate the side of amputation as well as their lower limb
213 dominance prior to amputation, using the item '*Which leg did you use to kick an object, for
214 example a ball, prior to amputation?*' (response alternatives: *right; left; both alike*). In
215 combination, the data of amputation side and limb dominance prior to amputation were used

to decide whether or not the dominant lower limb has been amputated. Participants who had no preference for the left or right leg prior to amputation (*'both alike'* responses) were considered non-dominant limb amputees. Participants were further asked for the presence of residual limb pain in the last three months as well as for the level of amputation (response alternatives: *foot amputation; transtibial amputation; knee exarticulation; transfemoral amputation; hip extraction or hemipelvectomy*), reason of amputation (response alternatives: *accident; cancer; peripheral vascular disease; injury; infection; congenital limb deficiency; other reasons*; multiple responses were allowed), and date of amputation, the latter which – in combination with the date of participation – was used to determine the time since amputation in years. Participants were further asked for their frequency of prosthesis use (one missing value in the noPLA group) a) per week (1 – *less than twice*; 2 – *every second day*; 3 – *almost daily*; 4 – *daily*) and b) per day (1 – *one to two hours*; 2 – *several hours, but not throughout*; 3 – *half a day*; 4 – *from morning to evening*). By multiplying both frequency ratings, an ordinality scaled frequency of prosthesis use index with nine ranks was obtained, ranging from 1 – *rare use* to 9 – *frequent use* (cf., Bekrater-Bodmann et al., 2021).

2.2.2 Phantom limb awareness

Participants were familiarized with the concept of PLA by providing the following short description: *'The following questions refer to the awareness of a phantom limb, meaning that the amputated limb can still be perceived. This awareness can relate to the whole limb or only to certain areas of it. Thus, we ask you for the perceived presence of distinct parts of the missing limb rather than any specific non-painful or painful phantom limb sensations. Phantom limb awareness does not refer to the residual limb.'* After reading the description, participants were asked to indicate whether they experienced PLA in the last three months. The response alternatives were a) *'No, I was never aware of a phantom limb'*, b) *'No, I am not aware of a phantom limb currently, but I was so in the past'*, and c) *'Yes, I am currently aware of a phantom limb'*. The first two response alternatives were pooled as current absence of PLA, whereas the last response alternative was coded as current presence of PLA. Participants who reported

PLA were further asked to indicate the frequency of awareness (nine ranks, from 1 – *less than once a month* to 9 – *permanently*), and whether or not they were aware of the phantom limb now, at the moment of data collection. Finally, participants were asked to check a list of given phantom limb sensations in addition to mere PLA, targeting phantom limb movements (voluntary or involuntary movements, phantom muscle activity), non-painful somatosensation (such as tingling, pressure, vibrations, thermal, or tactile sensations), phantom limb pain, and phantom limb distortions (such as telescoping or other deformations compared to the intact limb).

2.2.3 Phantom self-consciousness

Own unpublished data, obtained in a sample of $n = 41$ upper limb amputees, indicate that there is high inter-individual variance in the amputee's experience that the phantom limb is an integral part of the body. Beyond mere perceptual vividness of the phantom limb, these data thus indicate that amputees differ in the degree they are self-conscious of the representation of the former physical limb. As main components of bodily self-consciousness, a) ownership (that is, the sensation that a body part belongs to oneself), and b) agency (that is, the sense of being in control of a body part's movements), have been repeatedly identified (e.g., Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008; Tsakiris, Schütz-Bosbach, & Gallagher, 2007; Tsakiris, Longo, & Haggard, 2010). Thus, in the present study, participants who reported PLA in terms of a clear proprioceptive image were asked to rate their PSC on two items. The first item asked '*How much do you perceive your phantom limb as part of your body?*', accompanied by a numerical rating scale with the poles 0 – *the phantom limb is foreign to my body* and 10 – *the phantom limb is a part of my body*. The second item asked '*How much control do you have over the movements of your phantom limb?*', from 0 – *I have no control at all* to 10 – *I am in full control*. PSC was defined as the mean of both item ratings, potentially ranging from 0 to 10, with higher scores indicating higher PSC.

2.2.4 Prosthesis embodiment

The extent of prosthesis embodiment was assessed with the *Prosthesis Embodiment Scale for Lower Limb Amputees* (PEmbS-LLA; Bekrater-Bodmann, 2020), consisting of ten items targeting the prosthesis-related dimensions *Ownership/Integrity*, *Agency*, and *Anatomical Plausibility*. These dimensions correspond to the earlier identified embodiment components in the rubber hand illusion paradigm in non-amputated participants (Longo et al., 2008) and thus quantify the degree to which a prosthesis is cognitively integrated as part of the amputee's body (cf., Makin et al., 2017). Participants were asked to look at their donned prosthesis or walk with the prosthesis before indicating their agreement or disagreement with ten given statements (for example '*The prosthesis is part of my body.*'), using a 7-point Likert scale ranging from *strongly disagree* to *strongly agree*. Note that none of the PEmbS-LLA items asks for perceptual phantom-prosthesis interactions, since the development of the instrument specifically aimed at independence of PLA. Thus, all items are phrased in a way that allow for meaningful responses for amputees with or without PLA. This is of utmost importance in the present context, where the relationship between prosthesis embodiment and phantom-prosthesis interactions is investigated. In accordance to the published guidelines (Bekrater-Bodmann, 2020), the total score of the PEmbS-LLA, representing an overall measure of prosthesis embodiment, was calculated by averaging all valid items (up to one missing item was allowed in the present study, which was the case in $n = 4$ participants), ranging from -3 to +3, with higher scores indicating higher prosthesis embodiment. The instrument has previously been shown to have good to excellent reliability (Bekrater-Bodmann, 2020), and meaningful associations to individual and prosthesis characteristics, prosthesis satisfaction (Bekrater-Bodmann, 2021), and implicit behavioral measures (Fritsch et al., 2021) suggest validity of the instrument.

2.2.5 Phantom-prosthesis interactions

Previous studies divided amputees in a categorial fashion either into an obstacle tolerance or an obstacle shunning group (Jalavisto, 1950; Saetta et al., 2018). However, as Saetta et al. (2018) already recognized, this categorization might be problematic, since phantoms can intra-

individually respond in a variable manner. Thus, in the present study, a dimensional approach for the assessment of phantom prosthesis tolerance (PPT) and phantom prosthesis shunning (PPS) was operationalized. Based on previous reports (Jalavisto, 1950; Poeck, 1969; Saetta et al., 2018) and own theoretical reflections, ten items were created, adapted to prostheses as a special kind of obstacle, with six items targeting PPT and four items targeting PPS (an English translation of the items is given in Table 1). Participants were asked to put on their prosthesis, along with the following instruction: *'For each of the following statements, please indicate how much you currently agree with them. Answer spontaneously, without thinking twice, and do not leave out any statement'*. If participants were not aware of their phantom limb during data collection, the statements referred to everyday phantom responses. Participants were asked to indicate their agreement or disagreement with the statements, using a 7-point Likert scale ranging from *strongly disagree* to *strongly agree*. Items were presented in fixed order, with PPT items preceding those for PPS. Item responses were recoded from 0 to 6, with higher values denoting higher agreement with the statement.

insert Table 1 about here

2.3 Statistical analysis

First, noPLA and PLA groups are described providing either percentages, *M* and *SD*, and/or median (*Mdn*) and interquartile range (*IQR*), and the groups are compared regarding age and gender as well as amputation- and prosthesis related characteristics, using χ^2 -, parametric independent *t*-, or non-parametric Mann-Whitney-U-tests. Beside the test statistics, the absolute value for ϕ , *r* ($z/\sqrt{n}$), or Cohen's *d* (*d*) is provided as measure of effect size,

respectively. For the PLA group, proportions of phantom limb sensations are reported. If not stated otherwise, the two-tailed (exact) p -value is provided.

Exploratory principal axis factoring (PAF) was performed in order to test the hypothesis of a two-factor structure underlying the ten items targeting phantom-prosthesis interactions (that is, PPT and PPS). PAF was conducted with oblique rotation (direct oblimin, $\delta = 0$) applying Kaiser's criterion (i.e., factor eigen values > 1). Maximum number of iterations was set to 25. Extracted communalities, the Kaiser-Meyer-Olkin measure for sampling adequacy, Bartlett's test of sphericity, and explained variances are provided. Factor loadings (regression coefficients as provided by the pattern matrix) are reported. Conclusive factor loadings were defined as item loadings > 0.50 on a single factor while showing lower loadings for the other factor (Stevens, 2012). Item analysis was applied by providing M , SD , Mdn , and IQR of items. The mean value of PPT and PPS items served as PPT and PPS total score, respectively. Whenever internal consistency of a scale is reported, Cronbach's alpha (for scales with more than two items) or Spearman-Brown coefficient (for two-item scales) is reported (Eisinga, Te Grotenhuis, & Pelzer, 2013). Wilcoxon Signed-Rank tests were applied to compare the mean values of the scores, and Spearman correlation was used to examine the relationship between them (with the correlation coefficient ρ).

Two regression analyses on a) PSC and b) prosthesis embodiment were performed, entering PPT and PPS as regressors (simultaneous entry). Since the distribution of several core variables differed from normality (as indicated by significant Kolmogorov-Smirnov tests, see below), two-step rank-based inverse normal transformations (Templeton, 2011; Templeton & Burney, 2017) were applied prior to performing the regression analysis. In order to check whether the statistical assumptions for performing regression analyses were fulfilled, the residuals' normal distribution as well as the absence of multicollinearity (which was assumed if tolerances > 0.20 and variance inflation factors, VIF , < 4.0 ; Hair, Anderson, Babin, & Black, 2010), heteroscedasticity (using the Breusch-Pagan test), auto correlations (checking visually the Q-Q plot), and endogeneity (all correlations between residuals and regressors $r < .001$) were explored. For each model, the analysis of variance testing for significance of R^2 is

reported. Further, the author reports on the adjusted R^2 . For each regressor, the unstandardized coefficient B and its standard error (SE) is reported, along with the standardized regression coefficient (β) and the respective p -value. For visualization purposes, significant relationships were also displayed along with Pearson correlation coefficients (r).

A simple mediation analysis was conducted, using the partially transformed data, to examine whether the association between PSC and prosthesis embodiment is mediated by PPT, using the PROCESS macro (v3.5.3; model 4; Hayes, 2018) for IBM SPSS. Total (c) and direct effects (a, b, c'), reflected by the unstandardized and standardized regression coefficients, were evaluated. Crucially, the indirect effect of the product of coefficients ($a \times b$) was tested, representing the actual mediation (Zhao, Lynch, & Chen, 2010). Robust bootstrapping sampling (5,000 samples) together with heteroscedasticity-consistent standard errors (Davidson & MacKinnon, 1993) was used. Point estimates for the indirect effect were considered significant when the confidence interval (CI 95%) did not include 0.

Finally, explorative analyses were performed in order to test whether or not an advantageous PSC-PPT pattern in the PLA group is associated with prosthesis embodiment that outperforms the reports from the noPLA group (using non-transformed data). Mann-Whitney-U tests were conducted, and Bonferroni-correction (p_{Bonf}) was applied in the case of multiple testing. All statistical analyses reported in the present study were performed using IBM SPSS (v27.0.0).

3 Results

3.1 Participants without and with phantom limb awareness

Of the total sample of $N = 148$ participants, $n = 59$ (i.e., 39.9%) reported the current absence of PLA (noPLA group; a majority of 59.3% of these participants, however, were aware of a phantom limb in the past), while $n = 67$ (i.e., 45.3%) reported the current presence of PLA (PLA group). Another $n = 22$ (i.e., 14.9%) denied having PLA in terms of a clear proprioceptive image, but reported the presence of somatosensory phantom limb sensations, indicating a rather blurred representation of the phantom limb not allowing for clear spatial localisation; these participants were excluded from further analyses.

The average age of the noPLA participants ($M = 57.75$ years, $SD = 11.28$) did not significantly differ from the PLA participants ($M = 56.22$ years, $SD = 11.01$; $t_{124} = 0.77$, $p = .45$, $d = 0.14$). However, there was a significant difference in the distribution of gender between the noPLA (81.4% male) and PLA group (64.2% male; $\chi^2_1 = 4.61$, $p = .046$, $\phi = .19$).

Amputation-related details of the noPLA and PLA groups are given in Table 2. PLA and noPLA participants did not significantly differ regarding side of amputation, whether or not the amputated limb was the dominant one, or reason of amputation. Participants further did not differ in the prevalence of residual limb pain (all $p \geq .08$, all $\phi \leq .16$). However, participants significantly differed in their level of amputation, with noPLA participants having relatively more amputations at the lower parts of the leg compared to PLA participants ($p = .008$, $\phi = .30$).

There also was a significant group difference in the time since amputation, which dated back longer in the noPLA group ($M = 33.14$ years, $SD = 16.21$) than in the PLA group ($M = 23.92$ years, $SD = 16.37$; $t_{124} = 3.17$, $p = .002$, $d = 0.57$).

Participants of the noPLA group and participants of the PLA group did not significantly differ regarding prosthesis use frequency ($Mdn = 9$, $IQR = 0$ for both groups, $Z = -1.30$, $p = .20$, $r = 0.12$; the median of 9 represents the highest level of prosthesis use frequency, that is, daily use, from morning to evening). Participants of the noPLA group ($M = 1.64$, $SD = 1.16$, $Mdn = 1.90$, $IQR = 1.29$), however, reported significantly higher prosthesis embodiment compared to PLA participants ($M = 1.34$, $SD = 1.01$, $Mdn = 1.50$, $IQR = 1.32$), $Z = -2.10$, $p = .036$, $r = .19$; see also Figure 4).

insert Table 2 about here

3.2 Phantom limb characteristics in the PLA group

PLA participants were aware of their phantom limb with a high frequency ($Mdn = 8$, $IQR = 4$; the median of 8 implies that on average participants were usually aware of their phantom limb several times a day). Actually, 91.0% of participants reported awareness of their phantom limb during the collection of the present data. Mean phantom self-consciousness (PSC), composed of the participant's ratings of the items targeting perceived phantom ownership and phantom agency (Spearman-Brown coefficient of .70 suggesting acceptable internal consistency), was $M = 6.28$ ($SD = 2.85$), median was $Mdn = 6.50$ ($IQR = 5.00$). All PLA participants reported at least one additional phantom limb sensation for the last three months. Voluntary or involuntary movements of (80.6%) and non-painful somatosensations in (85.1%) the phantom limb were common. The majority further reported the presence of phantom limb pain (79.1%), while only a minority was aware of anatomical distortions of their phantom limb (28.4%).

3.3 Phantom-prosthesis interaction: psychometric structure and item and score analysis

Principal axis factoring (PAF) was conducted on the ten phantom-prosthesis interaction items. All extracted communalities were $\geq .34$. The KMO measure ($= .69$) verified sampling adequacy for the analysis. Bartlett's test of sphericity, $\chi^2_{45} = 377.85$, $p < .001$, indicated that correlations between items were sufficiently large for conducting PAF. Two factors had eigen values over Kaiser's criterion and in combination explained about 56% of the variance. The factor loadings after rotation (for the pattern matrix see Supplementary Table 1) indicated that all items load sufficiently high on a single factor each (all factor loadings $\geq .57$), while concurrently loading low on the other factor (all other factor loadings between $-.15$ and $.19$). The items #1-6 (see Table 1) that cluster on factor 1 target experiences of PPT, while the items #7-10 that cluster on factor 2 represent PPS, as expected. Items showed an acceptable range of difficulty (between $.20$ and $.80$ for all items), although particularly the phantom prosthesis shunning (PPS) items were characterized by rather low ratings (Supplementary Table 2). Cronbach's alpha was $.88$ for the PPT items and $.79$ for the PPS items, suggesting sufficient to high internal consistency of the scales.

The PPT score was defined as the mean of the six PPT items, and the PPS score as the mean of the four PPS items. Both PPT ($M = 3.13$, $SD = 1.59$, $Mdn = 3.17$, $IQR = 2.17$) and PPS scores ($M = 1.87$, $SD = 1.46$, $Mdn = 1.75$, $IQR = 2.50$) were low to medium and had relatively large variances. PPT scores were significantly higher than PPS scores ($Z = -4.25$, $p < .001$, $r = .37$). PPT and PPS scores were statistically almost unrelated ($\rho = .05$, $p = .66$).

3.4 Regression analyses for phantom-prosthesis interactions on phantom self-consciousness and prosthesis embodiment

Two regression analyses were performed in order to explore the relationship between phantom-prosthesis interactions and both PSC and prosthesis embodiment. Since the Kolmogorov-Smirnov test indicated that the distribution of PSC, PPS, and prosthesis embodiment differed significantly from normality (all $D_{67} \geq .13$, all $p \leq .01$), a two-step rank-based inverse normal transformation was applied, which normalized distribution (all $D_{67} \leq .07$, all $p \geq .20$). The distribution of the non-transformed PPT data was compatible with the assumption of normality ($D_{67} = .06$, $p \geq .20$).

In the first regression analysis, PPT and PPS total scores were entered as regressors, and PSC was used as criterion. This model fulfilled the statistical assumptions for performing regression analysis, since there was no evidence for deviation from normal distribution of the residuals ($D_{67} = .08$, $p \geq .20$), multicollinearity (tolerance: .99, VIF : 1.01), heteroscedasticity ($\chi^2_1 = 0.58$, $p = .45$), autocorrelation of residuals (checking visually the Q-Q plot), or endogeneity (correlations between residuals and regressors $r < .001$). The analysis revealed a significant model ($F_{2,66} = 6.23$, $p = .003$) which in total explained $R^2 = 16.3\%$ (adjusted $R^2 = 13.7\%$) of PSC variance. PPT emerged as specifically positively related to PSC ($p = .001$; for statistical details see Table 3A; for a visualization of the univariate relationship between PPT and PSC, $r_{65} = .38$, $p = .002$, see Figure 2A).

In the second regression analysis, prosthesis embodiment was used as criterion. Statistical assumptions for this model were fulfilled (no deviation from normal distribution for the residuals, $D_{67} = .09$, $p \geq .20$; no multicollinearity, tolerance: 0.99, VIF : 1.01; no heteroscedasticity ($\chi^2_1 =$

0.89, $p = .35$; no autocorrelation of residuals; no endogeneity, all correlations between residuals and regressors $r < .001$). The model became significant ($F_{2,66} = 7.32$, $p = .001$) and in total explained $R^2 = 18.6\%$ (adjusted $R^2 = 16.1\%$) of prosthesis embodiment variance. Again, only PPT emerged as positively related to prosthesis embodiment ($p < .001$; for statistical details see Table 3B, and for visualization of the univariate correlation between PPT and prosthesis embodiment, $r_{65} = .42$, $p < .001$, see Figure 2B).

insert Table 3 about here

insert Figure 2 about here

3.5 Mediation analysis

The results of the regression analyses suggest that PPT is positively related to both PSC and prosthesis embodiment. As described in the introduction, it can further be hypothesized that there is a relationship between PSC and prosthesis embodiment. However, this hypothetical relationship might represent no direct, but rather an indirect association, mediated through PPT. Thus, a simple mediation was performed (using the partially transformed data introduced in the regression analyses) to analyze whether PSC predicts prosthesis embodiment and whether the indirect path would be mediated by PPT. No total effect of PSC on prosthesis embodiment was observed ($B = 0.19$, $SE = 0.01$, 95% $CI [-0.03, 0.41]$, $p = .09$). After entering PPT as mediator into the model, PSC predicted the mediator significantly ($B = 0.62$, $SE = 0.19$,

95% *CI* [0.25, 1.00], $p = .002$), which in turn significantly predicted prosthesis embodiment ($B = 0.23$, $SE = 0.07$, 95% *CI* [0.09, 0.36], $p = .002$), basically replicating the effects reported for the regression analyses reported above. While the direct effect between PSC and prosthesis embodiment still was non-significant after entering the mediator ($B = 0.05$, $SE = 0.11$, 95% *CI* [-0.18, 0.27], $p = .66$), the indirect effect, that is, the actual mediation, became significant ($B = 0.14$, $SE = 0.06$, 95% *CI* [0.03, 0.28], $p < .05$). The pattern of effects suggests an indirect-only mediation (Zhao et al., 2010) where PPT mediates the association between PSC and prosthesis embodiment. The results of the mediation analysis are summarized in Figure 3.

insert Figure 3 about here

3.6 Explorative analyses on the importance of phantom-prosthesis interactions for prosthesis embodiment

As reported above, participants of the PLA group reported significantly lower prosthesis embodiment compared to the noPLA group (Figure 4), suggesting that PLA might have negative effects on prosthesis embodiment. However, since the mediation analysis revealed the importance of PPT for the relationship between PSC and prosthesis embodiment, the question arises whether or not PLA participants with beneficial prosthesis-related cognitive processes might outperform the noPLA participants regarding prosthesis embodiment. For this purpose, the product between PSC and PPT was calculated (PSC×PPT). High PSC×PPT values can only be obtained if a given participant has a high PSC score (that is, the phantom is vividly perceived as integral part of the bodily self) in combination with a high PPT score (that is, the phantom is perceived as being co-located with the prosthesis), which – based on the positive regression coefficients between PSC and PPT as well as between PPT and

prosthesis embodiment as obtained in the mediation analysis – appears to facilitate the cognitive integration of the prosthesis into the amputee’s body representation. The PLA group was split along the median of the PSC×PPT values, resulting in a PSC×PPT_{low} group ($n = 33$) and a PSC×PPT_{high} group ($n = 34$). Purposefully, the PSC×PPT_{low} and PSC×PPT_{high} groups differed significantly regarding PSC ($M = 4.29$, $SD = 2.50$, $Mdn = 4.00$, $IQR = 3.50$ vs $M = 8.22$, $SD = 1.54$, $Mdn = 8.75$, $IQR = 1.75$; $Z = -5.50$, $p < .001$, $r = .67$) and PPT ($M = 2.01$, $SD = 1.12$, $Mdn = 2.17$, $IQR = 1.58$ vs $M = 4.22$, $SD = 1.17$, $Mdn = 4.00$, $IQR = 1.75$; $Z = -5.82$, $p < .001$, $r = .71$). The PSC×PPT_{low} group reported prosthesis embodiment of $M = 1.05$ ($SD = 1.01$), $Mdn = 1.30$ ($IQR = 1.35$), while the PSC×PPT_{high} group reported significantly higher prosthesis embodiment of $M = 1.62$ ($SD = 0.94$), $Mdn = 1.75$ ($IQR = 1.25$), $Z = -2.30$, $p = .021$, $r = .28$. Bonferroni-corrected comparisons between both PSC×PPT groups and the noPLA participants revealed that the PSC×PPT_{low} group reported significantly lower prosthesis embodiment ($Z = -3.01$, $p_{Bonf} = .004$, $r = .32$), while the PSC×PPT_{high} group showed no significant differences ($Z = -0.45$, $p_{Bonf} = 1.00$, $r = .05$). The results are visualized in Figure 4.

insert Figure 4 about here

4 Discussion

The present study aimed at the characterization of perceptual phantom-prosthesis interactions and its importance for prosthesis embodiment, describing the cognitive integration of a prosthesis into an amputee’s body representation. Using a clear definition of phantom limb awareness (PLA) in a large sample of unilateral lower limb amputees, participants without (noPLA group) and with PLA (PLA group) have been identified. Phantom self-consciousness (PSC), that is, the degree to which the phantom limb is perceived as integral part of the

amputee's body, and phantom-prosthesis interactions were assessed in the PLA group. A psychometric approach revealed two a priori hypothesized dimensions of phantom-prosthesis interaction, that is, phantom prosthesis tolerance (PPT) and phantom prosthesis shunning (PPS), of which only the former one was significantly related to both PSC and prosthesis embodiment as assessed with the *Prosthesis Embodiment Scale*. Mediation analysis revealed a significant indirect effect for the relationship between PSC and prosthesis embodiment through PPT. Subsequent analyses indicated that high PSC in combination with high PPT is capable of compensating negative PLA-associated effects on prosthesis embodiment.

4.1 Phantoms, prostheses, and prosthesis embodiment – the potential role of peripersonal space representation

PPT significantly mediated the relationship between PSC and prosthesis embodiment, suggesting that the inherent vividness of a phantom limb can – at least partly – be transferred to a prosthetic device, but only if participants achieve perceptual phantom/prosthesis co-location. There was no significant total or direct effect for the relationship between PSC and prosthesis embodiment, indicating that high PSC alone is no sufficient condition for the incorporation of a prosthesis. This finding helps to specify the theoretical framework: high PSC of a phantom limb which is not coextensive with a prosthesis might result in two disintegrated percepts – an unphysical, but vivid own limb (the phantom) and a physical, but foreign artificial limb (the prosthesis) – which potentially interfere with each other. The previous reports regarding phantom limbs that negatively interact with prostheses (Bouffard et al., 2005) correspond well with this conclusion. This finding thus suggests the existence of a specific cognitive mechanism involved in the coupling between the self and an artificial body part in limb amputees, providing first-time empirical evidence for previous theoretical considerations (Giummarra et al., 2007; Saetta et al., 2018). While Giummarra et al. (2010) equated PPT with prosthesis embodiment, the present results imply that PPT is a distinct phenomenon, serving as a crucial intermediate step in the integration process of the phantom and prosthesis percepts.

579 Interestingly, noPLA participants reported higher prosthesis embodiment than participants in
580 the PLA group, which could lead to the conclusion that the presence a phantom limb per se
581 negatively affects the flexibility of the amputee's body representation (cf., Lyu, Guo, Bekrater-
582 Bodmann, Flor, & Tong, 2016). The present finding, however, has to be set into the context of
583 other variables distinguishing both groups of amputees: noPLA participants, compared to PLA
584 participants, were characterized by lower levels of as well as a longer time since amputation.
585 Both factors have been identified as covariates of higher levels of prosthesis ownership, i.e., a
586 subcomponent of prosthesis embodiment (Bekrater-Bodmann, 2020), in an independent
587 sample of prosthesis-using upper and lower limb amputees (Bekrater-Bodmann et al., 2021),
588 and might represent an unavoidable confounding associated with group membership. A lower
589 level of amputation might require less adaptation of the sensorimotor system, which likely has
590 the more progressed the more time has passed since the amputation. The high percentage of
591 vanished phantom limbs in the noPLA group might represent a perceptual correlate of this
592 adaptation process, which might further facilitate the embodiment of a prosthesis, potentially
593 explaining the association between group membership, level of and time since amputation,
594 and prosthesis embodiment in the present study.

595 However, the group differences – particularly in the level of amputation – could relate even
596 more directly to prosthesis embodiment, by affecting the amputees' limb-centered peripersonal
597 space, that is, the representation of the immediate surrounding of a limb. Compared to the
598 non-amputated limb, amputees exhibit a peripersonal space for the residual limb that is
599 reduced in extent (Canzoneri, Marzolla, Amoresano, Verni, & Serino, 2013). Peripersonal
600 space representation might be of special relevance in the context of prosthesis embodiment,
601 since the integration of body-related sensory input is facilitated within its limits (Serino, 2019).
602 For example, the application of conflicting multimodal sensory stimulation can elicit the so-
603 called rubber hand illusion (Botvinick & Cohen, 1998), during which non-amputated individuals
604 are induced to perceive an artificial hand as their own, but only, if the artificial limb is placed
605 within the boundaries of hand-centered peripersonal space (Lloyd, 2007). The extent of
606 peripersonal space for non-amputated lower limbs has been estimated at about 70cm (Stone,

Kandula, Keizer, & Dijkerman, 2018) – a size which would enclose a prosthesis all the better, the lower the level of the amputation. Since the cognitive processes in the rubber hand illusion paradigm have been related to prosthesis embodiment (Bekrater-Bodmann, 2020; Giummarra et al., 2007; Niedernhuber, Barone, & Lenggenhager, 2018), it is likely that the representation of the peripersonal space also plays a role for the incorporation of a prosthetic device. The characteristics of the peripersonal space, however, might be more advantageous in noPLA participants compared to PLA participants.

Beside anatomical differences, the phantom limb itself might constitute a source of representational impediments in the PLA group. Thus, the limb-centered peripersonal space has been shown to be anchored to the location where one's own body part is *perceived*, rather than to the physical body part itself: for non-amputated individuals, Brozzoli, Gentile, and Ehrsson (2012) demonstrated that the locus of the hand-centered peripersonal space shifts to the position of an artificial hand after the rubber hand illusion has been successfully induced. Although direct evidence for amputees is still missing, there is reason to assume that the peripersonal space representation of a residual limb can be influenced similarly by the presence of PLA, particularly if the phantom limb is experienced as integral part of the body (that is, if there are high levels of PSC). If this locus does not overlap with the prosthesis, embodiment of the device could be impeded, while an overlap facilitates integration of the prosthesis. However, as the present results also indicate, the beneficial effect might only compensate for (potentially) interfering effects of PLA, and does not necessarily lead to stronger prosthesis embodiment compared to participants who are not aware of a phantom limb. Whether or not the processes underlying prosthesis embodiment represent distinct cognitive processes, however, has to be investigated in future research.

4.2 Potential neural principles

Previous research revealed some of the neurocognitive processes involved in bodily self-consciousness, particularly based on the results obtained from non-amputated individuals. A recent meta-analysis (Grivaz, Blanke, & Serino, 2017) showed that in the interplay with other

brain areas such as temporo-parietal and ventral premotor regions, the posterior parietal cortex is involved in the processing of multisensory information related to the body and its close surroundings. This fits well with results showing that the posterior parietal cortex essentially encodes multimodal representations of external space (e.g., Andersen, Snyder, Bradley, & Xing, 1997; Azañón, Longo, Soto-Faraco, & Haggard, 2010) which are further combined with continuous proprioceptive signals originating from postural changes of the body and its parts (Bolognini & Maravita, 2007). Interestingly, the representation of non-painful phantom limb sensations has been related to the posterior parietal cortex (Andoh et al., 2017; Bolognini, Olgiati, Maravita, Ferraro, & Fregni, 2013; Nardone et al., 2015). Evidence for the representation of prostheses in amputees, however, is sparse. A previous study on prosthesis-using upper limb amputees showed that prosthesis use was associated with structural alterations in posterior parietal cortex (Preißler et al., 2013). The authors interpreted this result as structural adaptation of the dorsal visual stream (Goodale & Milner, 1992; Kravitz, Saleem, Baker, & Mishkin, 2011), which has been particularly related to the processing of spatial orientation of objects, the detection of movements, and eye-hand coordination. There is also evidence for a specialization in tools (Almeida, Mahon, Nakayama, & Caramazza, 2008), which fits well with its involvement in the use of upper limb prostheses. The dorsal stream arises in early areas of the occipital cortex and also involves posterior temporal regions, the junction of which has been found to be involved in the visual representation of prostheses in upper limb amputees (van den Heiligenberg et al., 2018). Certain overlap between the brain networks discussed here and its involvement in the integration of visual and proprioceptive limb position information (Limanowski & Blankenburg, 2016) suggests that they also play a role in perceived phantom/prosthesis co-location as identified in the present study. The actual neural processes underlying the perceptual integration of a phantom and a prosthesis, however, have to be elucidated in the future.

4.3 Limitations of the present study and open questions

The present study has several methodological limitations. First, the mediation analysis and the underlying model suggest causality (PSC leads to PPT leads to prosthesis embodiment), although – actually – the cross-sectional data only allow for correlative conclusions. Future studies thus have to focus on causal relationships, for instance by assessing longitudinal data in a sample reporting variability in everyday PSC or by manipulating the position of an artificial limb in respect to the phantom limb in a modified rubber hand illusion paradigm (cf., Ehrsson et al., 2008). Moreover, although the present sample is larger than in most other studies examining the interaction between the phantom limb with the environment, the present findings should definitely be replicated in an independent and larger sample, the latter which would generally increase the explanatory power of the multivariate statistical approaches.

The present data provide evidence for the importance of PPT for prosthesis embodiment. Interestingly, PPS was practically non-related to PPT, suggesting that both phenomena represent two independent dimensions rather than two poles of a single perceptual continuum. This contradicts previous categorical operationalization of obstacle tolerance and obstacle shunning in the past (Jalavisto, 1950; Saetta et al., 2018). It might simply be that prostheses represent a special kind of obstacle, due to their visual and functional similarity to a real body part, which might affect an individuals' body representation differently compared to an obstacle lacking these features (cf., Cardinali et al., 2021; Tsakiris, Carpenter, James, & Fotopoulou, 2010). Thus, future studies should directly compare within-subjects phantom responses to different types of obstacles in order to evaluate the specificity of results. Moreover, the ratings for PPS were significantly lower compared to PPT ratings, which raises doubts about the even distribution of obstacle tolerance and obstacle shunning reported in previous studies. It might be that the categorical approach, as established in the past, has overestimated the prevalence of obstacle shunning. The introduced and psychometrically evaluated set of items (Table 1) might be a useful instrument for future investigations on the dimensionality of both phenomena, where the wording of items could be easily adapted to other types of obstacles.

Further, it remains open whether the cognitive mechanism identified in the present study has a rehabilitative value. Giummarra et al. (2007) hypothesized that perceived

phantom/prosthesis co-location might help the amputee to coordinate movements and maintain motor control over the artificial limb. Empirical evidence for beneficial effects on prosthesis functionality, however, remains scarce. Bouffard et al. (2005) assessed negative and positive phantom-prosthesis interactions on a subjective level; however, the contribution of spatial convergence between the phantom and the artificial limb cannot be conclusively deduced. In this context, it is debatable whether lower limb amputees represent an ideal sample to answer the question of functional benefits. While walking is characterized by broad movement ranges, hand use often requires more fine-tuned sequences of movements, for example when interacting with the environment via tools. Spatially disintegrated percepts of the phantom limb and the prosthesis might particularly interfere with those tasks. However, even if the present results can be replicated for upper limb prosthesis users, it remains open which level co-location can be achieved: is the convergence between the phantom limb and the prosthesis limited to rather large parts like the forearm, or can it be also obtained for smaller parts like the fingers? And does the phantom remain in the prosthesis during movement, or do the fingers slip out at a certain velocity? Myoelectric prosthesis users actually reported that using the residual limb muscles to control their prosthesis can be accompanied by corresponding movements of the phantom (Bouffard et al., 2005). However, the visual control often involved in upper limb prosthesis use might strongly affect phantom/prosthesis co-location in upper limb amputees, so that the present results obtained in lower limb amputees cannot necessarily be generalized to this population. More experimental investigations are required, particularly those that combine behavioral paradigms for phantom limb location (Longo et al., 2012) and prosthetic functionality (e.g., Condie, Scott, & Treweek, 2006; Lindner, Nätterlund, & Hermansson, 2010), in order to evaluate the rehabilitative value of phantom-prosthesis interactions in both upper and lower limb amputees. Until then, the results presented here are mainly of theoretical value, potentially stimulating future research; however, no suggestions for clinical applications can be deduced.

4.4 Conclusions

The present results suggest that perceived phantom/prosthesis co-location contributes to prosthesis embodiment in lower limb amputees. Cognitively, the phantom limb appears to transfer its inherent vividness to the artificial limb which might facilitate the incorporation of the device as a part of the own body. These insights help to specify our theoretical considerations on bodily self-consciousness in limb amputees and might stimulate new research on the underlying neurocognitive principles. The results emphasize once more the complex interplay between the self and the environment. Whether or not the proposed cognitive mechanism is of relevance in rehabilitative contexts, however, remains open.

5 Conflict of Interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Tables

Table 1: Items targeting phantom-prosthesis interaction and its hypothetical assignment to phantom prosthesis tolerance and phantom prosthesis shunning.

Phantom-prosthesis interaction	Item #	Item wording	Item label
Phantom prosthesis tolerance	1	My phantom and the prosthesis fit together.	Match
	2	My phantom and the prosthesis are one and the same.	The very same
	3	My phantom is merged with the prosthesis.	Merging
	4	My phantom and the prosthesis form a unified whole.	Unity
	5	My phantom is in the prosthesis.	Connection
	6	My phantom and the prosthesis are in the same location.	Location
Phantom prosthesis shunning	7	My phantom retracts into the residual limb when I use the prosthesis.	Retraction
	8	My phantom evades the prosthesis.	Evasion
	8	My phantom disappears when I use the prosthesis.	Disappearance
	10	My phantom is less vivid when I use the prosthesis.	Fading

946 Table 2: Amputation-related details of the present samples of participants without (noPLA) and
 947 with (PLA) phantom limb awareness.

	noPLA (<i>n</i> = 59)	PLA (<i>n</i> = 67)	
	%		Test statistics and significance
Amputation and residual limb pain			
Right-sided amputation	40.7	37.3	$\chi^2_1 = 0.15$, ns
Amputation of dominant limb ^a	39.2	32.3	$\chi^2_1 = 0.60$, ns
Residual limb pain	25.4	40.3	$\chi^2_1 = 3.12$, ns
Level of amputation			
Foot amputation	1.7	4.5	$\chi^2_4 = 11.64^{**}$
Transtibial amputation	61.0	34.3	
Knee exarticulation	1.7	7.5	
Transfemoral amputation	33.9	53.7	
Hip extraction or hemipelvectomy	1.7	0.0	
Reason of amputation (multiple responses allowed)			
Accident	76.3	61.2	$\chi^2_1 = 3.29$, ns
Cancer	11.9	17.9	$\chi^2_1 = 0.90$, ns
Peripheral vascular disease	6.8	13.4	$\chi^2_1 = 1.50$, ns
Injury	20.3	9.0	$\chi^2_1 = 3.32$, ns
Infection	11.9	10.4	$\chi^2_1 = 0.06$, ns
Congenital limb deficiency	0.0	1.5	$\chi^2_1 = 0.89$, ns
Other reasons	5.1	9.0	$\chi^2_1 = 0.71$, ns

948 ^a based on valid data (two PLA and eight noPLA missing data due to not-remembering). ^{**} $p <$
 949 .01; ns = not significant; *n* = number.

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Table 3: Results of the regression analyses for phantom-prosthesis interactions on A) phantom self-consciousness and B) prosthesis embodiment.

Model	A				B			
Criterion	Phantom self-consciousness				Prosthesis embodiment			
Regressors	<i>B</i>	<i>SE</i>	β	<i>p</i>	<i>B</i>	<i>SE</i>	β	<i>p</i>
(constant)	-0.71	0.25		.005	-0.88	0.22		< .001
Phantom	0.24	0.07	.39	.001	0.23	0.06	.41	< .001
prosthesis tolerance								
Phantom	-0.13	0.11	-.14	.24	0.08	0.10	.09	.41
prosthesis shunning								

B = unstandardized regression coefficients; *SE* = standard error; β = standardized regression coefficients.

Figure legends

Figure 1: Phantom-prosthesis interactions and its proposed mediating role for the relationship between phantom self-consciousness and prosthesis embodiment. A) Amputees often report phantom limb awareness in terms of a discrete proprioceptive image of the lost limb, occupying a discrete volume in space (red dotted line); B) phantom prosthesis tolerance refers to the perception of phantom/prosthesis co-location; C) phantom prosthesis shunning refers to the sensation that the phantom limb avoids co-location with the prosthesis by fading, telescoping, or evasion; D) phantom prosthesis tolerance might mediate the relationship between phantom self-consciousness and prosthesis embodiment.

Figure 2: Relationships between phantom prosthesis tolerance and A) phantom self-consciousness and B) prosthesis embodiment (transformed data). The y-axis units are arbitrary. Given are Pearson correlation coefficients (r). ** $p < .01$; *** $p < .001$.

Figure 3: Results of the mediation analysis; given are the standardized regression coefficients. A) There was no total effect c of phantom self-consciousness on prosthesis embodiment; B) mediation model with path a and b of the significant indirect effect ($a \times b$; $\beta = 0.15$, $SE = 0.07$, 95% $CI [0.04, 0.30]$, $p < .05$) and the non-significant direct effect c' . β = standardized regression coefficients; SE = standard error; CI = confidence interval; ** $p < .01$; ns = not significant.

Figure 4: Prosthesis embodiment in participants without (noPLA group) and with phantom limb awareness (PLA group) (black box plots) and the median split PLA group, which was divided along their values for the interaction of phantom self-consciousness (PSC) and phantom prosthesis tolerance (PPT), resulting in a $PSC \times PPT_{low}$ and $PSC \times PPT_{high}$ group (grey boxplots). The red dotted line represents the mean value of the noPLA group against which the other mean values were compared (significances in red). The mean values of both median split PLA

groups were also compared (significances in black). Diamonds represent outliers ($> 1.5 \times$ the interquartile range). * $p < .05$; ** $p < .01$; ns = not significant; n = number.

Figures

Figure 1

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Supplement

Supplementary Table 1: Pattern matrix for the principal axis factor analysis with oblique rotation. Given are the factor loadings as regression coefficients. Bold font indicates the factor affiliation for the items.

		Factors	
Item #	Item label	Phantom prosthesis tolerance	Phantom prosthesis shunning
1	Match	0.71	0.00
2	The very same	0.67	0.09
3	Merging	0.90	0.00
4	Unity	0.88	0.04
5	Connection	0.77	0.06
6	Location	0.57	-0.15
7	Retraction	-0.10	0.58
8	Evasion	-0.14	0.64
9	Disappearance	0.16	0.75
10	Fading	0.19	0.84
Explained variance (%)		35.9	20.2

1067 Supplementary Table 2: Parameters of item analysis.

Item #	Item abbreviation	<i>M</i>	<i>SD</i>	<i>Mdn</i>	<i>IQR</i>
Phantom prosthesis tolerance					
1	Match	3.58	2.02	4.00	3.00
2	The very same	2.57	2.08	2.00	3.00
3	Merging	2.82	1.99	3.00	4.00
4	Unity	2.87	2.04	3.00	4.00
5	Connection	2.94	1.98	3.00	4.00
6	Location	4.01	1.89	5.00	3.00
Phantom prosthesis shunning					
7	Retraction	2.09	2.01	1.00	4.00
8	Evasion	1.24	1.57	0.00	3.00
9	Disappearance	1.84	1.94	1.00	3.00
10	Fading	2.28	1.89	2.00	3.00

1068 *M* = mean; *SD* = standard deviation; *Mdn* = median; *IQR* = interquartile range

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