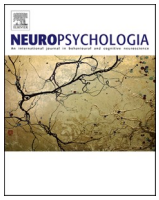
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Review article

On the relationship between pain and body ownership: A systematic review of rubber hand illusion studies

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1. Introduction

Pain is a multidimensional and subjective experience that cannot be reduced to nociceptive input alone; rather, it emerges from the integration of sensory, affective, cognitive, and motivational processes (Raja et al., 2020). Within this framework, body representation, defined as the set of neural and cognitive mechanisms through which the body is perceived, experienced, and acted upon (Medina and Coslett, 2016), constitutes a key determinant of pain-related outcomes, including pain perception, spatial localisation, and regulation. Conversely, pain itself has been shown to exert measurable effects on body-representation processes, particularly in populations characterised by altered sensorimotor input or chronic pain conditions (Aguado et al., 2025). Taken together, findings from experimental and clinical primary studies indicate a bidirectional association between pain-related processes and body-representation mechanisms, whereby each systematically influences the other (Beccherle and Scandola, 2025).

One central dimension of body representation is the sense of body ownership, operationally defined as the subjective experience that one's body and its constituent parts belong to oneself (Tsakiris, 2010). Experimental paradigms such as the rubber hand illusion (RHI) have demonstrated that body ownership can be experimentally manipulated, allowing individuals to attribute ownership to external objects when visual appearance, spatial alignment, and multisensory stimulation are congruent with the participant's body (Botvinick and Cohen, 1998). Neuroimaging evidence from primary studies has identified a distributed neural network, including the premotor and posterior parietal cortices, the extrastriate body area, the secondary somatosensory cortex, and the posterior insula, associated with ownership-related processing (Moro et al., 2023; Evans and Blanke, 2013; Crucianelli et al., 2024; Dary et al., 2023). Importantly, body ownership is best conceptualised as a continuous construct, ranging from full embodiment to partial or complete disownership, rather than a dichotomous state, as demonstrated across both experimental manipulations and clinical populations (Tsakiris and Haggard, 2025).

A growing number of experimental studies suggest that manipulations of body ownership and embodiment produce measurable effects on pain-related outcomes. Specifically, investigations employing the RHI, immersive virtual reality (e.g., Knobel et al., 2024), and visual manipulations of limb appearance (e.g., Wittkopf et al., 2017) have reported analgesic effects (Fang et al., 2019), hyperalgesia (Siedlecka et al., 2018), or null effects (Mohan et al., 2012) on pain intensity, pain threshold, pain tolerance, and pain unpleasantness. These effects appear to vary with experimental parameters, including multisensory congruency (Della Longa et al., 2022), limb appearance (e.g., healthy vs injured) (Osumi et al., 2014; Giummara et al., 2015), transparency, and colour (Pamplona et al., 2024). Such variability contributes to substantial between-study heterogeneity and suggests that the effects of embodiment-related manipulations on pain are highly context-dependent. Neuroanatomically, these effects are plausibly mediated by overlapping neural substrates implicated in both body ownership and pain processing, particularly within insular and parietal regions (Gallace and Bellan, 2018).

Conversely, evidence from both healthy participants and clinical populations indicates that pain conditions exert systematic effects on body-representation outcomes. Across scientific studies, pain has been associated with alterations in motor imagery performance (Moseley et al., 2008), distortions in laterality judgments (Ravat et al., 2020), and changes in vicarious pain responses (Young et al., 2017), often in a somatotopically specific manner. In clinical conditions such as spinal cord injury (Osinski et al., 2020; Ionta et al., 2016), fibromyalgia (Martínez et al., 2019; Scandola, 2022), phantom limb pain, and complex regional pain syndrome, pain intensity has been repeatedly linked to changes in the representation of the affected body parts. Crucially, emerging evidence challenges the view that pain solely disrupts body representation, suggesting that it may function as an informative somatosensory signal that helps maintain or preserve body representations when tactile or proprioceptive input is reduced or absent (Beccherle and

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Scandola, 2025).

Despite the rapid expansion in literature, the evidence base is characterised by substantial methodological heterogeneity. Experimental works differ widely not only in experimental paradigms and population characteristics, but also in the modalities used to elicit pain, the outcome measures used to assess pain (e.g., subjective ratings, pain thresholds, tolerance, or unpleasantness), and the instruments used to quantify body ownership or embodiment (e.g., questionnaire-based ownership ratings, single-item judgments, proprioceptive drift, or composite embodiment indices). This heterogeneity limits the interpretability and comparability of individual findings. While existing narrative reviews have provided valuable theoretical integration (Beccherle and Scandola, 2025), they do not permit quantitative estimation of pooled effect sizes, formal assessment of between-study heterogeneity, or systematic evaluation of publication bias.

This limitation is particularly relevant given the pronounced methodological diversity of the literature, which spans multiple approaches to pain induction, pain measurement, and body ownership assessment. Across studies, pain has been experimentally elicited using heterogeneous modalities, including thermal (heat or cold) (e.g., Coleshill et al., 2017), mechanical (e.g., pressure or pinprick) (e.g., Capelari et al., 2009; Ceylan et al., 2025), electrical (e.g., Gong et al., 2022), and laser stimulation (e.g., Fang et al., 2019), each engaging partially distinct nociceptive pathways and perceptual components. Pain-related outcomes have been assessed using a wide range of measures, from subjective pain ratings (e.g., numerical or visual analogue scales) to psychophysical indices such as pain threshold or pain tolerance, and, less frequently, physiological or behavioural responses. Similarly, body ownership and embodiment have been operationalised using diverse instruments, including multi-item questionnaire-based ownership scales, single-item ownership judgments, proprioceptive drift measures, or composite embodiment indices. Together, this methodological heterogeneity complicates the integration and comparison of findings across studies and represents a critical source of between-study variability that cannot be adequately addressed by narrative synthesis alone.

The present work was initially conceived and pre-registered as a systematic review and meta-analysis to quantitatively synthesise evidence on the bidirectional relationship between pain-related processes and body representation. However, the meta-analytic approach revealed substantial between-study heterogeneity, reflecting marked variability in experimental paradigms, pain induction methods, outcome measures, and operationalisations of body ownership. This level of heterogeneity limited the interpretability and generalizability of pooled effect estimates. Accordingly, we retained the systematic review component while abandoning the quantitative meta-analytic synthesis, opting instead for a structured and qualitative integration of the evidence that emphasises sources of variability across studies.

2. Research objectives

Embodiment literature is a vast topic engulfing different paradigms from the RHI, such as full-body ownership and out-of-body illusions, the mirror box, as well as body-swapping paradigms (Ehrsson, 2007; Lenggenhager et al., 2007; Medina et al., 2015; Petkova and Ehrsson, 2008; Slater et al., 2010), with clinical applications on chronic patients (Pamment and Aspell, 2017). To control for this heterogeneity and focus on the relationship between embodiment and pain, the current systematic review included only studies that adopted the RHI embodiment paradigm.

The current work aims to disentangle two different lines of research involving the use of RH in healthy individuals. On the one hand, several studies have examined whether the experience or anticipation of pain alters the sense of body ownership, typically using the Rubber Hand Illusion (RHI) to assess changes in embodiment and ownership-related processes. This line of research addresses the extent to which nociceptive and pain-related signals contribute to the construction and maintenance of body representations. On the other hand, a separate body of work has investigated whether experimentally manipulating body ownership through the RHI can influence pain perception itself, including changes in pain intensity, pain thresholds, and pain tolerance. While both approaches rely on the interaction between pain and bodily self-representation, they address different theoretical questions: the former concerns the impact of pain on body ownership mechanisms, whereas the latter examines the potential role of body ownership in shaping pain experiences. The present systematic review was designed to synthesise evidence from both research directions. Specifically, we examined studies investigating (a) the effects of RHI-induced changes in body ownership on pain perception, and (b) the effects of pain on the induction and modulation of the RHI. By distinguishing between these two complementary but conceptually different lines of inquiry, the review aims to provide a clearer understanding of the bidirectional relationship between pain and body ownership.

3. Methods

We conducted a systematic review of experimental studies investigating the relationship between the RHI and pain perception. The systematic review followed a pre-registered protocol on the Open Science Framework (OSF; DOI: 10.17605/OSF.IO/4VXS6) and is reported in accordance with the PRISMA guidelines (Page et al., 2021). Preregistration protocol and Supplemental Material can be found at osf.io/db4cf.

3.1. Search strategy

A systematic literature search was conducted in PsycINFO (via Ovid) and PubMed on April the 4th, 2025.

The following query string was used, with minor adaptations to database-specific syntax: (“Rubber hand” OR “RHI” OR “dummy hand” OR “rubber hand illusion”) AND (“pain” OR “pain perception”).

To validate the sensitivity of the search strategy, the query string was required to retrieve the following articles, which we identified as “gold-standard” in the research field (Hegedüs et al., 2014; Fang et al., 2019; Siedlecka et al., 2018; Mohan et al., 2012).

Duplicate entries were automatically evaluated using R (R Core Team, 2025) and the *revtools* package version 0.4.1 (Westgate, 2019), and manually screened by M.S., reaching a perfect match. Then, two independent reviewers (F.S. and M.L.) performed title/abstract screening using R (R Core Team, 2025) and *revtools* (Westgate, 2019). Full-text assessment was then carried out. During the screening procedure, we used the following inclusion (IC) and exclusion (EC) criteria reported in Table 1.

Inter-rater concordance was evaluated by using Cohen's kappa (i.e., the extent of agreement among reviewers; McHugh, 2012) and mean agreement. Discrepancies were resolved through consensus discussion with a senior researcher (M.S.).

Table 1
Inclusion and exclusion criteria to assess papers during screening.

Type of criteria	Rule
Inclusion criteria (IC)	IC1: Paper must include a manipulation of the Rubber Hand Illusion
	IC2: Paper must measure the perception of pain quantitatively
Exclusion criteria (EC)	EC1: Papers are not written in English or Italian language
	EC2: Papers that do not concern humans
	EC3: Articles that are not quantitative experimental research
	EC4: Articles that do not include a version of the rubber hand illusion
	EC5: Articles that do not assess pain in a quantitative way

Note: Across all studies, the administration of painful and non-painful stimuli induced ownership illusion.

3.2. Data abstraction and quality appraisal

Two reviewers (F.S. and M.L.) independently extracted data and assessed study quality using an adapted version of the Risk of Bias (RoB) tool (MacIntyre et al., 2022), focusing on the domains of risk of bias, inconsistency, indirectness, imprecision, and publication bias. In accordance with the assessment protocol, each criterion was classified as presenting a low, high, or unclear risk of bias. An overall quality score was then calculated for each study by dividing the number of criteria rated as low risk by the total number of criteria assessed. Studies with scores between 0.86 and 1.00 were classified as having a low risk of bias; scores between 0.60 and 0.85 as having a moderate-to-low risk of bias; scores between 0.40 and 0.59 as having a moderate-to-high risk of bias; and scores between 0.00 and 0.39 as having a high risk of bias. Additionally, the Transparency of Methods (TOM; Zogmaister et al., 2024) was used to assess the methodological rigour and reproducibility of each study. Researchers have been instructed to categorise the checklist criteria as present (1), absent (0) or not relevant (9). Following, the ratio between the number of reported features (i.e., those categorised as "1" = present) and the number of relevant features (i.e., those categorised as "1" = present or "0" = absent, i.e., all items except the irrelevant ones) was calculated. This score indicates the proportion of features reported transparently and ranges from 0 (no method transparency) to 1 (full transparency). To facilitate interpretation, transparency scores were categorised into four levels. Scores between 0.80 and 1.00 were considered indicative of high transparency; scores between 0.60 and 0.79, of moderate-to-high transparency; scores between 0.40 and 0.59, of moderate-to-low transparency; and scores below 0.40, of low transparency.

3.3. Data synthesis

Given substantial heterogeneity across studies in experimental paradigms, pain-induction methods, outcome measures, and operationalisations of body ownership, a quantitative meta-analysis was deemed inappropriate.

Instead, we conducted a structured qualitative synthesis to identify patterns of convergence and divergence across studies. Specifically, studies were grouped according to key methodological dimensions: (i) type of pain induction (e.g., thermal, mechanical, electrical, laser), (ii) type of pain outcome (e.g., pain intensity, unpleasantness, threshold), (iii) type of ownership measure (e.g., questionnaire-based measures, proprioceptive drift), and (iv) experimental contrast (e.g., effect of RHI on pain perception; effect of pain on ownership).

Within each grouping, we examined the direction and consistency of reported effects, as well as the extent to which findings converged across studies with similar methodological characteristics. This approach allowed us to assess whether inconsistencies in the literature could be attributed to systematic differences in study design and measurement.

Additionally, to explore the relationship between methodological quality and transparency, we examined the association between Risk of Bias (RoB) and Transparency of Methods (TOM) scores across studies. This analysis was treated as exploratory.

4. Results

4.1. Literature search

Systematic searches of the published and grey literature yielded 542 records. After removing duplicates, 509 records remained. These records were then screened for title/abstract, where 40 articles were kept. After this first screening session, Cohen's Kappa was 0.7 (95% CI = 0.58–0.82), and the mean agreement between screeners was 0.96.

We then proceeded to the full-text screening and data extraction after successfully retrieving all the articles included so far. The subsequent screening phase yielded the inclusion of 30 papers, ultimately included in the review and integrated into the data extraction process. Across both screening and data extraction phases, the inter-rater Cohen's Kappa was 0.44 (95%CI = 0.11 – 0.77), and the mean agreement between screeners was 0.82. Following, Fig. 1, we report the PRISMA flowchart describing the different steps of the screening process.

4.2. Study characteristics

All the works included have been published between 2009 and 2025, with the highest number of publications (5) in 2022. As shown in Fig. 2, the trend is similar across time, with no papers in 2010, 2021, and 2023.

The total number of participants across all studies was 1180, with an average of 41 per study. Participants' demographic characteristics, including age, were reported as mean values (83%) or ranges (17%). On average, participants were 24.7 years old (SD = 3.70), with a total age range of 18 to 65 years. Furthermore, the proportion of participants who were women was slightly higher, averaging 69% across the studies considered.

Most of the papers included in our work tested multiple hypotheses using different experiments, including multiple studies in a single publication. In general, the relationship between pain sensation and RHI was investigated in two different ways. As for the first one, 79% (n = 23) of papers used a classic illusion induction paradigm, stroking participants' hands with a brush and then administering nociceptive stimuli to assess the analgesic effect. On the other hand, 26.7% (n = 8) of studies used a pain stimulus to induce the RHI effect on participants. Only two studies included in our review had different experiments examining both relationships (Cordier et al., 2020; Della Longa et al., 2022).

In general, around half of the studies (n = 15, 48.38%) used heat-related stimuli to investigate the association between RHI and pain, followed by pressure (n = 10, 32.25%), electrical (n = 4, 12.92%), and visual pain sources (n = 2, 6.45%). Only one article used both pressure and heat as sources of pain in its experiment (Choi et al., 2022). Following, Table 2, we highlight the association for each group of works between the pain source and the specific methods used.

Across studies evaluating the effect of RHI on pain, exposure time to the nociceptive stimulus was reported in around 52%(n = 12) of cases and, on average, lasted 20.27 s. Conversely, studies evaluating the effect of pain on RHI reported more frequent nociceptive time exposure (n = 6, 75%) with an average duration of 86.4 s.

Concerning pain evaluation methods, most of the studies (n = 13, 59,09%) applied subjective pain outcomes (e.g., visual analog scale, verbal rating scale, and numerical rating scales), followed by Quantitative sensory testing (QST) (e.g., button pressure paradigms, and finger withdrawal) (n = 6, 27.27%), combinations of this two methods (n = 1, 4.54%), and, in smaller amount of cases, the use of specific assessment techniques like acupuncture sensory outcomes (n = 1, 4.54%) (e.g., Massachusetts General Hospital Acupuncture Sensation Scale, Korean version) and skin conductance responses (n = 1, 4.54%). Participants' RHI embodiment was evaluated via proprioceptive and nociceptive drift, embodiment questionnaires, and intensity answers to pain (e.g., visual analogue scale for pain intensity, and delay in mechanical button pressure) (Capelari et al., 2009; Kammers et al., 2011; Botvinick and Cohen, 1998; Cordier et al., 2020; Della Longa et al., 2022; Tanaka et al., 2022; Coppi et al., 2024; Coppi et al., 2025). Besides the evaluation method, pain outcomes varied across studies, with five works measuring more than one type of pain (Höfle et al., 2012; Vandenbroucke et al., 2013; Fang et al., 2019; Ho et al., 2022; Mosch et al., 2025). The most commonly used outcome variables were pain intensity (n = 11, 40.74%) and thresholds (n = 9, 33.33%), followed by unpleasantness (n = 5, 18.51%) and sensitivity (n = 2, 7.40%). Only in one case (Pamplona et al., 2024) was pain measured using skin conductance as the outcome measure.

The effect of the Rubber Hand Illusion on pain perception was examined in 22 studies comprising 29 experiments and 693 participants, as some papers reported multiple studies. Experimental studies focused

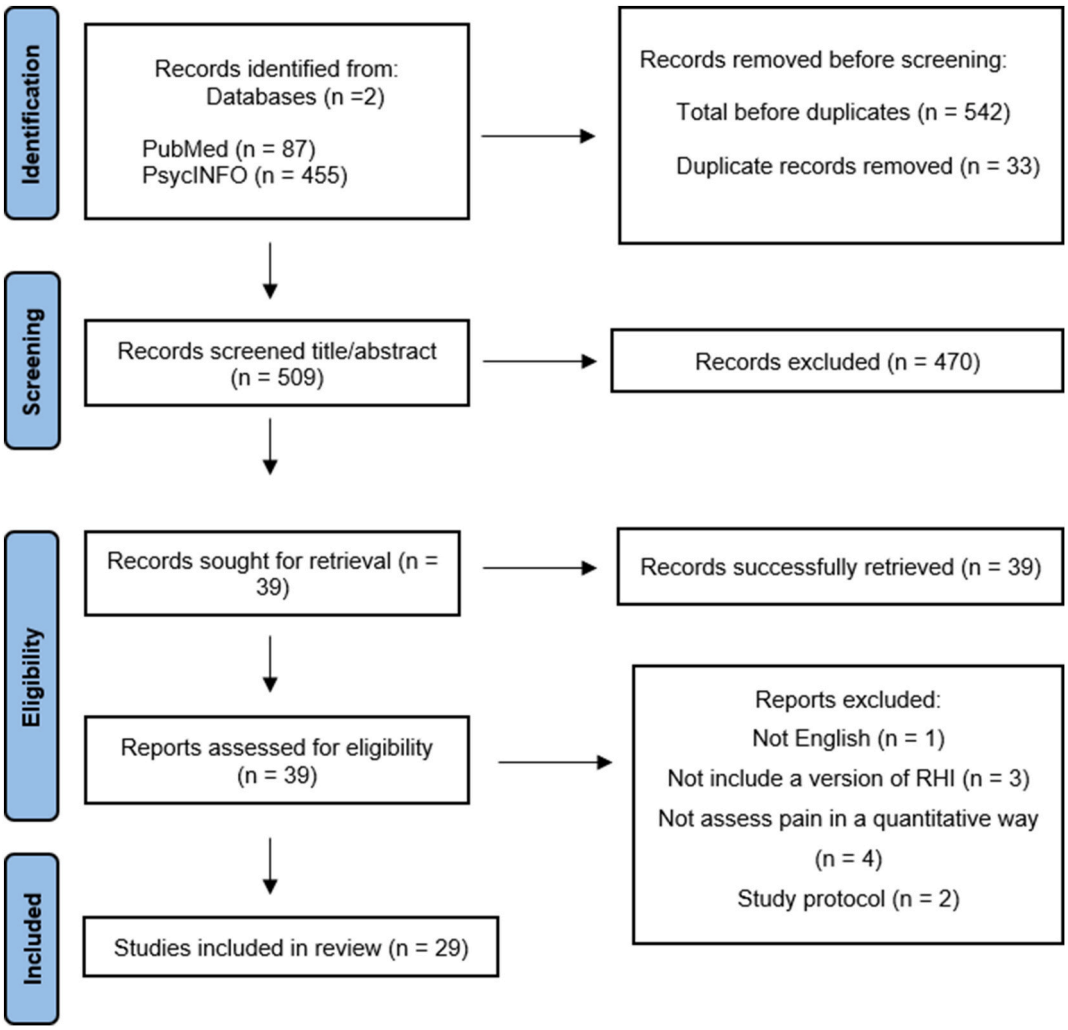


Fig. 1. PRISMA flowchart containing the number of included and excluded papers of the meta-analysis.

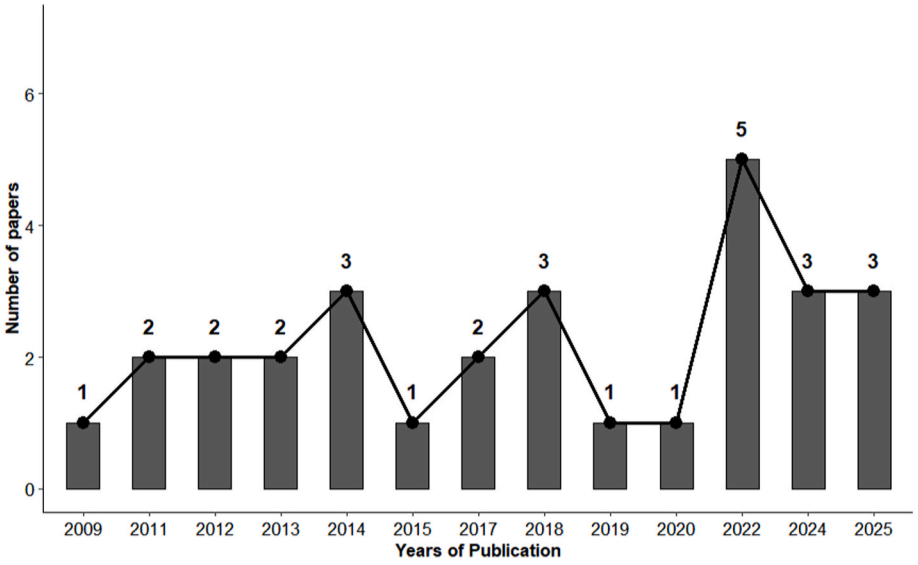


Fig. 2. Number of papers published per year.

on how painful stimulation can elicit the RHI included 8 studies, comprising 13 studies and 542 participants.

In both groups of studies, the RH embodiment relied predominantly on self-reported questionnaires. Most of the studies (n = 19, 63%)

Table 2
Pain source and specific method occurrences used for nociceptive stimuli across the two groups of papers.

RHI effect on pain	Heat	Thermode (7); Laser (1); Probe (1); Heat (1)
	Pressure	Acupuncture needles (2); Cold pressor (2); Mechanical pressor (2); Pinprick (1); Pinwheel (1)
	Electrical skin stimuli	Electrical stimulation pad (4)
	Visual	Video (1)
Pain effect on RHI induction	Heat	Laser (2); Thermode (1); Probe (1); Temperature change (1).
	Pressure	Pinprick (1); Pinwheel (1).
	Visual	Video (1)

employed, or adapted, assessment tool based on the work of Botvinick and Cohen in 1998 (e.g., Fang et al., 2019; Giummara et al., 2015; Nierula et al., 2017), while others used validated alternatives such as the one proposed by Longo et al. (2009) or Ho et al. (2022) as well as Coleshill et al. (2017) (e.g., Höfle et al., 2012; Osumi et al., 2014; Ho et al., 2022), and the Rubber Hand Illusion Perception Scale (Choi et al., 2022). Among implicit measures, proprioceptive drift was the most used method, together with other questionnaire-based assessments (e.g., Capelari et al., 2009; Hegedüs et al., 2014) and nociceptive drift tasks (Coppi et al., 2024; Coppi et al., 2025). One study (Gong et al., 2022) used body-location drift combined with Sense of Ownership (SoO) ratings, while Kammers et al. (2011) used perceptual relocation of the finger as an implicit ownership index. Methodological diversity was particularly evident in studies employing multiple converging measures. For example, Della Longa et al. (2022) combined subjective embodiment ratings, proprioceptive drift, and questionnaire-based ownership assessments.

A table presenting information on the type of RHI-pain relationship investigated, the pain source, the presence of a placebo, and a brief summary of the results obtained for each paper is shown in Table 3 below.

Before proceeding with the qualitative analysis of core differences between studies characteristics, we decided to run a series of exploratory meta-analyses to investigate the association of RHI and pain in three distinct scenarios: (1) The Rubber hand Illusion modulating pain, (2) The pain modulating sense of ownership over a Rubber Hand: synchronous v. asynchronous, and (3) the pain modulating sense of ownership over a Rubber Hand: painless-touch v. painful-touch. Across all meta-analyses, substantial between-study heterogeneity was consistently observed, reflecting important methodological and conceptual differences. Consequently, the pooled effect estimates reported below should be interpreted with considerable caution and viewed as descriptive summaries of a highly heterogeneous literature rather than as robust estimates of a common underlying effect.

While examining the extracted effects of RHI on pain modulation quantitative synthesis initially suggested a small positive effect of RH induction on pain-related outcomes (Hedges' d = 0.34, 95% CI [0.01, 0.66], $p = .04$). However, substantial heterogeneity was observed across studies ($I^2 = 90.71\%$), and this effect was no longer significant when methodological and experimental moderators were considered (Hedges' d = −0.08, 95% CI [−1.08, 0.93], $p = .88$). Moderator analyses indicated that the observed effects varied according to the type of pain outcome assessed, with significant effects emerging primarily for self-reported pain ratings (Hedges' d = 1.69, 95% CI [1.10, 2.29], $p < .001$). Overall, publication bias analyses did not indicate substantial concerns, as supported by non-significant Egger's test results ($p = .079$) and trim-and-fill analyses that did not meaningfully alter the estimated effect.

To investigate the effects of pain on RH induction, we conducted two separate analyses. The first one, concentrated on pain modulating sense of ownership over a Rubber Hand in synchronous v. asynchronous conditions, the results suggested a moderate effect of pain on RHI-induced body ownership when comparing conditions (Hedges' d = −0.67, 95% CI [−1.32, −0.02], $p = .04$). However, substantial heterogeneity was observed across studies ($I^2 = 94.61\%$), limiting the interpretability of the pooled effect. Given the relatively small number of eligible studies, no moderator analyses were conducted. Publication bias analyses did not reveal substantial concerns, as supported by a non-significant Egger's test ($p = .629$) and trim-and-fill results that did not meaningfully alter the overall findings. The second analysis focused on studies that compared synchronous touch and synchronous painful stimulation. The results did not support a reliable effect of painful versus non-painful synchronous stimulation on RHI-induced body ownership (Hedges' d = 0.16, 95% CI [−0.22, 0.54], $p = .41$). Considerable heterogeneity was observed across studies ($I^2 = 86.44\%$), indicating substantial variability in the reported effects. Sensitivity analyses showed that the pooled estimate remained stable after adjusting for potentially missing studies, although Egger's test suggested possible asymmetry in the funnel plot ($p = .024$), warranting cautious interpretation of the findings.

For each meta-analysis, detailed analyses and results can be found in Supplemental Materials 1, 2, and 3, respectively.

4.3. Quality assessment and correlation between risk of bias and Transparency of Methods

We evaluated the quality of papers using the Risk of Bias (RoB) (MacIntyre et al., 2022) and Transparency of Methods (TOM; Zogmaister et al., 2024) tools. Across all papers, we identified high to moderate levels of transparency ($M_{TOM} = 0.62$) and low to moderate levels of factors leading to publication bias ($M_{RoB} = 0.65$). The evaluations of Risk of Bias and Transparency of Methods evaluations correlate at a statistically significant level ($S = 1448.1$, $p < .001$; $\rho = 0.60$), with a ρ suggesting a strong correlation between the two constructs, as shown in Fig. 3. This result underlined an inverse relationship between method transparency and risk of bias during publication. Our result stands as proof of the role of implementing transparent, valid, and reliable practices in mitigating publication bias. In general, the studies included in the systematic review exhibit good quality in terms of randomisation, control of confounding variables, reporting of outcomes, and the percentage of missing data during data collection (below 15%).

4.4. Methodological differences across studies

To facilitate the synthesis and interpretation of the heterogeneous evidence identified in this review, the qualitative findings are organised according to the primary methodological focus of the included studies. Specifically, studies were grouped based on whether they investigated the influence of the Rubber Hand Illusion (RHI) on pain perception and modulation, or conversely, examined the role of painful and nociceptive stimuli in the induction and modulation of the RHI. This methodological distinction provides a structured framework for comparing findings across studies and for highlighting the bidirectional relationship between pain processing and body ownership. Detailed information for each study can be found in the table presented in Supplemental Material 4.

4.4.1. Qualitative analysis - effects of RHI on pain

The examination of the Rubber Hand Illusion in pain perception took different trajectories, including the use of an injured or modified RH, the integration of immersive technologies into the methodological framework, and the adoption of placebo control conditions.

The direction of pain and the effect of RHI tended to vary across studies but followed consistent patterns based on the characteristics of the embodied limb. Studies employing healthy body representations tended to report analgesic effects of the RHI in synchronous touching conditions (Hegedüs et al., 2014; Siedlecka et al., 2014; Nierula et al., 2017; Fang et al., 2019; Cordier et al., 2020; Choi et al., 2022; Ceylan

Table 3
Studies' key characteristics, including the type of RHI-pain relationship investigated, the pain source, the presence of a placebo, and a brief summary of the results.

In-text citation	Type of effect studied	Pain source	Placebo present?	Brief summary of results
Bauer et al. (2018)	Effect of RHI on pain	Pressure	No	RHI induction was associated with increased pain sensitivity, reflected by lower pain thresholds, whereas control conditions produced no significant changes in pain sensitivity.
Botvinick and Cohen, 1998	RHI induction with pain	Visual	NA	Higher pain localisation and perception abilities were associated with stronger RHI embodiment, except in the real-hand-only and rubber-hand-only conditions.
Capelari et al. (2009)	RHI induction with pain	Pressure	NA	The induction evaluated via the questionnaire was the same across conditions, whereas the proprioceptive drift evaluation was stronger with tactile-painful stimuli.
Ceylan et al. (2025)	Effect of RHI on pain	Pressure	No	Applying mechanical pressure during RHI increased pain thresholds, indicating an analgesic effect; however, this effect did not persist after the illusion ended.
Chang et al. (2013)	Effect of RHI on pain	Pressure	No	Across two experiments, RHI induction did not affect pain sensitivity, regardless of whether the needle was synchronous or provided visual feedback.
Choi et al. (2022)	Effect of RHI on pain	Mixed	No	Acupuncture-induced RHI increased pain tolerance, suggesting an analgesic effect, while EEG activity remained unchanged.
Coleshill et al. (2017)	Effect of RHI on pain	Heat	Yes	The researchers discovered a reduction in pain sensitivity (analgesic effect) only when the placebo (fake) treatment was applied to the RHI, and not when the RHI was induced.
Coppi et al. (2024)	RHI induction with pain	Heat	NA	Pain induced the RHI only with synchronous, spatially congruent stimulation; spatial incongruence abolished the illusion, whereas painful and non-painful stimulation produced similar embodiment.
Cordier et al. (2020)	Effect of RHI on pain and RHI induction with pain	Heat	NA	Via thermal stimuli, the authors managed to induce embodiment with both a human rubber hand and a non-human object
Della Longa et al. (2022)	Effect of RHI on pain and RHI induction with pain	Pressure	NA	Authors successfully induced the RHI both with pleasant and unpleasant stimuli. The proprioceptive drift was stronger in the pleasant stimulation.
Fang et al. (2019)	Effect of RHI on pain	Heat	No	RHI induction reduced both pain sensitivity and pain unpleasantness, with stronger embodiment associated with greater analgesic effects.
Giummara et al., 2015	Effect of RHI on pain	Pressure	No	RHI produced analgesia under normal conditions but induced hyperalgesia when a wounded rubber hand was combined with capsaicin-induced sensitisation.
Gong et al. (2022)	Effect of RHI on pain	Electrical skin stimuli	No	RHI did not significantly alter pain thresholds or sensitivity in either human or non-human hand conditions, although EEG findings suggested differences in pain-related processing.
Hegedüs et al. (2014)	Effect of RHI on pain	Heat	No	Higher pain thresholds were found in the synchronous condition, but not compared to the own-hand condition, suggesting no specific analgesic effect of the RHI.
Ho et al. (2022)	Effect of RHI on pain	Heat	Yes	Placebos reduced pain sensitivity across all reality settings, while embodiment intensity was unrelated to analgesia. The lack of an asynchronous control prevented assessment of RHI-specific effects.
Höfle et al. (2012)	Effect of RHI on pain	Electrical skin stimuli	No	Congruent visual feedback increased perceived pain, with needle stimuli rated as more painful than Q-tip stimuli.
Kammers et al. (2011)	RHI induction with pain	Heat	NA	The RHI was induced across all temperature conditions, with the strongest effect reported during medium-cold and warm stimulation.
Knobel et al. (2024)	Effect of RHI on pain	Pressure	No	Research found no analgesic or hyperalgesic effect of the VR embodiment on pain sensitivity. In this case, the embodiment was not just the hand, but the whole body.
Mohan et al. (2012)	Effect of RHI on pain	Heat	No	Across two experiments, RHI induction did not significantly affect pain sensitivity or pain thresholds, providing no evidence of either analgesic or hyperalgesic effects.
Mosch et al. (2025)	Effect of RHI on pain	Heat	No	From their results, the authors identified a pain-reducing (analgesic) effect of the RHI across continuous pain ratings.
Nierula et al. (2017)	Effect of RHI on pain	Heat	No	Pain reduction was greater in the colocated than in the 30 cm distance condition, despite no synchronous versus asynchronous differences within either condition.
Osumi et al. (2014)	Effect of RHI on pain	Heat	No	No analgesic effect of the illusion was found while comparing sync and async within each condition. Authors found that, under the RH sync condition, only the injured RH manifested a hyperalgesic effect
Pamplona et al. (2024)	Effect of RHI on pain	Visual	No	Reduced visibility was associated with greater PMC and FBA activation, suggesting higher perceived pain.
Siedlecka et al. (2014)	Effect of RHI on pain	Pressure	No	The authors conclude that RHI induction (without visual feedback) has an analgesic effect.
Siedlecka et al. (2018)	Effect of RHI on pain	Electrical skin stimuli	No	The illusion had a hyperalgesic effect on the painful stimuli.
Tanaka et al. (2022)	RHI induction with pain	Heat	NA	Illusion strength did not differ between normal and injured rubber hands, and fear-inducing verbal suggestions did not affect the embodiment of the injured rubber hand.
Valenzuela-Moguillansky et al. (2011)	Effect of RHI on pain	Heat	No	In Experiment 1, pain reduction was observed only at 46°C, but not at 48°C. Experiment 2 replicated this effect with the rubber hand, whereas no analgesic effect was found with the rubber foot illusion.
Vandenbroucke et al. (2013)	Effect of RHI on pain	Electrical skin stimuli	No	The rubber hand did not modulate pain, but individuals reporting vicarious pain experiences showed more vicarious pain errors, particularly when hypervigilance to pain was low.
Coppi et al. (2025)	RHI induction with pain	Heat	NA	The RHI was induced by both painful and non-painful stimuli, but differences in illusion strength were inconsistent across experiments.

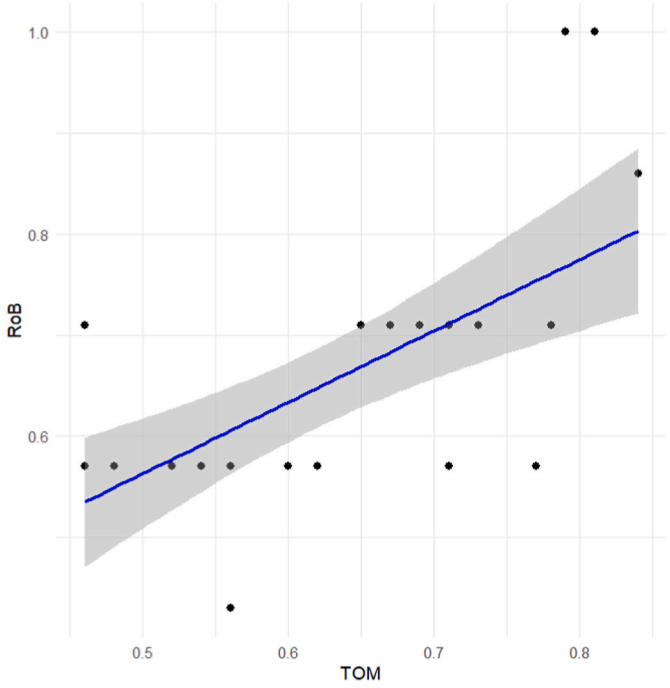


Fig. 3. Correlation between Risk of Bias assessment and Transparency of Methods scale.

et al., 2025; Mosch et al., 2025). An interesting analgesic effect was obtained by Cordier and colleagues (2020). In their work, the researchers induced the illusion solely through visual nociceptive stimuli. The embodiment comprised two types of objects: a healthy rubber hand and a glass ball. From their results, the authors observed an analgesic effect, reducing pain sensitivity, in both the RH and the non-human object during synchronous inductions. Surprisingly, the analgesic effect was stronger in the glass ball condition than in the rubber hand condition ($p = .001$), suggesting that pain attenuation may be driven by multisensory ownership processes rather than the specifically human appearance of the embodied object. However, the order of the two experiments (rubber hand or glass ball) was not counterbalanced across participants, so the effect in the glass ball condition might be a cumulative effect between the two conditions (Cordier et al., 2020). In contrast, four works involving injured or sensitised RH (Osumi et al., 2014; Giummara et al., 2015, experiment 2; Bauer et al., 2018; Siedlecka et al., 2018) indicate that the embodiment of a visually threatening or damaged body representation tends to increase pain sensitivity (hyperalgesia). Altogether, the results of analgesia and hyperalgesia effects highlight the role of RH characteristics in determining the influence on pain. On the other hand, while aforementioned research found empirical effects of RH on pain modulation, others (eight works) could not find any relationship (Valenzuela-Moguillansky et al., 2011; Höfle et al., 2012; Mohan et al., 2012; Chang et al., 2013; Della Longa et al., 2022; Gong et al., 2022; Knobel et al., 2024).

In addition to hand characteristics, seven studies explored other factors influencing the effect. Among these, stimulus expectation was investigated by varying visibility, congruence, and verbal cues. Only three studies explored the visibility aspects in pain reduction. In one case (Bauer et al., 2018), the lack of visual feedback led to the disappearance of hyperalgesia, whereas others (Chang et al., 2013) showed no effect of visual feedback on pain modulation. Similarly, Pamplona and colleagues (2024) wanted to explore the role of visibility in changes in pain sensitivity during RHI. The authors, using modified glasses, adjust the visibility of nociceptive stimuli on the hand across three conditions: low, medium, and high. From the fMRI results, the response in bilateral body-related cortical regions (premotor cortex and fusiform body area) was higher in low- and intermediate-visibility conditions than in high-visibility conditions. The authors conclude that perceived pain is higher in low-visibility conditions than in high-visibility conditions. In general, visual congruency seems to increase the painfulness of the stimuli, showing that visually congruent painful cues increased unpleasantness ratings even when the delivered stimulus was non-painful (needle v. Q-tip), highlighting the contribution of top-down expectations (Höfle et al., 2012). Another type of expectation arises from the individual's knowledge of the stimuli to be assessed. In the work of Choi and colleagues (2022), the authors found that prior information about acupuncture stimulation increased individuals' pain tolerance, highlighting the roles of beliefs and visual information in interactions with sensory processing. In conclusion, two additional studies reported evidence of this phenomenon. Coleshill et al. (2017) found reductions in pain sensitivity only when a visible placebo analgesic was applied to the rubber hand, whereas ownership induction alone did not produce significant analgesia. Similarly, Ho et al. (2022) observed comparable placebo-induced reductions in pain sensitivity across physical, virtual, and augmented reality conditions, with embodiment strength failing to predict the magnitude of analgesia. Taken together, these three studies report divergent results on pain modulation but highlight the role of pain's multisensory characteristics rather than just its physical ones.

Another methodological moderator that varied across the papers was the adoption of technological devices that could place participants in different settings, such as augmented or virtual realities. Five studies incorporated this manipulation into their experimental designs, thereby enabling confirmation of RH embodiment in virtual settings. A notable example is the study by Knobel et al. (2024), which, even without reporting analgesic or hyperalgesic effects after embodiment, provided empirical evidence of whole-body embodiment in a virtual setting. Overall, across studies, the direction of pain modulation is not clear, with some works acknowledging analgesic effect across settings (i.e., virtual reality, augmented reality and physical reality), only in the contingency of placebo conditions, such as protective gloves (Ho et al., 2022), or in the case of proximity in spatial co-location between virtual and real hand (Nierula et al., 2017).

4.4.2. *Qualitative analysis - Induction of RHI with painful stimuli*

Classically, the RHI paradigm involves the embodiment of an external object using synchronous visuotactile stimuli. The RH ownership has usually been studied using non-painful stimuli. In the current review work, we identified eight studies that used nociceptive stimuli to induce RHI (Capelari et al., 2009; Kammers et al., 2011; Botvinick and Cohen, 1998; Cordier et al., 2020; Della Longa et al., 2022; Tanaka et al., 2022; Coppi et al., 2024; Coppi et al., 2025). A notable example of these works is the one proposed by the research teams of Coppi et al. (2024, 2025), who developed a Nociceptive Rubber Hand Illusion (N-RHI) paradigm using laser-evoked stimulation that selectively targets C and Aδ fibres while minimising tactile co-stimulation. The use of purely nociceptive stimulation yields new insights into embodiment research, with participants reporting ownership experiences despite the absence of conventional tactile inputs. Furthermore, authors highlighted that disrupting the spatial congruence between the stimulated body part and the RH made the illusion disappear (Coppi et al., 2024), highlighting the role of co-location in successfully maintaining the illusion and its characteristics in line with other works included in the present review (Nierula et al., 2017). In general, the works of Coppi and colleagues further expand the literature on the difficulty of unravelling the intertwined contributions of nociception and touch in generating the RHI. By manipulating the spatial and temporal correspondence between the stimulated body and the RH, these studies isolated nociceptive signals from tactile cues more effectively than the other investigations.

Concurrently, to account for the tactile characteristics of stimuli, five studies examined the strength of embodiment as a function of touch valence (pleasant v. unpleasant) and intensity. The nature of the touch

seems to have differential power in eliciting the strength of the RHI, with embodiment emerging during both painful and non-painful stimulation. The effect seems to follow different patterns: some works highlight stronger effects during the first type of stimulation (Capelari et al., 2009; Coppi et al., 2024; experiment 2), while others suggest stronger embodiment with the latter (Della Longa et al., 2022; Coppi et al., 2024; experiment 1). Furthermore, intensity characteristics seem to play a key role, with stronger stimuli more likely to elicit RH embodiment than weaker ones. In particular, cold stimuli elicited a stronger sense of ownership than warm ones (Kammer et al., 2011).

Beyond direct nociceptive stimulation, one study examined whether pain-related representations contribute more broadly to bodily self-consciousness. The results showed that participants with a higher ability to localise and feel pain when watching a video are more likely to exhibit stronger embodiment during RHI than those with lower scores. In particular, the embodiment encompassed all the types of induction stimuli provided (Botvinick and Cohen, 1998). Evidence from this area suggests that pain may influence ownership not only through sensory input but also through higher-order representations of bodily threat and vulnerability.

In conclusion, all studies in the current group used acute pain conditions to elicit embodiment, not chronic ones. The closest work investigating the embodiment of an injured RH is that of Tanaka and colleagues (2022), who tested ownership alongside the presentation of fear-related verbal suggestions. Neither the visual appearance of injury nor the induced expectation of threat significantly altered the strength of the illusion, suggesting that pain-related contextual information alone may be insufficient to modify ownership experiences. Since no study directly compared chronic pain populations with healthy controls in RHI inductions, it remains unclear whether the mechanisms linking nociception and embodiment observed in laboratory settings generalise to chronic pain conditions.

5. Discussion and conclusions

The current systematic review sought to explore the literature examining the relationship between RHI and pain. To investigate the types of pain induction and outcome, the type of ownership measure, and the experimental contrast, we collected a sample of 30 studies published between 2009 and 2025. The wide methodological heterogeneity across studies led us not to adopt a meta-analitical approach, and rather to summarise the results to identify gaps and discrepancies in the literature.

Overall, the studies reviewed here suggest a bidirectional relationship between body ownership and pain. Some studies investigated the effect of the RHI on pain sensations, whereas others investigated whether the RHI can be induced by painful or nociceptive stimulation. Taken together, these two groups of studies do not allow us to disentangle a simple causal direction between body ownership and pain. However, considering the complex nature of pain, this might not necessarily be a limitation. Pain involves at least sensory salience, namely the degree to which a stimulus is distinguished from others in terms of intensity, location, duration, and spatial and temporal frequency; affect, namely the pleasantness-unpleasantness dimension of sensory experience; and motivational dominance, namely the degree to which a sensation determines behaviour, reallocates attentional resources, and orients decision making (Casey and Lorenz, 2000). Moreover, given the brain's parallel, non-linear organisation, the relationship between pain and body ownership may not require a direct, linear causal interpretation. A more realistic description may instead refer to a set of correlative, reciprocal interdependencies among nociceptive, affective, motivational, cognitive, and multisensory processes.

In general, results suggest that when the rubber hand is presented as healthy and multisensory stimulation is congruent, the effect on pain is tendentially analgesic (Hegedüs et al., 2014; Siedlecka et al., 2014; Nierula et al., 2017; Fang et al., 2019; Cordier et al., 2020; Choi et al., 2022; Ceylan et al., 2025; Mosch et al., 2025). Conversely, when the rubber hand is presented as damaged, ill, or sensitised, the effect on pain tends to be hyperalgesic (Osumi et al., 2014; Giummara et al., 2015, experiment 2; Bauer et al., 2018; Siedlecka et al., 2018). However, null findings are also common (Valenzuela-Moguillansky et al., 2011; Höfle et al., 2012; Mohan et al., 2012; Chang et al., 2013; Della Longa et al., 2022; Gong et al., 2022; Knobel et al., 2024), suggesting that embodiment alone is insufficient to reliably modulate pain across all paradigms. This pattern indicates that the relevant factor is not only whether the rubber hand is embodied, but also the kind of body representation it embodies. A healthy embodied limb may support a reduction of pain, whereas an injured or threatening embodied limb may increase pain sensitivity or unpleasantness.

This aspect may be particularly relevant to studies examining how manipulations of bodily appearance affect pain (see the articles in Table 3 and Table in SM4 for more details, classified under "Type of effect studied" as "Effect of RHI on pain"; see also Preston and Newport, 2011; Stanton et al., 2018; Matamala-Gomez et al., 2019 for clinical studies). As suggested by Preston and Newport (2011), "manipulating the appearance of those body parts might be a useful tool in the reduction of pain" (p. 2314). Research on chronic neuropathic pain conditions, including spinal cord injury, complex regional pain syndrome, and phantom limb pain, suggests that these conditions are associated with distorted body representations (for reviews, see Maggio et al., 2025; Matamala-Gomez et al., 2019; Donegan et al., 2022). Manipulating bodily appearance may, to some extent, temporarily restore these representations and thereby provide pain relief. This is the classical mechanism proposed to underlie the mirror-box method for phantom limb pain (Foell et al., 2014).

However, the findings reviewed in the present work also indicate that manipulating bodily appearance may increase pain sensitivity. These observations might make it tempting to hypothesise a linear causal relationship among these phenomena: bodily appearance influences body representation, which, in turn, affects pain perception. Nevertheless, these relationships are likely to be bidirectional (Beccherle and Scandola, 2025). Moreover, pain perception is shaped by multiple interacting factors, including prior beliefs and expectations (Koban et al., 2019), motivational and reward-related processes (Navratilova and Porreca, 2014), physiological sensitisation of nociceptive pathways (Woolf, 2011), placebo and nocebo mechanisms (Wager and Atlas, 2015; Zunhammer et al., 2021), and individual differences in responsiveness to suggestion, including limited responsiveness and resistance to suggestion (Desmarteaux et al., 2021). Thus, even when an association between bodily appearance and pain is observed, the numerous variables that may moderate or mediate this relationship should be acknowledged, making it difficult to establish a complete account of the underlying mechanisms.

Nevertheless, the finding that a healthy embodied limb may support a reduction of pain, whereas an injured or threatening embodied limb may increase pain sensitivity or unpleasantness, is particularly relevant when considered alongside evidence that the vision of one's own real body can have an analgesic effect (Longo et al., 2009).

This result raises the question of why some RHI studies did not induce analgesia. One possible explanation is that pain is a complex, subjective experience, and its modulation may require larger sample sizes to be reliably detected, especially when individual variability in pain sensitivity, affective state, expectations, and attentional orientation is high. A second possibility is that, in some studies, the rubber hand was not sufficiently embodied to reproduce the analgesic effect observed when participants viewed their own hand. Indeed, a relevant finding by Longo and colleagues (2009) was that pain was reduced when participants observed their own hand, but not when they observed another person's hand. Notably, in an fMRI study, participants observed videos of painful and tactile stimuli applied to an adult hand, a baby hand, a puppy paw, and a robotic hand. The right supramarginal gyrus showed increased activity for painful stimuli applied to adult and baby hands,

while the anterior cingulate cortex was more sensitive to painful stimuli applied to the baby hand, likely due to stronger psychological closeness (Ionta et al., 2020).

These findings align with an EEG study where participants viewed photos of a stranger or a close friend, followed by a photo of a hand in a painful or happy situation. Observing a close friend's photo followed by a painful stimulus resulted in a smaller N110 amplitude and a larger late positive potential (Wang et al., 2016).

Additionally, in an fMRI study, synchronous visuo-tactile stimulation led participants to perceive virtual bodies as part of their own. This was accompanied by increased functional connectivity between occipital, sensorimotor, and default mode brain regions (Pamplona et al., 2025).

Therefore, the degree of embodiment of the rubber hand and its psychological closeness may represent an important source of individual variability. Some aspects of this variability may not be fully captured by explicit questionnaires and may therefore act as a confounding factor in these experimental paradigms.

Studies focusing on the induction of the RHI via painful stimulation further clarify this issue. They showed that the RHI can be evoked not only by neutral touch, but also by painful or nociceptive stimulation, including pinprick (Capelari et al., 2009), thermal stimulation (Cordier et al., 2020), and laser-evoked nociceptive input targeting C and Aδ fibres (Coppi et al., 2024, Coppi et al., 2025). Findings from these latter studies are particularly relevant because they suggest that nociceptive signals can be integrated into multisensory body-ownership mechanisms when spatially and temporally congruent with visual information. Moreover, laser-evoked stimulation allows a more selective investigation of nociceptive input, independent of other somatosensory signals. This aspect could not be fully disambiguated in studies using pinprick or other forms of stimulation that also involve non-nociceptive components. These results, therefore, represent a further step in the study of nociception's contribution to the representation of the body. They may also be consistent with the proposal that nociception can serve as a source of surrogate sensory information that supports body representation in clinical conditions in which tactile and proprioceptive information are missing or impaired (Beccherle and Scandola, 2025).

However, pain sensation is more complex than nociception. It includes pain intensity, stimulus valence, contextual cues, affective components, and motivational aspects, which do not act uniformly (Casey and Lorenz, 2000). Similarly, body representations are more than somatosensory representations, because they also include affective, cognitive, and semantic components (Cash, 2004; Longo, 2016). Therefore, a more comprehensive account should consider both pain and body representation as multidimensional constructs. Such an account should include subjective, affective, motivational, and cognitive variables and explain why the same multisensory manipulation can produce analgesia, hyperalgesia, or no effect depending on the experimental context and individual characteristics.

A further element of interest is represented by studies using vicarious pain rather than direct pain. For example, Fusaro et al. (2016) compared subjective reactivity, including perceived pleasantness, intensity, and ownership, in response to vicarious painful, pleasant, and neutral stimulation administered in virtual reality. Painful stimulation consisted of a syringe prick, pleasant stimulation consisted of a caress, and neutral stimulation consisted of a ball touch. Interestingly, among the explicit subjective evaluations collected, the painful condition induced a stronger sense of ownership toward the virtual hand than the pleasant and neutral conditions. Convergent evidence comes from Pamplona et al. (2022), who observed that only when participants experienced ownership of a virtual hand did vicarious pain videos elicit lower activation in the premotor and anterior cingulate cortices. These findings suggest that pain-related visual information can interact with body ownership mechanisms even in the absence of direct nociceptive stimulation. Therefore, pain may influence body representation not only as a direct bodily signal but also as a visually mediated, affectively salient event attributed to an embodied body part.

Finally, most of the available evidence concerns the RHI. This is an important limitation because the hand is a special body part. It is the main tool through which we interact with the external world, and it is also one of the main tools used to explore our own bodies, other people's bodies, and objects. Therefore, studying the relationship between pain and body ownership through the hand does not necessarily allow generalisation to the rest of the body. Specific studies should investigate whether similar mechanisms apply to other body parts and to full-body representations. Some initial evidence suggests that this may be the case. For example, full-body illusions have been shown to reduce chronic pain in participants with mixed aetiology (Pamment and Aspell, 2017), and Pozeg et al. (2017) showed, in a sample of individuals with spinal cord injury, that neuropathic pain sensations were associated with mild analgesia during a full-body illusion task. These findings suggest that full-body illusions may also modulate pain sensations, but further research is required to clarify whether the mechanisms involved are the same as those observed in hand-ownership paradigms.

A related limitation concerns the population from which the reviewed evidence derives. All studies included in this review induced pain experimentally, in acute form, in healthy participants; no study assessed RHI-related effects in patients with an ongoing chronic pain condition. This distinction is unlikely to be trivial. Acute experimental pain reflects transient, bottom-up nociceptive signalling delivered to an otherwise intact somatosensory system, whereas chronic pain conditions such as phantom limb pain, complex regional pain syndrome, and neuropathic pain following spinal cord injury are characterised by central sensitisation and by stable, pre-existing distortions of body representation (Woolf, 2011; Matamala-Gomez et al., 2019; Maggio et al., 2025). In these populations, the baseline relationship between body ownership and pain is already altered before any experimental manipulation takes place. As a result, the analgesic or hyperalgesic effects of RHI-related paradigms reported here for acute pain in healthy participants cannot be assumed to generalise, either in direction or in magnitude, to chronic clinical pain. Preliminary evidence from full-body illusion studies in chronic pain samples (Pamment and Aspell, 2017; Pozeg et al., 2017) suggests that embodiment-based manipulations may still have analgesic potential in these populations, but this remains to be tested directly using the RHI paradigm. We therefore regard the near-complete absence of clinical samples as a substantial gap in the current evidence base, and recommend that future studies compare RHI-induced effects on pain directly between healthy participants undergoing acute experimental pain and patients with chronic pain conditions, within the same experimental design.

The role of expectations should also be considered. The study by Choi and colleagues (2022) showed that expectations can also affect pain in experimental contexts related to RHI. This is relevant because expectations have a well-established influence on pain perception (Fields, 2018) and can also affect the outcomes of chronic pain treatments (Cormier et al., 2016). These effects have been modelled within a predictive-coding framework. For example, Geuter et al. (2017) showed that anterior insula responses followed predictions derived from predictive coding, whereas posterior insula activity encoded stimulus intensity. This distinction is important because it suggests that pain is determined not only by nociceptive input but also by prior expectations and the precision attributed to sensory signals. Within this framework, congruent multisensory stimulation may increase the credibility of the embodied limb as part of the body, while expectations and contextual cues may determine whether this embodied representation is interpreted as safe, therapeutic, damaged, or threatening.

Placebo and nocebo effects may be relevant in these experiments. However, only a small number of studies have deliberately included a placebo condition to improve control over the experimental findings (Coleshill et al., 2017; Ho et al., 2022). Future experimental designs should more carefully account for these effects, as well as potential biases arising from demand characteristics, the Hawthorne effect, and other forms of participant reactivity.

The knowledge summarised in this paper may inform the development of future assessments and interventions. For example, accounting for the relationship between pain and body ownership could lead to a more precise and standardised classification of clinical conditions involving body-related processing. This, in turn, could improve the focus on cognitive neuroscience concepts (e.g., empathy and vicariousness) targeted by specific rehabilitation programs. In particular, using less visually shocking bandages and presenting the painful body area in a way that appears as normal and healthy as possible—at least visually—may help reduce perceived pain.

Taken together, these findings indicate that the relationship between body ownership and pain should not be reduced to a simple causal effect of embodiment on pain, or of pain on embodiment. Rather, the two constructs appear to interact through a set of multisensory, affective, motivational, and predictive mechanisms. Larger samples are needed to investigate this interaction more directly, taking into consideration not only nociception and body ownership, but also individual variables such as pain sensitivity, affective state, expectations, motivational relevance, and subjective embodiment. Moreover, future experimental paradigms should be designed to investigate the bidirectional relationship between RHI and pain without imposing a unidirectional causal interpretation, either from RHI to pain or from pain to RHI. A more informative approach would be to manipulate, within the same design, both the characteristics of the embodied body representation and the characteristics of the pain-related input, to assess how their congruence, valence, and predictive meaning jointly modulate both pain perception and body ownership.

CRediT authorship contribution statement

Marco Lezcano: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesca Santoni:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Michele Scandola:** Writing – original draft, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Open science

This systematic review and meta-analysis were preregistered on the Open Science Framework (OSF) prior to data extraction and analysis (https://osf.io/4vxs6/overview). All data included in the meta-analysis, along with the full analysis code necessary to reproduce the reported results, are publicly available on OSF (https://osf.io/db4cf/overview). These materials allow full transparency of the analytical procedures and facilitate reproducibility and secondary analyses.

Ethics approval

The article is a systematic review of the literature and does not involve any studies with human participants or animals conducted by the authors. Ethical approval was not required.

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On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix A. Supplementary data

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