Behavior Research Methods (2021) 53:2615–2630
https://doi.org/10.3758/s13428-021-01600-x

ORIGINAL MANUSCRIPT

The rubber hand illusion in children: What are we measuring?

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Accepted: 14 April 2021 / Published online: 21 May 2021

Abstract
The rubber hand illusion (RHI) is a much-studied bodily illusion that has been used in a wide number of populations to investigate the plasticity of the mental body representation. In adult participants, the wide adoption of the illusion has led to a proliferation of experimental variations of the illusion, and with that, considerable apparent inconsistencies in both empirical results and conceptual interpretations. In turn, this makes it challenging to integrate empirical findings and to identify what those findings together can tell us about the representation of the body in the brain. More recently, scientists have started applying the illusion to populations of children, in order to better understand how body representations develop in both typically developing children and in clinical populations. With this field now starting to expand, we believe it is both urgent and important to prevent unintended methodological variability from hindering the consistency of the paediatric literature as it has the adult literature. With this aim in mind, we review the 12 currently available paediatric RHI studies, and summarise their key methodological choices and conceptual definitions. We highlight a number of important discrepancies, particularly where seemingly equivalent analysis choices might significantly affect the interpretation of results, and make recommendations for future studies. We hope this will allow this important and emerging field to benefit from the synergy that results from multiple studies using convergent and consistent empirical methods.

Keywords Rubber hand illusion · Development · Childhood · Body representation

Introduction

The experience that we own a body seems at first glance straightforward. We do not generally lose our limbs or mistake them as belonging to someone else. When we close our eyes, we can imagine where our limbs are, and what our body looks like. We can usually move our body without much effort, and our body seems to be always just "present". This everyday sense of being localised within our body is generally called embodiment (Arzy et al., 2006).

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Over the last century, numerous patient studies have shown that when the neural mechanisms underlying these experiences are compromised, it can lead to very specific deficits in the experience of embodiment (Head & Holmes, 1911). Examples include the experience that an individual's limb belongs to someone else (somatoparaphrenia; Bottini et al., 2002), that a limb's actions are controlled by someone else (alien hand syndrome; Doody & Jankovic, 1992), and an individual perceiving sensations from an amputated limb (phantom limb pain; Ramachandran, 1998).

In addition to studies with brain-damaged patients, researchers have more recently also studied body representations in healthy adults using bodily illusions. A particularly well-studied illusion is the rubber hand illusion (RHI; Botvinick & Cohen, 1998). In this illusion, a participant is seated at a table, viewing a lifelike rubber hand in front of them whilst their own corresponding hand is occluded. The experimenter then synchronously touches both the visible rubber hand and the occluded real hand. The multisensory correspondence between the tactile sensation of touch and vision of the rubber hand being touched then leads to the illusory experience that the rubber hand belongs to the participant's own body.

In addition to an illusory experience of ownership over the rubber hand, the RHI has been found to induce a range of other psychological and physiological effects. For instance, it has been associated with a shift in the perceived proprioceptive position of the participant's occluded hand towards the position of the rubber hand (Botvinick & Cohen, 1998). Remarkably, the RHI has also been found to interact with homeostatic thermoregulation, causing a drop in the temperature of the "disowned" hand (Moseley et al., 2008a; but see de Haan et al., 2017), as well as depending on the actual temperature of the real hand (Kammers et al., 2011). Finally, the RHI modulates the motor readiness of the motor cortex associated with the disowned hand (della Gatta et al., 2016).

In the past few years, several studies have started using the RHI in children to investigate the evolution and development of the body representation during childhood. Understanding how body representations develop during this stage is important because physical and psychological development during childhood potentially has far-reaching and long-term consequences for later life, including not just physical strength and dexterity, but also psychological and cognitive factors such as the child's relationship with his or her body. Furthermore, childhood and early adolescence are typically periods of rapid growth and physical change, requiring precisely the kind of plasticity of body representation that the RHI is thought to measure.

Unfortunately, the extremely broad adoption of the RHI as a tool to study body representations in a wide range of experimental paradigms has resulted in a profuse growth of methodological variations of the illusion (Riemer et al., 2019). Because the illusion has a wide range of effects (some of which are interconnected, e.g. Longo et al., 2008; Moseley et al., 2008), and the underlying neural mechanisms remain poorly understood (Guterstam et al., 2019), this has led to numerous apparent contradictions in the literature. Critically, Riemer et al. (2019) recently noted that there are so many divergent methodological choices in the adult RHI literature that it has become very difficult, if not impossible, to compare and integrate studies to be able to draw conclusions across multiple studies.

In addition to variability in methodological approaches, another challenge evident in the RHI literature is that the psychological experiences associated with having a body are rich and complex, as well as being elusive and difficult to describe (Longo et al., 2008). This has led to inconsistent usage of terms such as embodiment, bodily self-consciousness, and bodily awareness, whereby it is unclear to what degree these terms are intended to refer to the same or different concepts. Indeed, several concepts have different definitions in other (but related) fields, such as the concept of body image (Gallagher, 1986). Overall, the reference to psychological concepts and constructs in the RHI literature is characterised by confusion, disagreement and inconsistency (Longo et al., 2008).

Compared to the wealth of studies available using the RHI in adult populations, the available literature on the RHI in paediatric populations is relatively young. Nevertheless, even among the available studies, the diversity of experimental implementations of the RHI already makes it difficult to compare and integrate findings across studies. Likewise, there is substantial variation in the concepts that different research groups use to interpret their findings. For example, the concept of "body awareness" has been used to encompass all experiences related to having a body (e.g. Filippetti & Crucianelli, 2019) or conversely to refer to only those experiences of which a person is consciously aware (e.g. Schauder et al., 2015). Altogether, this makes it difficult to summarise what these studies have taught us about body representation in the developing brain. Given the lessons from the adult RHI literature, we believe that now is the time for the paediatric field to take stock of what we, as a field, believe that the RHI actually measures, and how we can best implement this in the paediatric population to make our studies more comparable.

In this paper, we review the 12 currently available peer-reviewed papers using the RHI in children (last search in February, 2021). We review induction methods, outcome measures, analysis approaches, and properties of the different populations investigated. We also make an inventory of the psychological constructs and concepts that these studies relate to these measures, in order to provide a synthesis of both the differences and the degree of overlap of the various concepts used. Altogether, we aim to provide a framework on which to build future paediatric RHI studies, to prevent the same challenge that now faces the adult literature: that we have decades worth of findings that are difficult to integrate because of divergent methodological choices and incompatible theoretical constructs.

A brief overview of paediatric RHI studies

We have identified 12 studies applying the RHI or an analogous illusion to children. To our knowledge, this includes all studies using this technique in the paediatric population that have been published in peer-reviewed scientific journals as of February 2021. Here, we provide a brief overview of these studies, organised according to whether those studies included typically developing (TD) children (Bremner et al., 2013; Cowie et al., Cowie et al., 2013, Cowie et al., 2016; Filippetti & Crucianelli, 2019; Greenfield et al., 2017; Nava et al., Nava et al., 2017, Nava et al., 2018), or atypically developing children (Cascio et al., 2012; Greenfield et al., 2015; Prikken et al., 2019; Ropar et al., 2018; Schauder et al., 2015).

We have chosen to include studies using both a fake physical limb (such as a rubber prosthetic hand, as in the classical RHI; Botvinick & Cohen, 1998), as well as studies using other approaches to create a visual image of a hand. Although these paradigms differ in significant ways (e.g. a directly visible physical prosthetic that the participant knows is fake), they have been interpreted in very similar ways to more standard RHI paradigms. Of the 12 paediatric studies, one used the mirror illusion (Holmes et al., 2004), in which the participant's occluded hand is replaced by the mirror image of the contralateral hand (Bremner et al., 2013). Three other studies used a virtual reality setup called MIRAGE to create a real-time video image of the participant's occluded hand, which could be manipulated in temporal and spatial dimensions (Greenfield et al., 2015, 2017; Ropar et al., 2018).

Typically developing children

The available studies in TD children primarily investigated developmental changes in visual, proprioceptive, and tactile contributions to perceived hand position, as well as how they impact the subjective experience of ownership over the rubber hand.

Studies in children ranging from 4 to 13 years old consistently show that the RHI includes a subjective experience of ownership over the rubber hand in children in much the same way as it does in adults (Cowie et al., 2013, 2016; Filippetti & Crucianelli, 2019; Nava et al., 2017, 2018). Furthermore, the subjective experience induced during the illusion appears remarkably stable across children of different ages, and also does not differ from the experience reported by adults (Cowie et al., 2013, 2016; Nava et al., 2017, 2018).

The findings regarding the effects of the RHI on perceived hand position in children are more complex. This effect is typically operationalised as *proprioceptive drift* (the change in the felt position of the hand over the course of the illusion). Overall, the RHI studies investigating proprioceptive drift in children do report the classical effect that synchronous stroking causes the felt position of the hand to drift towards the rubber hand (Bremner et al., 2013; Cowie et al., 2013, 2016; Nava et al., 2017, 2018), with the sole exception of Filippetti and Crucianelli (2019). However, the pattern of dependence on age during development seems to differ depending on the methodological details of the experimental paradigm.

Bremner et al. (2013) used a mirror paradigm and observed equivalent proprioceptive drift from children as young as 5 years old through to adults. Using the classical RHI paradigm developed by Botvinick and Cohen (1998) in which an experimenter strokes the participant's finger, Cowie and colleagues (Cowie et al., 2013, 2016) instead observed that proprioceptive drift was largest for young children, and decreased with age, reaching adult magnitudes at around age 10 (Cowie et al., 2016). Conversely, Nava and colleagues (Nava et al., 2017, 2018) used an adapted RHI paradigm in which the participant strokes his or her own hand, and observed the opposite relationship: using this paradigm, proprioceptive drift was smallest for the youngest children, and remained below adult levels until at least age nine. In a direct comparison of paradigms, Nava et al. (2018) confirmed that the two paradigms produced opposite results for adults and children, and concluded that the action involved in the adapted paradigm contributed to the illusion in children, but reduced the illusion in adults. Interestingly, although both paradigms induced comparable feeling of ownership in children, the adapted paradigm failed to induce ownership in adults, providing convergent evidence for significant differences between the paradigms.

Finally, it is interesting to note that several studies report that children demonstrate a strong baseline bias in proprioceptive drift measures. Children tended to localise their hand toward the rubber hand (or the body midline, if no rubber hand is visible), even without any stroking (Cowie et al., 2013, 2016; Filippetti & Crucianelli, 2019; Nava et al., 2017). Here too, studies do not agree on the relationship with age: Cowie et al. (2013) report an increase with age, whereas Nava et al. (2017) report a decreasing trend. Greenfield et al. (2017) directly investigated how that spatiotemporal integration window develops during childhood, and report that children's ability to detect both spatial and temporal mismatches increases with age, but although this is clearly important during the RHI, it is unclear how this finding maps onto the age-related trends observed in the different RHI paradigms.

Atypically developing children

Five studies have explored the RHI in atypically developing children. Of these, four investigated children with autism spectrum disorder (ASD), and one investigated children with familial risk of either schizophrenia or a mood disorder.

ASD is associated with social and communication difficulties, which have been attributed to atypical multisensory integration in this population (Brock et al., 2002; Cascio et al., 2012; Ropar et al., 2018). Because the RHI relies on multisensory information processing, it is hypothesised that the susceptibility of children with ASD to the RHI might be distinctive. Indeed, Cascio et al. (2012) discovered that a longer RHI induction period was necessary to produce proprioceptive drift in children with ASD compared to healthy controls. They interpreted this as evidence for atypical multisensory temporal integration, as well as an unusually strong reliance on proprioceptive cues in this population.

Both of these proposed mechanisms are broadly consistent with the other RHI studies in children with ASD. Ropar et al. (2018) used a pointing task to show that proprioceptive drift was reduced in children with ASD, compared to typically developing children. Furthermore, both Greenfield et al. (2015) and Ropar et al. (2018) specifically investigated sensitivity to synchrony in children with ASD, and found that children with ASD had a wider temporal integration window than typically developing children, which was interpreted as a reason why synchronous stroking in the RHI was less effective at overriding conflicting proprioceptive input. Finally, Schauder et al. (2015) combined an RHI paradigm with a heartbeat counting task, and observed a negative correlation between interoceptive awareness and proprioceptive drift in the RHI. Children with ASD scored higher on interoceptive awareness than typically developing children, and although the two groups were not directly compared on the RHI task, these findings are consistent with the other ASD studies showing an increased reliance on internal cues leading to reduced proprioceptive drift in this population.

As the only paediatric RHI study to investigate developmental disorders other than ASD, Prikken et al. (2019) examined the RHI in children and adolescents with a familial risk of schizophrenia or mood disorders. Although they observed altered RHI effects in adult patients with schizophrenia, in children and adolescents no differences were observed between participants with and without increased familial risk to these disorders.

Summary

Overall, findings from the studies described above provide some grounds for consensus about what we know about the RHI in children. Firstly, children of all ages appear to experience the subjective feeling of ownership over the rubber hand in the same way as adults. Secondly, in general, children demonstrate a drift in the perceived position of their hand during the RHI in a similar way to adults. However, the way proprioceptive drift depends on age during childhood appears to depend on the methodological details of the experimental paradigm. Finally, studies in populations with ASD converge on the idea that the extent of dependence on proprioception, as well as the temporal integration of visuo-tactile cues, can be disrupted in atypical development.

Methodological variation in paediatric RHI studies

Decades of RHI studies in adults have resulted in a proliferation of different experimental methods, measurements, and conceptual ideas around what the RHI actually shows and what it is good for. As noted by Riemer et al. (2019) in an extensive review of methodology used in the adult RHI literature, this variation makes it difficult to integrate the conclusions of different studies. Unfortunately, the same is threatening to characterise the much younger literature on the RHI in children. In this section, we map out methodological variation in this literature, broadly using the same classifications of RHI methodology as presented by Riemer et al. (2019), with two aims in mind:

1) to provide an overview of the points of consensus;
2) to highlight where different authors make different methodological choices and how this might influence their conclusions.

In both cases, we hope this overview will inform the design of future studies in ways that allows those studies to be more easily incorporated with the currently available literature. The methodological parameters of each of the 12 available published paediatric RHI studies are summarised in Tables 1, 2, 3, 4 and 5.

Considering the methodological approaches used by the available studies, we can make a number of observations. Firstly, the available studies are relatively consistent in how they probe the subjective experience of ownership in the RHI using a questionnaire. Seven studies asked one or more target questions (" …feel as if you could feel the touch where the fake hand was"; " …feel like the fake hand was your hand or belonged to you"; (Cascio et al., 2012; Cowie et al., 2013, 2016; Filippetti & Crucianelli, 2019; Nava et al., 2017, 2018; Prikken et al., 2019), whilst five did not use this measure (Bremner et al., 2013; Greenfield et al., 2015, 2017; Ropar et al., 2018; Schauder et al., 2015). In addition, three studies asked a control question (" …felt as if I had three hands"; Cascio et al., 2012; Nava et al., 2017, 2018) while the other nine did not. An important point to note is that Nava et al. (2017) report that children reject control questions less than adults do. We do not believe this affects the interpretation of any current study, but this may be relevant for future studies to take into account particularly when "the effect" of the RHI is only measured in one condition and strength is determined on the difference between illusion and control questions. Finally, several studies included design-specific questionnaires, such as measures of empathy (Cascio et al., 2012), interoceptive abilities (Schauder et al., 2015), and a weight estimation task (Filippetti & Crucianelli, 2019). Overall, questionnaire approaches to probing subjective feeling of ownership are relatively consistent.

Secondly, there are substantial **differences between studies in terms of how the RHI is induced**. This is perhaps unsurprising as we deliberately chose to include RHI-like paradigms using mirrors or virtual reality instead of a prosthetic limb. While most studies used passive touch as the method of induction, one (Bremner et al., 2013) used active movements, another (Greenfield et al., 2017) used passive movements, and a third used active self-stroking (Nava et al., 2018). In adults, movements of the hand typically eliminate the illusion (Kammers, de Vignemont, et al., 2009), casting doubt on whether this induction approach recruits the same mechanisms. For those studies in which the RHI is induced via stroking, the duration of the induction phase varies from just 10 seconds all the way to three minutes long. Evidence indicates that (at least in adults) the RHI builds up gradually

Table 1 Sample

		Population [1]	Total no.	No. per group [1]	Age range(s)
Cascio et al. (2012)		TD, ASD	49	ASD: 21; TD: 28	8–17 years
Bremner et al. (2013)		TD	45	Not specified	5; 6; 7 years
Cowie et al. (2013)		TD	90	30	4–5; 6–7; 8–9 years
Schauder et al. (2015)		TD, ASD	45	ASD: 21; TD: 24	8–17 years
Greenfield et al. (2015)		TD, ASD	87	29	5–15 years
Cowie et al. (2016)		TD	60	30	10–11; 12–13 years
Nava et al. (2017)	Exp 1	TD	72	18 per condition	4–5; 8–9 years
	Exp 2		33	18 in sync, 15 in async	4–5 years
Greenfield et al. (2017)		TD	56	28 (median split)	5–12 years
Prikken et al. (2019)	Cohort 1	TD, SZ	110	SZ: 54; TD: 56	18–50 years
	Cohort 2	SZO, BPO, CO	75	SZO: 24; BPO: 33; CO: 18	11–22 years
Nava et al. (2018)		TD	108	18	4; 5; 6 years
Ropar et al. (2018)		TD, ASD	84	ASD: 29; MA: 27; CA: 28	5–15 years
Filippetti and Crucianelli (2019)		TD	68	17	6–8 years

[1] TD: typically developing; ASD: autism spectrum disorder; SZ: schizophrenia; SZO: offspring of schizophrenia; BPO: offspring of bipolar disorder; CO: offspring of healthy controls

(Rohde et al., 2011), although effects observed at very short induction durations also suggest that there may be a rapid onset component (Kalckert & Ehrsson, 2017). Furthermore, effects may build up differently for different measures of the RHI (Rohde et al., 2011). As a result, an 18-fold difference in induction duration is very likely to have different effects on the multisensory integration process underlying the RHI. Finally, **studies differ widely in which portion of the hand is stroked**. This is relevant because (in adults), proprioceptive drift is strongly restricted to the stimulated region, with no concomitant effects on neighbouring areas of the hand (Kammers, Longo, et al., 2009).

The significance of even subtle differences between experimental paradigms is underscored by the direct comparison of three versions of the RHI reported by Nava et al. (2018). Of particular interest are a classical RHI version (e.g. Botvinick & Cohen, 1998), in which the experimenter strokes a visible rubber hand, and a second version in which participants do the stroking themselves (using a special apparatus to simultaneously stroke both their own occluded hand and the visible rubber hand). Although matched for tactile and visual input, the two induction methods produce very different patterns of results. In children, both methods were found to induce a sense of ownership over the hand, but in adults only the classical version had this effect. Moreover, in children only the self-stroking version had an effect on proprioceptive drift, whereas the classical method induced nearly no drift. Strikingly, this pattern of results was reversed for adults, who showed proprioceptive drift only after the classical induction method, and not after self-stroking. This shows that the choice of induction method, even when seemingly controlled for relevant factors, can have substantial effects and interact in complex ways with other variables.

Thirdly, **different measures are used to estimate proprioceptive drift**—a key measure used to indicate participants' perception of hand position. Two studies used active movements of the illusion hand (Bremner et al., 2013; Ropar et al., 2018), four used active matching responses with the opposite hand (Cascio et al., 2012; Cowie et al., 2013, 2016; Filippetti & Crucianelli, 2019), one used a verbal report (Prikken et al., 2019), and two used a pointing response to the position of the illusion hand on a visible ruler (Nava et al., 2017, 2018). A further study did not specify how this measure was taken (Schauder et al., 2015), and three others used a match/mismatch choice task. None of the studies reported whether movements were ballistic or slow. The difference between slow matching and ballistic pointing judgments is important because in adults, different aspects of motor control can be differentially affected by the RHI. For example, slow matching and ballistic pointing have been dissociated during the RHI (e.g. Kammers, de Vignemont, et al., 2009; although note that Riemer et al., 2013 did observe an RHI effect on ballistic movements). Similarly, during grasping movements, hand position and hand aperture size are influenced differently by the RHI (Heed et al., 2011). This means that apparently similar action-based measures can in fact probe different underlying processes and therefore cannot be considered equivalent. This makes it important to explicitly report details about the movements, such as whether they were ballistic or not.

Finally, studies **differ in their approach to analysis and statistical testing**. Of particular relevance is **the choice of baseline**. All studies employ a condition with synchronous

Table 2 Design

		Baseline condition	Manipulation comparison [2]	Repeats per condition	Single trial duration	Experiment duration	Non-responders removed	Handedness
Cascio et al. (2012)		No visible hand	Within	2	3 min	12 min	No	Both
Bremner et al. (2013)		Synchronous tapping in matched mirror position	Within	6	Until subject reports illusion	Not reported	No	Not reported
Cowie et al. (2013)		No visible hand	Between	4	Not reported	Not reported	No	Not reported
Schauder et al. (2015)		No visible hand	Within	1	Not reported	3 min	1 outlier removed	Not reported
Greenfield et al. (2015)		Visible hand	Mixed	2	10 s	Not reported	No	Both
Cowie et al. (2016)		No visible hand	Between	4	Not reported	Not reported	No	Not reported
Nava et al. (2017)	Exp 1	No visible hand	Between	3	60 s	Not reported	No	Right only
	Exp 2							Not reported
Greenfield et al. (2017)		None	Within	5	Not reported	10 min total	No	Not reported
Prikken et al. (2019)		Unstimulated hand	Within	4	Not reported	Not reported	No	Not reported
Nava et al. (2018)		Pre-induction	Between	1	~3 min	~3 min	No	Not reported
Ropar et al. (2018)		Visible hand	Within	2	Not reported	15 min	No	Not reported
Filippetti and Crucianelli (2019)		No visible hand	Between	1	Not reported	Not reported	No	Not reported

[2]: Comparisons between experimentally manipulated conditions can be made as a within-subjects or between-subjects design

stroking or movement, depending on the paradigm. However, to establish *the strength of the RHI,* some compare this to a measure with no visible hand (six studies; Cascio et al., 2012; Cowie et al., 2013, 2016; Filippetti & Crucianelli, 2019; Nava et al., 2017; Schauder et al., 2015), another compares this to a condition in which the participant views the rubber hand pre-induction, without any stroking or movement (Nava et al., 2018), two studies use a condition where the participant's own hand is visible (Greenfield et al., 2015; Ropar et al., 2018), and another uses the unstimulated hand (Prikken et al., 2019). Importantly, studies also differ in whether experimental manipulations (such as synchronicity) are compared within individual participants (six studies; Bremner et al., 2013; Cascio et al., 2012; Greenfield et al., 2017; Prikken et al., 2019; Ropar et al., 2018; Schauder et al., 2015), between groups (five studies Filippetti & Crucianelli, 2019; Nava et al., 2017, 2018), or both (Greenfield et al., 2015).

The choice of analysis approach has far-reaching effects on the conclusion that might be drawn from the data. For example, when we consider the results presented by Nava et al. (2017), they observe that all age groups considered in their experiment (four to five years, eight to nine years, and adults) show an RHI effect on questionnaire measures of ownership, but only eight-to-nine-year-olds and adults show an RHI effect on proprioceptive drift. Proprioceptive drift is calculated as pointing error in the synchronous condition, minus pointing error in the baseline condition. They conclude that calibration of hand position is still ongoing at age nine. However, visual inspection of their data shows that the absolute magnitude of pointing error is actually comparable for the synchronous condition across all age groups (Figure 1A in Nava et al (2017) shows that post-trial pointing error is around +3 cm across all three age groups). Instead, it is the baseline pre-test that differs between groups (the same figure shows that baseline pointing error varies from +1 cm in the youngest group to −1 cm in the adult group). If the authors had made the entirely defensible and seemingly equivalent choice to operationalise the strength of the RHI as the difference between the synchronous and asynchronous conditions (which is the standard way of testing the RHI in adults, rather than the pre-trial baseline; Botvinick & Cohen, 1998), then this measure would be nearly identical across all age groups. Although we have not formally reanalysed their original data, it is evident from the averages reported in their figure (i.e. comparing post-trial pointing error in the synchronous condition [Figure A] to the asynchronous condition [Figure B]) that the conclusion of the study would be completely different: children as young as four would then already have an adult-level effect of the RHI on perceived hand position.

We emphasise that we are not claiming that any of the studies considered here used incorrect or inappropriate approaches to analyse their results. Rather, the point is that different analysis approaches (each conceptually justifiable and

Table 3 Setup

	Displacement direction [3]	Distance between real and fake hand	Hand type	Laterality
Cascio et al. (2012)	H	Distance not specified	Prosthetic	Left
Bremner et al. (2013)	H	5 cm mismatch with mirror image	Mirror	Right
Cowie et al. (2013)	H	25% arm length	Prosthetic	Left (Right for baseline)
Schauder et al. (2015)	H	Distance not specified	Prosthetic	Left
Greenfield et al. (2015)	H	1 hand width	MIRAGE	Both
Cowie et al. (2016)	H	25% arm length	Prosthetic	Left
Nava et al. (2017)	H	15 cm	Prosthetic	Left
Greenfield et al. (2017)	H	0, 0.5, 1, 1.5 or 2 hand widths	MIRAGE	Right
Prikken et al. (2019)	H	25% arm length	Prosthetic	Left
Nava et al. (2018)	H	20 cm	Prosthetic	Left
Ropar et al. (2018)	H	Distance not specified	MIRAGE	Right
Filippetti and Crucianelli (2019)	H	15 cm	Prosthetic	Left

[3]: Direction in which the fake hand is displaced; H: horizontal, V: vertical

in many ways probably seeming to be equivalent) yield dramatically different conclusions. This means that to be able to integrate findings across studies, we need to form a consensus about how to analyse those findings.

Conceptual variation in paediatric RHI studies

In addition to methodological differences, the 12 studies considered here also use a range of **different conceptual terms to describe what the RHI actually measures**. However, what is unclear at first sight is the degree to which these terms are used to refer to meaningfully distinct constructs, or alternatively that they are treated as equivalent, and used interchangeably to refer to the same construct.

Answering this question is complicated for two reasons. Firstly, many of these constructs are abstract and/or refer to abstract experiences that are difficult to articulate. As noted by Longo et al. (2008), the body typically forms the background of mental life, rather than the focus, and the verbal labels of our language are better suited to describing the different physical parts of the body, rather than the experience that those parts together constitute the self (de Vignemont et al., 2005).

Additionally, the RHI itself has a multitude of both psychological and physiological effects, many of which are experimentally dissociable. Physiologically, the RHI of course is well known to affect proprioception, but has also been found to affect responses to threat (Armel & Ramachandran, 2003; Ehrsson et al., 2007), influence homeostatic thermoregulation (Moseley et al., 2008), interact with thermosensation (Kammers et al., 2011), and influence motor control (e.g. della Gatta et al., 2016). Likewise, the psychological effects of the RHI are far from unidimensional. For example, Longo et al. (2008) used a psychometric approach to identify multiple different components of the conscious experience of the illusion: embodiment of the rubber hand, loss of the own hand, movement, affect, and deafference (in the asynchronous condition). The embodiment component was further dissociable into effects on ownership, location, and agency. Of these three sub-components, only ownership and location correlate to proprioceptive measures of the illusion, further emphasising the complexity and multidimensional nature of the effects of the RHI.

The following six concepts emerge from the paediatric RHI literature:

Body Ownership

Consistent with the original report of the RHI by Botvinick and Cohen (1998) and the majority of the adult RHI literature, a prominent concept in the paediatric RHI literature is sense of *body ownership*. Most studies use this to mean a subjective experience of ownership over (part of) the body—in the context of the RHI, this typically means the feeling that the rubber hand belongs to the participant's body. However, several studies diverge from this definition in important ways. For instance, Prikken et al. (2019) define body-ownership experiences as "feeling that we are the subject of our own bodily experiences". This includes not only ownership over a body part, but over conscious experiences as a whole—a significantly broader definition than is typically used, and more akin to what other authors describe as the sense of self (see below). Most authors would agree that the RHI involves a sense of ownership over the rubber hand, but we believe that few would argue that it affects the feeling "that we are the subject of our own bodily experiences". Blurring this definition is a problem because it conflates an experimental effect (the sensation that a visible rubber hand belongs to your body) with

Table 4 Induction

		Method	Tactile properties	Finger(s)	Duration	Synchrony/SOA	Predictability [4]
Cascio et al. (2012)		Touch	Brush	Second and third knuckles of index finger	3 min	Sync & Async (500 ms delay)	Yes
Bremner et al. (2013)		Active movement	Tapping on table	Both index fingers tapped	Until subject reports illusion	Sync only	Yes
Cowie et al. (2013)		Touch	Brush	Not reported	2 min (first trial); 20 s (later trials)	Sync & Async (Async also mismatched position)	No
Schauder et al. (2015)		Touch	Brush	Not reported	3 min	Sync & Async (500 ms delay)	Yes
Greenfield et al. (2015)		Touch	Brush	Right index finger	10 s	Sync & Async (SOA 0, 60, 180, or 300 ms)	Yes
Cowie et al. (2016)		Touch	Brush	All fingers and back of the hand	2 min (first trial); 20 s (later trials)	Sync & Async (Async also mismatched position)	No
Nava et al. (2017)		Touch	Self-stroking	Randomly across all fingers, knuckles and parts of the hand	1 min	Sync & Async (Async was alternating strokes)	No
Greenfield et al. (2017)	Exp 1	Vision only	N/A	N/A	Not reported	N/A	N/A
	Exp 2	Touch	Pencil	Single touch to side of tip of index finger	2 s	Sync & Async (SOA 0, 100, 150, 200, 300, or 400 ms)	N/A
Prikken et al. (2019)		Touch	Brush	Back of hand and index finger	2 min (first trial); 20 s (later trials)	Sync & Async (Async mismatched timing and direction)	No
Nava et al. (2018)	Version 1 Version 2	Active self-stroking	Brush	Not reported	~3 min	Sync and None (NB: Position match was not controlled; Async condition had no touch at all)	Yes
	Version 3	Touch				Sync & Async (position match not reported)	Not reported
Ropar et al. (2018)		Touch	Brush	Right index finger	10 s	Sync & Async (viewed simultaneously on two hand images; SOAs 0, 60, 180 or 300 ms)	Yes
Filippetti and Crucianelli (2019)		Touch	Brush	Not reported	1 min	Sync & Async	Not reported

[4]: Stimulation in asynchronous condition could be predictable (e.g. by insertion of a constant delay between vision and touch) or unpredictable (e.g. by random timing or position)

Table 5 Quantification

		Scale	Target questions	Control questions	Proprioceptive Drift [5]	Other measures
Cascio et al. (2012)		7 points (−3 to 3)	1. "It seemed as if I were feeling the touch of the brush in the location where I saw the rubber hand touched"; "It seemed as though the touch I felt was caused by the brush touching the rubber hand"; "I felt as if the rubber hand were my hand."	Six questions from Botvinick and Cohen (1998)	Active matching of hand position on ruler	Empathy – autism diagnostic observation schedule; imitation – autism diagnostic interview-revised
Bremner et al. (2013)		N/A	N/A	N/A	Active reach with illusion hand	N/A
Cowie et al. (2013)		7 points (0 to 6)	"[...] did it sometimes seem as if you could feel the touch of the brush where the fake hand was?"; "[...] did you sometimes feel like the fake hand was your hand, or belonged to you?"	N/A	Active matching of hand position below table	N/A
Schauder et al. (2015)		N/A	N/A	N/A	Not reported	Heartbeat counting task; Visual counting control task; - Autism Diagnostic Observation Schedule (ADOS); - Autism Diagnostic Interview Revised (ADI-R)
Greenfield et al. (2015)		N/A	N/A	N/A	Critical task was selecting one of two visual hands as matching the physical position.	Social Communication Questionnaire (SCQ); Social Aptitude Scales (SAS); Strengths & Weaknesses of ADHD Symptoms and Normal Behaviour Scale (SWAN)
Cowie et al. (2016)		7 points (0 to 6)	"When I was stroking with the paintbrush, did it sometimes seem as if you could feel the touch of the brush where the fake hand was?"; - "When I was stroking with the paintbrush, did you sometimes feel like the fake hand was your hand or belonged to you?"	N/A	Active matching of hand position below table	N/A
Nava et al. (2017)	Exp 1	11 points (−5 to 5)	"I felt as if I were touching my ownhand"	"I felt as if I had three hands."	Active pointing to hand position on ruler	N/A
	Exp 2	7 points (0 to 6)	"[...] did you feel as if you were touching your own hand?"; "[...] did you feel as if the rubber hand were your own hand?"	"Did you feel as if you had three hands?"; "Did you feel as if your own hand had disappeared?"		
	Exp 1	N/A	N/A	N/A		

Table 5 (continued)

	Scale	Target questions	Control questions	Proprioceptive Drift [5]	Other measures
Greenfield et al. (2017)				Task was to report whether visible hand matched physical position	British Picture Vocabulary Scale III (BPVS-III)
Exp 2	N/A	N/A	N/A	Task was to report whether vision and touch were synchronous or not	
Prikken et al. (2019)	7 points (0 to 6)	"[...] did it sometimes seem as if you could feel the touch of the brush where the fake hand was?"; "[...] did you sometimes feel like the fake hand was your hand or belonged to you?"	N/A	Verbal report when the experimenter indicated a matching position	SZ group: Self-Experience Lifetime Frequency Scale (SELF); SZO, BPO, CO groups: Schedule for Affective Disorders & Schizophrenia for School-Age Children – Present & Lifetime Version (K-SADS-PL)
Nava et al. (2018)	7 points (−3 to 3)	"I felt as if the rubber hand was my own hand."	"I felt as if I had three hands."	Pointing to visible ruler	N/A
Ropar et al. (2018)	N/A	N/A	N/A	Active reach with illusion hand	Social Communication Questionnaire (SCQ); Social Aptitude Scale (SAS); British Picture Vocabulary Scale-III (BPVS-III)
Filippetti and Crucianelli (2019)	7 points (0 to 6)	"[...] did it sometimes feel like the rubber hand was your hand or belonged to you?"; "[...] did you sometimes feel like the fake hand was your hand or belonged to you?"; "[...] did it sometimes feel as if you could feel the touch of the brush where the fake hand was?"	N/A	Active matching of hand position below table	Weight estimation task

[5]: Task used to estimate proprioceptive drift. Studies using the term "pointing" to mean sliding along a horizontal trajectory until the position matches the target are classified as matching tasks.

the homeostatic system that it affects. As an example, Prikken et al. refer to RHI studies in schizophrenia showing "impairments in body ownership"—whilst explaining that people with schizophrenia rate the illusion as stronger, not weaker. What is impaired (or at least altered) in this population is the homeostatic mechanism by which the brain establishes what visual input belongs to the body and what does not, and this manifests in the RHI as a change (in this case, an increase) in the subjective experience that the visible rubber hand belongs to the body.

Ropar et al. (2018) uses sense of body ownership to mean "awareness and understanding that our body belongs solely to us, and that we can see, feel and move it." This includes not just the subjective experience that a body part belongs to us, but also the higher cognitive understanding of what that means. The mirror illusion (Holmes et al., 2004), used by Bremner et al. (2013) highlights one of the problems this causes. When we see ourselves in a mirror, we clearly have an understanding that the mirror body belongs to us, thereby satisfying this definition of body ownership. However, in the illusion reported by Holmes et al, viewing the left hand reflected in a mirror such that its image appears in the position of the right hand, an experience of ownership develops over the image that is different than in the first case: we feel ownership over the image as if it *were* the right hand, contiguous with the rest of our body rather than a reflection of it. Ambiguity in this definition risks implying that the RHI influences participants' *understanding* of their body, which it clearly does not.

Finally, blurring or broadening the definition of constructs such as body ownership causes them to encroach on other related, but dissociable, constructs. For example, the definition of body ownership used by Ropar et al. (2018) explicitly includes the sense that we can move that body part, which is a sub-component of embodiment that Longo et al. (2008) and Tsakiris et al. (2010) previously demonstrated to be dissociable from body ownership per se. The combination of psychometric (Longo et al., 2008), neuroimaging (Tsakiris et al., 2010), and theoretical (e.g. Tsakiris, 2017) dissociations currently forms the best available evidence for how the underlying constructs and processes relate to one another. If we do not use these insights, then progress in understanding these constructs will stagnate.

In general, the problem caused by imprecise use of concepts such as body ownership is that claims and evidence can be misinterpreted or misunderstood, and propagate through the academic literature via second-hand citation. For example, both Prikken et al. (2019) and Ropar et al. (2018) cite Gallagher (2000) as a source for their definition of body ownership. However, Gallagher (2000) does not actually address *body* ownership—instead discussing ownership over conscious experiences as a philosophical basis for the self.

Body Representation

In the adult literature, the RHI is frequently presented as a tool to study how the body is represented in the brain (Ramakonar et al., 2011). This representation, in terms of the populations of neurons that together represent some kind of information about the body's state, has been called the neural or mental *body representation*. Indeed, various authors have argued for the existence of multiple such representations on the basis of dissociable experimental effects (Gallagher, 1986; Kammers et al., 2010; Paillard, 1999; Tsakiris et al., 2007; Wold et al., 2014). There is an unfortunate historical use of terminology in this body representation literature, whereby dissociable body representations were first proposed by Head and Holmes (1911), who called them "body schemata". Others later further characterised the different representations, prominently including Gallagher's introduction of the *Body Image* and the *Body Schema* (Gallagher, 1986). In the current context, both of those terms are confusing. *Body Image* here refers to a specific neural representation of certain aspects of the body's position in space, whereas nowadays in general parlance "body image" is more commonly taken to mean how we feel psychologically about our body and its appearance (often in relation to societal ideals). Likewise, in this dissociation *Body Schema* referred to a specific neural representation primarily involved in motor control. However, outside of this specific literature, "body schema" is frequently used as a synonym for body representation, to refer to *any* kind of neural representation of the body in the brain (e.g. Carlson et al., 2010). The seemingly polysemantic nature of these two body representations, and the observation that it might be possible to further subdivide them, led Kammers et al. (2010) to conclude that dissociating and naming different body representations might not be especially useful, and indeed more recently the body image-body schema dissociation has featured less prominently in the adult literature (Pitron & de Vignemont, 2017).

The 12 paediatric studies are generally consistent with the adult literature in their use of the term "body representation" to mean the way the brain represents information about the body, and although several studies note dissociations between developmental processes, they do not advocate for dissociable body representations per se. Ropar et al. (2018) is the only study to explicitly situate their results within the body image-body schema framework.

Body Perception

Three of the paediatric RHI studies introduce the concept of *own-body or bodily perception* (Cowie et al., 2013, 2016; Schauder et al., 2015). Cowie et al. (2013, 2016) use this term to refer to the perception of one's own body as being one's own body. In this, use of the term seems very similar to *body ownership*, although the latter is more commonly used to refer to the *feeling* that a body part belongs to one's own body, rather than the percept. Schauder et al. (2015) uses the term bod(il)y perception differently. In their study, the term is used interchangeably with *bod(il)y awareness* (please see below) and further divided into internal and external body awareness, with the authors arguing that the RHI is a measure of external bodily awareness. This definition was clearly motivated by Tsakiris et al. (2011), who noted more specifically that the RHI paradigm makes it possible to evaluate the interoceptive (i.e. proprioceptive) and exteroceptive (i.e. visual) contributions to body localisation. In any case, the concept of (external) body perception is clearly used inconsistently by the paediatric literature, and it seems to be used in a general sense, rather than to refer to a specific process or sensation.

The problem, as for the body ownership concept, is that inconsistent use makes it difficult to identify the specific effects of manipulations such as the RHI. One characteristic of the RHI is that participants *feel* that the rubber hand belongs to their body, despite *knowing* that it does not (Botvinick & Cohen, 1998). Because of this paradox, the question of whether they *perceive* the hand to be part of their body (or are *aware* of the hand as being part of their body, see below) is underspecified.

Body Awareness

The term *body awareness* is used by both Schauder et al. (2015) and Filippetti and Crucianelli (2019). It is not entirely clear how this term relates to the concepts already cited above. On the one hand, it appears to be used as an overarching concept to encompass all research related to this field. For example, it is used in the title of Schauder et al. (2015) and in the very first sentence of Filippetti and Crucianelli (2019) to broadly mean how the body is represented in the brain. Filipetti and Crucianelli use "body awareness" interchangeably with "bodily self-consciousness", in a way that seems to overlap with how many other authors have used the general term "body representation" (particularly in reference to its malleability, e.g. Tsakiris et al., 2011, and plasticity, e.g. Longo & Serino, 2012; Martel et al., 2016).

A problem with this usage is that the body of literature in this field clearly includes both conscious and unconscious processes. On the other hand, Schauder et al. use "body awareness" to specifically refer to a conscious experience (Schauder et al., 2015), consistent with the dictionary definition of "awareness" as having conscious knowledge of something. The use of the term "body awareness" is therefore also inconsistent in the paediatric literature, and it is not quite clear whether this is a distinct concept or whether it is subsumed by one of the other concepts.

Bodily Self and Sense of Self

The concept of the *self* has been much-studied in adults using the RHI and related paradigms (Tsakiris, 2017), and many of the paediatric studies likewise refer to this concept (Cascio et al., 2012; Cowie et al., 2013, 2016; Filippetti & Crucianelli, 2019; Nava et al., 2017, 2018; Ropar et al., 2018; Schauder et al., 2015). Although none of these studies explicitly define how they use the construct, there appears to be an implicit consensus. Ropar et al. (2018) equates the bodily self to body representation, as a concept that incorporates other constructs (including body localisation and body ownership). Cowie et al. (2013) similarly considers body localisation and ownership to be "aspects of the bodily self", consistent with the conclusions of Cowie et al. (2016) that "the bodily self is not a unitary construct […] but rather consists of several processes". There is also a general consensus that the self is the product of multisensory integration (Cowie et al., 2013, 2016; Filippetti & Crucianelli, 2019; Nava et al., 2017; Ropar et al., 2018; Schauder et al., 2015), although this is perhaps unsurprising as these studies were selected due to their use of the RHI paradigm, which unambiguously relies on multisensory integration.

Embodiment

A final key concept that features in the paediatric literature (as in the adult literature) is *embodiment*. Most studies use this concept interchangeably with "body ownership" (Filippetti & Crucianelli, 2019; Greenfield et al., 2015, 2017; Nava et al., 2017, 2018; Ropar et al., 2018). It is also used as a verb (Nava et al., 2018), to express the process of having or acquiring body ownership (e.g. "children integrate synchronous visual and tactile inputs to embody a fake hand"; Greenfield et al., 2015). Cowie et al. (2013) and Nava et al. (2018) specifically refer to a questionnaire asking about limb ownership as measuring embodiment. This reinforces the idea that embodiment and body ownership are used to mean the same construct. The same is mostly true for the adult literature. However, as previously noted, Longo et al. (2008) reported a dissociation between different subcomponents of embodiment in the RHI. Specifically, they observed that the explicit experience of *body ownership* over the rubber hand was only one of several aspects of embodiment of the rubber hand (the others being the perceived location of the limb and the experience of agency over the limb's movements). This important nuance does not feature in the paediatric literature, which is a missed opportunity to build on existing insights.

Altogether, these findings highlight the importance of being extremely careful around the use of different conceptual constructs when addressing "the effect" of the RHI. If we are inconsistent or unclear about what aspect of the RHI a given experiment investigates, it not only becomes difficult to integrate the results of that experiment with the rest of the literature, and hence to the broader paediatric population, but also makes misinterpretation of the specific findings very likely.

Conclusions and Recommendations

The rubber hand illusion (RHI) is a bodily illusion that has been used extensively in the adult population over the past two decades to investigate body representations in a wide range of experimental paradigms. Unfortunately, the adult RHI literature is characterised by such significant variation in experimental methodology that it has become difficult to integrate findings across different studies (Riemer et al., 2019). In addition, the complexity of the psychological experience associated with the illusion (and embodiment more generally) has led to the introduction of a profusion of psychological and cognitive concepts, with no clarity about the degree to which these concepts overlap, or how they are best operationalised experimentally.

More recently, a number of studies have started using the RHI in paediatric populations, to answer important questions about how body representations develop in children, whose bodies, brains, and minds are all rapidly developing. Here, we have considered the available paediatric RHI studies, evaluated the variation in methodological approaches and psychological concepts evident in these studies, and below we make a number of recommendations for future RHI studies in paediatric populations, aiming to guide the field away from the disorder that now characterises the adult RHI literature.

Recommendations

The first thing to note is that it has become clear in both the adult and paediatric literature that there is no single effect of the RHI. The RHI has a range of different psychological and physiological effects, which are experimentally dissociable, build up at different speeds during illusion induction, and develop at different rates during childhood. This means it is unhelpful or even incorrect to speak of *the effect of the RHI*, or even *the effect of X on the RHI*. In designing and interpreting experiments, it is important to be aware that the RHI is a complex and multidimensional phenomenon. If we do not make explicit reference to the individual dimensions of the RHI that are being considered in a given experiment, it is difficult to know what is being measured, to compare conclusions from different studies, and to integrate findings into a theoretical framework and hence advance the understanding of the developing brain in relation to its representation of the body. Below we provide recommendations for the induction, quantification, and conceptualisation of the RHI.

Induction

Methodologically, probably the most significant source of variability between studies is the method and duration of induction. Across the paediatric RHI studies investigated, studies have used both traditional tactile stimulation or actual hand movements, involving either isolated fingers or encompassing larger parts of the hand, and for durations varying from as little as 10 seconds to as long as three minutes. These are three crucial factors identified by Riemer et al. (2019) in the adult RHI literature, and are all known to differently affect various components of the RHI (Kammers, de Vignemont, et al., 2009; Kammers, Longo, et al., 2009; Rohde et al., 2011). As such, we recommend that when designing experiments, researchers are aware that the different versions of the RHI paradigm are not equivalent or interchangeable—they involve different mechanisms and will quite possibly evoke different experiences in participants, leading to different interpretations by researchers. Hence, we recommend that researchers make a deliberate and informed choice of induction method that not only aligns with their question but also allows comparisons to other available literature.

Many of the different variations on the RHI paradigm (such as different induction methods) lead to effects on RHI measures such as proprioceptive drift or subjective reports. However, numerous reported dissociations show that these paradigmatic variations should not be considered equivalent (Riemer et al., 2019). For this reason, if the RHI is being used as a tool (for example to probe the development of an underlying construct during childhood) we suggest that researchers use the "classical" RHI paradigm in which a participant sees a rubber hand being stroked (Botvinick & Cohen, 1998), and avoid introducing factors with largely unknown effects (such as participants moving their hand, or themselves stroking the rubber hand). Of course, if understanding the effects of the methodological variation is the aim of the study, then there is no problem—what is important is that different variations on the RHI paradigm should not be treated as equivalent or interchangeable without due consideration to their (largely uncharted) differences.

In a similar vein, unless the effect of induction duration is of specific interest, we recommend that induction phases are at least 40 seconds (after which in adults effects have been reported to plateau (Kalckert & Ehrsson, 2017; Rohde et al., 2011). Furthermore, the order of trials within participants should be randomised or counterbalanced, since successive induction phases can have cumulative effects (Fuchs et al., 2016). In addition, we suggest that future studies focus on stroking and localising an individual finger. Although an RHI can be induced by stroking larger regions of the hand, effects such as proprioceptive drift can include parts of the hand without including others, such that the spatial configuration of the hand does not stay constant (Kammers, Longo, et al., 2009). This makes it important that the stroked location on the hand specifically matches the localisation task of the participant. In other words, if only the index finger is stroked, the participant should be asked to localise that index finger specifically, rather than the hand as a whole or another point on the hand. Furthermore, proprioceptive drift effects tend to be subtle (on the order of a few centimetres), making it important that participants are asked to localise a precisely defined point (such as a specific point on a specific finger). This avoids the unwanted variability that might result from a more ambiguous instruction, such as "point to your hand"—which might be interpreted differently by different participants.

Quantification

In a similar vein, the majority of studies in the paediatric RHI literature have used some estimate of proprioceptive drift—the change in the perceived position of the participant's occluded hand. However, studies differ in important ways in their procedure for doing so. In particular, some studies asked participants to verbally report a visual landmark that was perceived to be aligned with the position of the hand (for example using a ruler), whereas others have used pointing or matching movements with the opposite hand. Although these tasks seem equivalent, previous work in adults has shown that they can have dramatically different effects on reported estimates of perceived limb position (Kammers et al., 2006; Kammers, de Vignemont, et al., 2009). As noted by Riemer et al. (2019), given the complexity of body representations and the multifaceted effects of the RHI, it is important to keep in mind that motor actions targeting a limb involve a very different set of mechanisms than verbalising a belief about that limb's position based on a visual estimate, and it is a mistake to consider those response methods equivalent.

In this context, pointing tasks are particularly problematic, for two reasons. Firstly, individual participants might make fast, ballistic motor actions without online guidance, or slower pointing movements that might be better described as position matching (and they might potentially even switch between trials). As these actions have dissociable effects on RHI measures, this introduces unwanted variability. Secondly, this ambiguity also propagates into published literature: if a study describes a task as "pointing", it is unclear what participants in that study actually did, and as a result how the results of that study should be interpreted. Verbal responses (such as indicating when a sliding marker matches the perceived position of the target finger, or reporting the position on a ruler) avoid these complications, and we therefore suggest that future studies might avoid motor responses altogether unless motor control itself is the target of the study. However, we note that verbal responses also require a careful experimental approach, to eliminate potential confounds of memory (to avoid a participant duplicating or comparing successive reports), hysteresis (by starting a sliding marker from random directions on different trials), or timing cues (by sliding the marker at random speeds across trials). Again, we recommend that researchers make deliberate choices for different response options in line with their research question and prior research to which the experiment is intended to be compared.

Conceptualisation

Finally, our review of the psychological concepts used in the paediatric RHI literature reveals a number of terms and concepts that are used inconsistently, and in many cases appear to be used effectively interchangeably. This includes terms such as *embodiment*, *body awareness*, the *bodily self*, and *bodily self-consciousness*. Although this is understandable given the complexity and richness of the experience of embodiment combined with the wide range of experimental questions that researchers would like to ask, it also makes it unclear whether or not authors actually intend to refer to distinct concepts. As such, we recommend that authors avoid using (apparent) synonyms to circumvent replication when discussing findings and concepts in this field. Additionally, when placing a study within the broader field, it would be helpful to not only make the definitions explicit, but also to indicate whether (and how) that definition agrees with or differs from other concepts and published papers. In this respect, work by Longo et al. (2008) has been very influential in providing conceptual structure to the adult literature, and this could serve the same function in the paediatric literature.

In sum, in our review of the methodological and conceptual variation evident in the available paediatric RHI literature, we have identified a number of points on which studies show significant differences. These differences have the potential to lead to confusion and misinterpretation, and thereby threaten to hinder scientific progress in developing an understanding of how mental body representations develop throughout childhood. We hope that this overview will allow future studies to more effectively integrate with the literature that is already available. Moving forward, we also hope that this will provide a basis to develop a more coherent body of literature for paediatric RHI studies than the conceptual dispersal that currently characterises the adult literature.

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