BODY, MOVEMENT AND THE DIGITAL IN EARLY CHILDHOOD: PHYSICAL LITERACY AND EMBODIED INTERACTION IN IMMERSIVE ENVIRONMENTS

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ABSTRACT
This study investigates how children aged 3–6 engage their bodies in immersive digital environments and how such environments can be child-centred. Across 136 systematic observations in three settings, using a 91-item Physical Literacy grid, the environment strongly configured embodied experience, and bodily action and social interaction together accounted for 40% of the variance in cognition. Findings are associational. The settings proved inclusive across age and disability.

KEYWORDS
physical literacy; embodied cognition; immersive digital environments; early childhood; systematic observation.

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1. Introduction and objectives

Digital technologies are now part of the everyday ecology of early childhood, yet their educational use is frequently framed in terms of screen exposure, passivity and bodily disengagement. The LABZEROSEI project reverses this framing. It treats the digital not as an accessory tool but as a cultural and operational environment—programmable, interactive, connected, traceable—that can amplify the expressive, perceptual and relational possibilities of young children. Within this vision, the body is repositioned as an active mediator of exploration and of knowledge construction in digital settings, rather than as something the screen suppresses.

This re-framing is timely. Although Physical Literacy is increasingly recognised as a foundation for lifelong engagement in movement, the preschool years remain comparatively under-researched, and validated tools for the 3–6 range are scarce; most target school-aged children or reduce the construct to motor-skill testing (Longmuir & Tremblay, 2016; Cairney et al., 2019). Meanwhile, technology-based embodied learning has matured into a substantial field, with growing evidence that movement-based, multisensory and immersive interaction can support engagement and conceptual learning (Lindgren & Johnson-Glenberg, 2013; Johnson-Glenberg, 2018). Yet, despite an abundant literature on each separate strand, no systematic observation has so far integrated projection-based immersive rooms, multidimensional Physical Literacy, the 0–6 age band, and the embodied/affordance/agency paradigm. The present study addresses this gap with a group-level, ecological observational approach: rather than scoring individual competence, it documents how groups of children inhabit three contrasting immersive settings, shifting the frame from "exposure to stimuli" to the environment as a system of affordances with the child as agent—an emphasis that is, to our knowledge, novel for this age band.

We analyse data collected through the systematic observation grid "Body, Movement and the Digital (3–6 years)", developed within LABZEROSEI and administered in immersive environments designed to elicit movement, spatial exploration and active participation. The grid operationalises Physical Literacy not as a mere set of motor skills but as an integrated competence encompassing physical, affective, cognitive and social dimensions (Whitehead, 2010; Cairney et al., 2019). Two research questions guide the work:

D1. How does the child, through the body, interact with the digital?

D2. How can a truly child-centred immersive digital environment be designed?

Four hypotheses were formulated. H1: immersive digital environments significantly influence levels of Physical Literacy, producing differences across the physical, affective, cognitive and communicative-social dimensions. H2: consistent with embodied cognition, the physical dimension is positively associated with and contributes to predicting the cognitive dimension. H3: the affective dimension partially mediates the relationship between the physical and cognitive dimensions, so that emotional involvement amplifies the cognitive effect of bodily action. H4: the cognitive and communicative-social dimensions are strongly interrelated, reflecting the socio-constructive nature of meaning-making in immersive contexts.

2. Theoretical framework

The study rests on four interlocking constructs—Physical Literacy, embodied cognition, affordances and incorporation—which together support a reading of the digital as a relational and symbolic environment for the moving body.

2.1 Physical Literacy as a situated, multidimensional construct

Physical Literacy is understood here as the motivation, confidence, physical competence, knowledge and understanding that allow a person to value and take responsibility for movement throughout life (Whitehead, 2010). The construct is, importantly, *born embodied*: Whitehead grounds it in a monist, phenomenological view of the person as a being incarnate in the world, so that Physical Literacy and embodied cognition are not two frames to be welded together but share the same anti-dualist root. Its dimensions—physical, affective, cognitive and social—do not operate in isolation but continuously interweave, making Physical Literacy a dynamic and situated process rather than a checklist of abilities (Cairney et al., 2019). In the preschool years these competences are still emerging (Longmuir & Tremblay, 2016), and a dedicated framework links Physical Literacy, movement and cognitive development precisely in early childhood (Cairney et al., 2016)—the body–thought nexus this study examines. Measurement, however, has concentrated on older children, with only recent extensions to the preschool years (Pre-PLAy; Cairney et al., 2018), while evidence that educator-led, non-specialist provision can promote Physical Literacy in 0–6 services (Buckler et al., 2023) supports the figure of the educator as accompanying mediator adopted here.

2.2 Embodied cognition: the body builds thought

A second pillar is the thesis that the body constructs thought rather than merely serving it. From the enactive perspective, cognition arises from the sensorimotor coupling of an agent with its environment (Varela, Thompson & Rosch, 1991); perception is already the act of an incarnate subject (Merleau-

Ponty, 2012). For young children this is not a metaphor: motor activity scaffolds executive functions, emotional regulation and social interaction, and gesture frequently precedes verbal understanding. Embodied design translates this principle into the deliberate engineering of movement-based learning, in which bodily action mapped onto target concepts can support reasoning and the construction of connected mental models (Abrahamson & Lindgren, 2014; Lindgren & Johnson-Glenberg, 2013). A crucial qualification, however, is that not any movement learns: the notion of *congruence*—the coherence between the movement performed and the content to be learnt—separates superficial bodily involvement from movement that actually sustains conceptual processing (Johnson-Glenberg et al., 2014). Experimental work without immersive technology converges with this view, showing that integrating physical activity and congruent gestures improves vocabulary, science and numeracy already in preschoolers (Mavilidi et al., 2018), while a cognitive-load reading adds a caution: movement helps when it is automatised and congruent, not when it competes with working memory in a dual-task. Immersive and mixed-reality systems make the body–environment coupling especially direct, because the learner's movements continuously transform the perceptual field (Johnson-Glenberg, 2018); the present study extends this literature downward, to the 3–6 range, and outward, to ecological educational settings.

2.3 Affordances: the environment as an active device

The environment is theorised, following Gibson (1979), as a system of affordances—situated invitations to action—rather than a neutral backdrop. Antle (2013) has mapped the affordances of embodied interaction (offloading cognition into the world, using movement to think, exploiting bodily metaphors), offering a vocabulary for what a responsive environment invites the child to do. The sub-strand closest to reactive projection rooms, the Full-Body Interaction Learning Environments, shows that effectiveness depends on the quality of the sensorimotor experience designed (Malinverni & Parés, 2014) and describes a passage from "sense-in-action" to "sense-making" in which the digital does not replace bodily action but augments it, returning in real time a feedback that turns movement into an object of thought. On this basis the project treats the environment not as a container of stimuli to be administered but as a fabric of action possibilities that the child explores, selects and recombines—the affordances of a 360-degree responsive room differing qualitatively from those of a manipulative atelier.

2.4 From immersion to incorporation

A terminological point precedes the fourth construct. The immersive rooms studied here are projection-based, multisensory environments of the *CAVE*

type, distinct from head-mounted displays (HMD). The distinction matters in early childhood: projection systems leave the body free, do not isolate the child and sustain collective experience, which makes them generally preferable to headsets at an early age. Within such settings the project distinguishes *immersion*—a passive sense of being "elsewhere"—from *incorporation*, an active inhabiting of the digital with one's own body (Calleja, 2011): incorporation foregrounds agency, responsiveness and the continuous connection with the real body, so that play becomes an intensification of the here-and-now (Chee, 2016), and the degree of embodiment is associated with the depth of children's engagement (Connolly et al., 2021).

These commitments are corroborated by a maturing empirical base. Meta-analyses of immersive learning report, with particular relevance for early childhood, that effects tend to be larger in younger children than in older students (Wu, Yu & Gu, 2020), and the now-dominant Cognitive-Affective Model of Immersive Learning describes a chain from immersion through presence and agency to embodiment and outcomes (Makransky & Petersen, 2021). A design-critical mechanism is visuomotor synchrony—the real-time correspondence between movement and feedback—identified as the strongest predictor of body ownership and agency (Mottelson et al., 2023): exactly the condition reactive projections realise when they answer the child's gesture. Evidence with children under seven remains scarce, which defines the originality of this work; the few design studies for the youngest converge on a triad—agency, embodiment and affect—interwoven in meaning-making during play (Keifert et al., 2017), almost coextensive with the project's architecture. Together, these constructs support a view of the digital in early childhood as a relational, exploratory and symbolic environment that valorises the body as an active mediator of learning.

3. Method

3.1 Design and protocol

The protocol adopts a systematic, non-participant observational design in ecological settings, intended to preserve the authenticity of the educational experience. It is naturalistic (activities were not altered for research purposes), structured (a grid with predefined indicators), multi-situated (several immersive environments) and short-longitudinal (observations repeated across sessions), balancing ecological validity, comparability and interpretive depth. Each session lasted about fifty minutes; when children rotated across environments, the whole cycle was treated as a single observational unit. Observers kept a lateral, peripheral position, intervened only for safety, and focused on the whole group rather than on pre-selected individuals.

The protocol unfolded in three phases: a preparation phase, in which observers and atelieristi took part in a shared XXX-coordinated training course that defined the activities, aligned observers on the indicators and the grid, and ran a pilot round; a detection phase, in which the sessions were observed systematically and grids and qualitative notes were completed in real time; and a post-observation phase, in which debriefing focus groups reviewed the grid and the observations, completed missing parts, and triangulated the data toward design guidelines.

3.2 Settings

Three environments at the LABZEROSEI, serving educational services of the Municipality of XXX, were observed. The *Nido–Immersive Room* projects 360-degree visuals that respond to children's gestures, offering contingent multisensory feedback and a continuity between bodily action and the transformation of the visual-sonic context. The *Teatrino-Cubotto* is a more structured space in which the gesture-projection relationship is explicit and decipherable. The *Atelier* has a minimal digital setup (an audio source for music) and centres on manipulation, drawing and graphic exploration, where movement leaves concrete, visible traces. The three settings thus instantiate three distinct profiles of affordance.

3.3 Sample

The corpus comprises 136 systematic observations collected between November 2025 and February 2026 by seven trained observers (trainees of the Master "The Digital to the Measure of the Zero-Six" and Media Education thesis students, Università Cattolica del Sacro Cuore, Milan; coordinated by CREMIT). Observations were balanced across settings: Teatrino-Cubotto n = 45 (33.1%), Nido–Immersive Room n = 45 (33.1%), Atelier n = 46 (33.8%). Age groups: 4 years n = 76 (55.9%), 5 years n = 57 (41.9%), mixed 4–5 n = 3 (excluded from age comparisons). In 39 observations (28.7%) at least one child with a disability or with Italian as a second language (L2) was present.

3.4 Unit of analysis

The grid is completed at group level: the observer rates the collective conduct of the group within each environment, not the single child. Scores therefore reflect the group's experience, no inferences about individual Physical Literacy are possible, and comparisons by age or by disability/L2 concern group composition rather than individual functioning. This choice captures the ecological dynamics of bodily-digital interaction—imitation, cooperation, co-construction and conflict—consistent with systematic observation in preschool research, where the unit is the context rather than the individual (Sylva et al., 2004; Harms et al., 2014).

3.5 Instrument

The grid contains 91 items (plus a 12-item material-use scale for the Nido) organised into four dimensions: Physical (DF, 37 items: locomotion, transitions, control/manipulation, balance, coordination, adaptation to context), Affective (DA, 15 items: engagement, autonomy/regulation), Cognitive (DC, 20 items: intentionality/problem solving, narration/awareness) and Behavioural/communicative-social (DCOM, 19 items: interaction with peers and with adults). Items are rated on a four-level scale (1 = No to 4 = Yes), with an N/A option treated as missing. A free-text field records qualitative notes on significant or unforeseen episodes, in descriptive, non-judgmental language. The grid was built on recent literature on Physical Literacy in early childhood (Longmuir & Tremblay, 2016), on digital embodiment (Calleja, 2011; Connolly et al., 2021) and on the pedagogical principles of LABZEROSEI.

3.6 Likert treatment, reliability note and analysis

Given the ordinal four-point data, the uneven and limited subsamples and the non-normal distributions, non-parametric tests (Kruskal–Wallis, Mann–Whitney U) were used for all group comparisons, while arithmetic means served as summary indices—a pragmatic approach widely endorsed in the methodological literature, where averaging many Likert items yields approximately continuous indices robust to scale assumptions (Carifio & Perla, 2008; Norman, 2010; Sullivan & Artino, 2013); ANOVA results, reported for comparison, were concordant. The decision to observe rather than test Physical Literacy follows the model of observed physical literacy, which defines behavioural indicators detectable in situ (Dudley, 2015); educator completion with checking of observer agreement mirrors instruments such as Pre-PLAy (Cairney et al., 2018); and the profiling of interaction styles is analogous to the latent-profile approaches already used to describe Physical Literacy profiles (Brown, Dudley & Cairney, 2020). Reliability was assessed with Cronbach's alpha; structural validity with exploratory factor analysis (EFA; ML extraction, Promax rotation), with sampling adequacy checked through the KMO index and Bartlett's test and the number of factors determined via Parallel Analysis (Horn, 1965). Spearman's rho served for correlations (and partial correlations controlling for environment); K-means clustering identified interaction profiles; OLS multiple regression and bootstrapped mediation (5,000 resamples; Baron & Kenny, 1986; Preacher & Hayes, 2008) examined the associations among dimensions; qualitative notes were analysed thematically (Braun & Clarke, 2006) and via content analysis (Bardin, 1977/2011). Analyses were run in Python 3.12; $\alpha = .05$.

Three caveats frame the inferential analyses and are developed in the limitations. Bonferroni correction was applied to the post-hoc environment

comparisons, but the study comprises many tests, so the family-wise error rate is not fully controlled and results beyond the principal environment effects are exploratory. Inter-rater agreement indices were not computed: consistency was supported through shared training, a common protocol and pilot calibration, but this does not substitute for a quantified estimate. And because all four dimensions are rated by the same observer, on the same group, at the same moment, the associations among them are susceptible to halo effects and common-method variance, which qualifies the correlational, regression and mediation results.

4. Results

4.1 Descriptive statistics and reliability

On the 1–4 scale the four dimensions ranged between 2.05 and 2.63. The Affective dimension scored highest (M = 2.63, SD = 0.31), followed by the Physical (M = 2.42, SD = 0.42) and Behavioural (M = 2.29, SD = 0.30) dimensions; the Cognitive dimension was lowest (M = 2.05, SD = 0.50) with a marked positive skew (0.95). The hierarchy DA > DF > DCOM > DC is consistent with the developmental picture: in the preschool years emotional involvement is the primary channel of relation with the environment, followed by bodily activation, while advanced cognitive competences—symbolic narration, verbalised bodily awareness, intentional problem solving—are still developing (Longmuir & Tremblay, 2016).

Table 1: Descriptive statistics by dimension (scale 1–4, N = 136)

Dimension	M	SD	Mdn	Skew
Physical (DF)	2.42	0.42	2.38	0.21
Affective (DA)	2.63	0.31	2.60	0.16
Cognitive (DC)	2.05	0.50	2.00	0.95
Behavioural (DCOM)	2.29	0.30	2.26	0.75

Internal consistency was excellent for the full 91-item scale (α = .918). Among dimensions, DC (α = .899) and DF (α = .851) were good, whereas DA (α = .619) and DCOM (α = .656) fell below the conventional .70 threshold. Two subscales returned negative alphas—Balance (α = -.095) and Autonomy/regulation (α = -.005)—because they aggregate heterogeneous or oppositely worded indicators (e.g. "standing still" versus "balance on one foot"; "experiments without prompts" versus "avoids tasks"). These local weaknesses indicate concrete

revisions (reversing negatively worded items, reorganising subdimensions) rather than a failure of the instrument as a whole.

4.2 Structural validation (EFA)

The exploratory factor analysis must be read as heuristic rather than confirmatory, and none of the study's conclusions rests on it. Sampling adequacy was mediocre (KMO = .621), the subject-to-item ratio was far below convention (≈ 1.5:1), and the retained solution explained only 23.3% of the variance; Bartlett's test was significant (χ^2 = 9236.5, df = 4095, $p < .001$) and Parallel Analysis retained seven factors. Within these strong limits, the theoretical four-factor solution received only partial support: cognitive and communicative-social items tended to merge into a single "cognitive-narrative-social" grouping; the physical dimension split into functionally distinct sub-profiles (ground motricity, sensorimotor adaptation, rhythmic motion); and the affective dimension distributed transversally rather than emerging as an autonomous factor. This tentative pattern is coherent with the notion of a "felt sense" in Physical Literacy (Whitehead, 2010), in which affect is a background tone rather than an isolable module, and it suggests a hypothesis to be tested—a parsimonious structure of three macro-factors (corporeal-adaptive, cognitive-social, rhythmic motricity) with affect as a transversal construct—via confirmatory factor analysis on a substantially larger sample. The negative subscale alphas reported above are consistent with this provisional picture and flag specific items for revision.

4.3 Comparison between environments (D2)

The comparison across settings is the core of the analysis. Statistically significant differences emerged for three of the four dimensions. The strongest effect concerned the Physical dimension ($H(2) = 31.875$, $p < .001$, $\eta^2 = .234$, large), with the Nido highest (M = 2.687), followed by the Teatrino (M = 2.374) and the Atelier (M = 2.204). The Cognitive dimension showed a medium-large effect ($H(2) = 21.254$, $p < .001$, $\eta^2 = .144$), again favouring the Nido. The Affective dimension showed a small but significant effect ($H(2) = 10.779$, $p = .005$, $\eta^2 = .080$), whereas the Behavioural dimension did not differ across settings ($H(2) = 1.820$, $p = .403$). At subdimension level, Adaptation to context produced the largest effect of the whole dataset ($\eta^2 = .382$), confirming that the immersive room most strongly solicits the child's capacity to modulate movement in response to the digital.

Figure 3. Dimension means by environment (Kruskal–Wallis: *** p<.001, ** p<.01)

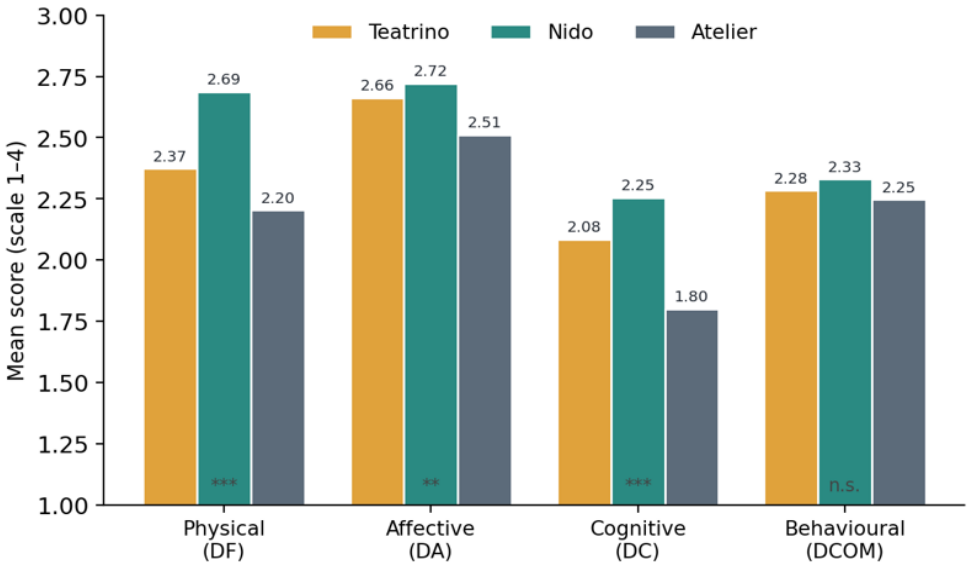


Figure 1: Dimension means by environment and omnibus test (Kruskal–Wallis).

Post-hoc comparisons (Mann–Whitney U, Bonferroni) showed the Nido dominating the Atelier with large effects on DF (r = -.686) and DC (r = -.522), with the Teatrino intermediate and cognitively richer than the Atelier. The lower Atelier scores do not warrant a deficit reading: the qualitative notes show it activating a different, manipulative and symbolic grammar of experience, with affective engagement that grows from the first to the third visit (rho = .404, p < .01), suggesting it needs time to be fully inhabited. The Teatrino emerged as a "cognitive laboratory" in which children try to decode the gesture-projection mechanism (49% of the notes about discovering how the environment works came from this setting).

4.4 Age, visit order and the structure of relations

Age differences (4 vs 5 years) were significant only for the Cognitive dimension (U = 1661, p = .022, r = .233); the physical, affective and behavioural dimensions did not differ, indicating that the settings are accessible across the 4–5 range without requiring age-specific competences. Visit order had no effect on any dimension (all p > .41), validating the counterbalanced design, the only exception being the growth of Atelier engagement across repeated visits. All six pairwise Spearman correlations were positive and significant and, importantly, remained significant in partial analyses controlling for environment, showing

that the associations are not artefacts of certain settings producing globally higher scores (Table 3). The strongest was DF–DA (rho = .604), followed by DC–DCOM (rho = .455) and DF–DC (rho = .413); the weakest was DF–DCOM (rho = .232), suggesting that body and social relation are relatively independent channels.

Table 2: Bivariate and partial (controlling for environment) Spearman correlations among dimensions (N = 136).

Pair	rho	p	Partial rho	p
DF–DA	.604	< .001	.568	< .001
DF–DC	.413	< .001	.291	< .001
DF–DCOM	.232	< .01	.206	< .05
DA–DC	.361	< .001	.283	< .001
DA–DCOM	.396	< .001	.381	< .001
DC–DCOM	.455	< .001	.449	< .001

4.5 Interaction profiles (cluster analysis)

K-means clustering identified three profiles of bodily-digital interaction: a Low-engagement profile (n = 69, 51%) with low scores throughout, prevalent in the Atelier; a Motor-affective profile (n = 51, 38%) high on DF and DA but moderate on DC and DCOM, prevalent in the Nido; and an Integrated profile (n = 16, 12%) high on all dimensions—the "ideal" Physical Literacy configuration. The cluster-environment association was highly significant ($\chi^2 = 28.74$, $p < .001$), whereas the cluster-age association was not ($p = .538$); the solution was stable across methods (K-means vs Ward, ARI = .671). These styles of embodied interaction—exploratory-cautious, corporeal-emotional and integrated—depend on the environment rather than on age, which is strong evidence for D2: it is the context, not individual development, that is associated with the type of interaction. This results reinforce the reading of interaction style as configured by the setting.

Motor-affective 51 (38%) 2.73 2.78 2.09 2.26 Nido (0.27) (0.22) (0.32) (0.19)

Integrated 16 (12%) 2.83 3.05 2.96 2.80 Nido (0.35) (0.23) (0.44) (0.27)

Table 3: Centroids of the three interaction profiles (k-means, k = 3) on the four dimensions, in the original 1–4 scale (M and SD; N = 136).

Profile	n (%)	DF M (SD)	DA M (SD)	DC M (SD)	DCOM M (SD)	Setting
Low-engagement	69 (51%)	2.10 (0.22)	2.42 (0.22)	1.80 (0.33)	2.19 (0.24)	Atelier
Motor-affective	51 (38%)	2.73 (0.27)	2.78 (0.22)	2.09 (0.32)	2.26 (0.19)	Nido
Integrated	16 (12%)	2.83 (0.35)	3.05 (0.23)	2.96 (0.44)	2.80 (0.27)	Nido

4.6 Associations among dimensions: regression and mediation (D1)

A multiple regression predicting the Cognitive dimension from the physical, affective and behavioural dimensions accounted for 40% of its variance (R^2 = .400, $F(3,132) = 29.34$, $p < .001$). The significant predictors were the Behavioural dimension (β = .450, $p < .001$) and the Physical dimension (β = .338, $p < .001$); the Affective dimension did not contribute once the others were controlled (β = .021, p = .814), with all VIF < 1.71. In this context, then, higher cognitive scores are statistically associated with bodily action and social interaction rather than with emotional involvement per se. A parallel model for the Affective dimension showed it to be associated with the physical (β = .489) and behavioural (β = .307) dimensions. These models are correlational and cross-sectional; the labels "predictor" and "mediator" are used in their statistical sense and do not imply temporal or causal precedence.

Table 4: Multiple regression predicting the Cognitive dimension (N = 136, R^2 = .400).

Predictor	β	t	p
Physical (DF)	.338	4.13	< .001
Affective (DA)	.021	0.24	.814
Behavioural (DCOM)	.450	6.03	< .001

A bootstrapped mediation model DF → DA → DC indicated a partial indirect association (ab = .148, 95% CI [.029, .309]), corresponding to 27.6% of the total association, with 72.4% remaining direct; an alternative path through social

interaction (DF → DCOM → DC) carried a further 22.6%. Read cautiously, these results are compatible with H2 and H3 and qualify H4, pointing to an interwoven body–affect–relation system rather than to separable domains. Two cautions are essential here. The data are cross-sectional, so the decomposition into direct and indirect effects describes statistical structure, not a temporal process. Moreover, because all dimensions share a single rater and moment of observation, part of the inter-dimensional covariance—and hence part of the 40% "explained"—may reflect common-method variance and halo rather than relations among the children's behaviours; the magnitude of the associations should be treated as an upper bound.

Figure 2. Partial mediation of the body–cognition association by affective involvement

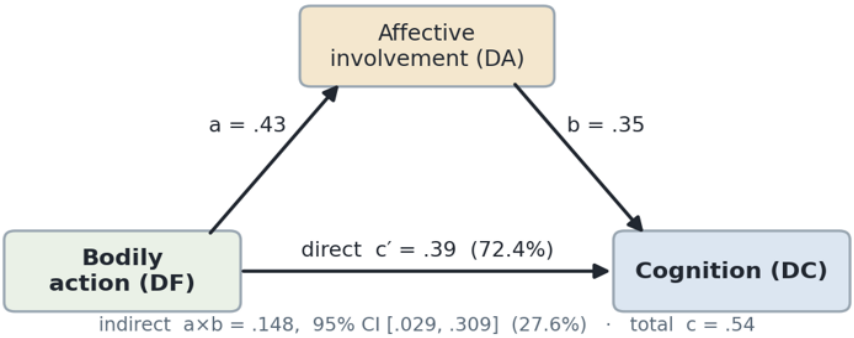


Figure 2: Partial mediation of the body–cognition association by affective involvement (N = 136).

4.7 Inclusiveness (disability and L2)

No main dimension differed significantly between groups with and without children with disability or L2 (all $p > .23$, all $|r| < .14$); the only significant subdimension was DF-Coordination, slightly higher in groups including such children ($p = .047$). The cluster-disability association was likewise non-significant ($\chi^2 = 1.75$, $p = .417$). The immersive environments thus appear genuinely inclusive: they offer multiple, naturally accessible channels of participation—body, gesture, rhythm, perceptual attention—so that group composition in terms of disability does not alter the patterns of bodily-digital interaction. A vignette is telling: a child on the autism spectrum followed at

length the shadows moving with him and, without verbalising, showed he had grasped the relationship between his own movements and the projected ones.

4.8 Qualitative thematic analysis of observational notes

Of the 136 observations, 92 (67.6%) contained non-empty qualitative notes. A deductive-inductive thematic analysis (Braun & Clarke, 2006) yielded 17 themes in five macro-themes: agency and intentionality, relation and sociality, embodiment, emotion and involvement, and inclusion. The dominant macro-theme was agency: children appeared as active agents who verbalise, interpret, hypothesise mechanisms and create stories. The most frequent themes were verbalisation of the experience (53% of notes), symbolic play (32%), discovery of how the environment works (28%) and bodily exploration (26%). The frequency of symbolic play is notable—children transform the projections into narrative worlds ("we are in space", "there's water, help!")—and the qualitative evidence converges with the quantitative findings, strengthening the overall reading through triangulation.

5. Discussion

Read against the four hypotheses, and within the evidential limits set out below, the pattern is largely confirmatory. H1 is supported: the environments differ significantly on three of the four dimensions, with a large effect on the physical dimension, so the setting clearly shapes the levels of Physical Literacy expressed. H2 is supported in associational terms: the physical dimension is positively related to, and a significant statistical predictor of, the cognitive dimension. H3 receives partial support: affect carries a significant but modest indirect share of the body–cognition association (about 28%), consistent with partial rather than full mediation. H4 is partially supported and partly reframed: the cognitive and communicative-social dimensions are strongly interrelated, yet social interaction appears to act as a co-determinant of cognition alongside the body rather than merely correlating with it. The sections that follow develop these verdicts and the cautions that qualify them.

5.1 Reading the environment and the body together (D1, D2)

The most robust result of the study concerns the role of the environment, and it speaks directly to D2. The differences between settings are structural rather than marginal: the Physical dimension shows a large effect ($\eta^2 = .234$) and the subdimension Adaptation to context the largest of the dataset ($\eta^2 = .382$), implying that the environment is not a neutral container but a factor that configures the kind of experience a child can have. The three settings appear to afford three complementary forms of embodied experience: the Nido behaves as an *embodied-reactive* space that "wraps" every child relatively uniformly

(lowest variability, CV = 13.8% for DF); the Atelier as a *symbolic-reflective* space whose manipulative affordances need time to be discovered; and the Teatrino as a *guided-interactive* space in which children decode the gesture-projection mechanism. The answer to D2 is therefore not that "the Nido works best"—the lower Atelier scores index a different grammar of experience, not a deficit—but that a complete pathway should orchestrate all three affordance types.

Turning to D1, the body occupies a central place in the data. The physical dimension correlates with the cognitive (rho = .413) and, more strongly, with the affective dimension (rho = .604), and in the regression it remains a significant correlate of cognition alongside social interaction. Taken together, these patterns are consistent with an embodied-cognition reading in which movement is closely bound up with, rather than merely accompanying, the child's sense-making in the immersive setting—consistent, too, with what observers describe as the moment when the effect of a gesture becomes perceptible and attributable. We frame this associationally by design: the study is cross-sectional and single-rater, so part of the inter-dimensional covariance may reflect halo and common-method variance rather than relations among the children's behaviours. The figure of "40% of cognitive variance" is therefore best read as an upper bound, and the direct/indirect decomposition as statistical structure rather than temporal sequence.

5.2 An interwoven, socio-constructive system

Within these limits, the convergence of several analyses is informative. The tendency of cognitive and communicative-social items to group together, the strong DC–DCOM correlation (rho = .455) and the leading weight of the behavioural dimension in the regression (β = .450) are jointly compatible with a socio-constructive reading, in which narration and social interaction operate as a single process and cognition is intrinsically social. Yet the disappearance of any independent contribution of affect once body and relation are controlled, and the weak DF–DCOM correlation (rho = .232), suggest that the dimensions are interwoven without collapsing into one another. In this light the instrument is best understood not as a device for isolating pure domains but as one for making visible the configurations in which body, emotion, thought and sociality combine. The qualitative material reinforces this by foregrounding the child's agency, and the three interaction profiles capture different ways of inhabiting the digital. That these profiles depend on the environment rather than on age, and that the presence of children with disability or L2 does not alter the group patterns, reframes "difference" as a design variable rather than a developmental given.

5.3 A tentative conceptual model

The findings can be drawn together into a provisional, hypothesis-generating model with four interrelated levels: the environment operates as a system of affordances, each setting offering a specific profile; these affordances are associated with bodily activation, which co-occurs with affective involvement and social interaction; and the cognitive dimension patterns as the product of this interwoven system, related to bodily action both directly and through emotion and social exchange. Rather than a linear pipeline, the model is best imagined as dynamic and circular, with cognition feeding back to reorganise action, relation and involvement. So framed, it integrates Physical Literacy (Whitehead, 2010), embodied cognition (Varela et al., 1991) and affordance theory (Gibson, 1979), and sits alongside contemporary embodied-design principles for immersive learning (Lindgren & Johnson-Glenberg, 2013; Johnson-Glenberg, 2018). Because the supporting evidence is correlational and single-rater, the model is advanced as a structure to be tested—ideally with multilevel, longitudinal and multi-rater designs—rather than as a confirmed causal account.

Figure 3. A dynamic, circular model of embodied learning in immersive environments.

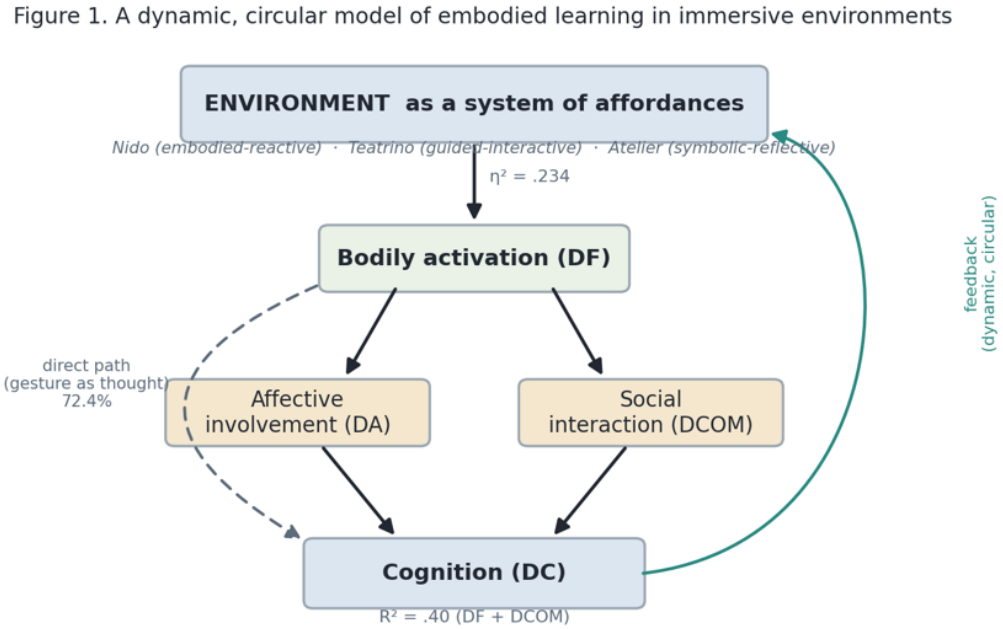


Figure 3: A dynamic, circular model of embodied learning in immersive environments

These patterns extend, to a younger and more ecological context, results obtained mainly with school-aged learners in controlled mixed-reality settings (Lindgren & Johnson-Glenberg, 2013; Johnson-Glenberg, 2018): whereas embodied-design studies typically manipulate a single task and measure individual gains, the present work shows whole groups of 3–6-year-olds spontaneously mobilising body, emotion and social interaction across contrasting environments, connecting the embodied-learning tradition with the early-childhood Physical Literacy agenda. The convergence is not without tension, since the disappearance of affect as an independent predictor once body and relation are controlled suggests that emotional involvement here is a pervasive "felt sense" rather than a separable lever—a nuance that purely cognitive accounts of immersive learning tend to miss.

6. Pedagogical implications

With the evidential caveats above in mind, the study still yields coherent, design-relevant guidance for immersive digital environments in the 3–6 range, each suggestion anchored to a specific observation. The clearest implication is that the three settings should be treated as complementary rather than as hierarchical alternatives: because each affords a distinct grammar of experience—the Nido inviting children to inhabit the digital with the body, the Teatrino to decode it, the Atelier to re-elaborate it creatively—a complete pathway would include all three rather than privilege the one with the highest mean scores. The sequence also seems to matter: since affective engagement in the Atelier grows across repeated visits (rho = .404, $p < .01$), the data are compatible with opening in the Nido, continuing in the Teatrino and closing in the Atelier.

The adult's posture emerges as a second lever. Qualitatively, adult involvement is more salient in observations with lower cognitive scores, and the same intervention can either facilitate—through open questions such as "Where are you?" or "Try moving with your whole body"—or interfere, by anticipating discoveries or imposing rules; when the adult supplies the answer, the child loses the chance to construct it. This argues for training in non-directive observation, open questioning, tolerance of the initial "empty" minutes as part of discovery, and the valorisation of children's findings—a posture best understood as maieutic and reflective, the adult acting as a "thinking witness" who observes, documents and relaunches (Schön, 1983; Rinaldi, 2006). Mediation should also be differentiated by age where the setting demands it: the cognitive gap between four- and five-year-olds widens in the Atelier, where multisensory affordances do not "flatten" age differences as in the immersive

room, so younger children there benefit from more time, more explicit bodily prompts and the modelling of older peers.

Two further indications concern materials and grouping. Physical objects appear to compete with the projections when introduced too early, so the more productive sequence is free spatial exploration, then consolidation of the body-projection relationship, and only then materials offered without instructions as "amplifiers" of an experience already under way. Grouping, finally, can be inclusive by default: the absence of differences linked to disability or L2, and the lack of association between disability and interaction profiles, indicate that the immersive environments neither exclude nor distort the interaction patterns of heterogeneous groups. Beyond the children, the research device itself proved formative, as the debriefing focus groups shifted the professionals' gaze from a descriptive toward an epistemological and design-oriented stance—an outcome that suggests institutionalising systematic observation and collective re-elaboration as part of educational practice, in the spirit of a reflective community of practice (Mezirow, 1991; Wenger, 1998).

7. Limitations and future directions

Several limitations bound the interpretation of these results. The most consequential is methodological: all four dimensions are rated by a single observer, at a single moment, on the same group, so the associations among them are vulnerable to halo effects and common-method variance, and the reported magnitudes—including the regression and mediation estimates—should be read as upper bounds. Compounding this, inter-rater agreement indices (Cohen's κ or ICC) were not computed: shared training, a common protocol and pilot calibration supported consistency but do not substitute for a quantified estimate, a notable gap for a study whose contribution includes the instrument. The EFA is constrained by the subject-to-item ratio (≈ 1.5:1) and the mediocre KMO (.621) and is offered as heuristic only. Because the plan comprises many tests, with Bonferroni correction applied only to the principal post-hoc comparisons, the family-wise error rate is not fully controlled and secondary results are exploratory. The study is single-site and short; the unit of analysis is the group, so no inferences about individual children are possible; the disability/L2 variable indicates group presence rather than individual observation; and the mixed 4–5 group was too small (n = 3). Crucially, the same groups rotated across the three settings, so the observations are not fully independent, which the present analyses do not model. Future work should therefore prioritise multilevel and longitudinal designs with multiple independent raters; a confirmatory factor analysis on a larger sample (≥ 450); inter-rater reliability; a fuller integration of the qualitative material; a revision

of the problematic items; an extension to the 3–4 range; and the study of environment × profile interactions.

8. Conclusions

The LABZEROSEI data yield a rich and internally coherent picture, read here cautiously given the correlational, single-rater, group-level design. The observation grid is highly reliable (α = .918), and its (exploratory) factor structure suggests that the dimensions of Physical Literacy behave less as separate compartments than as interconnected aspects of the bodily-digital experience. The central pattern is that the cognitive dimension is associated with bodily action and social interaction—together accounting for about 40% of its variance, with a partial indirect path through affect—a configuration compatible with an embodied, socio-constructive account of early learning rather than a demonstration of causal direction. The immersive room is the setting most often associated with integrated Physical Literacy profiles, yet each environment affords a distinct and pedagogically valuable form of experience, and the absence of effects of age, visit order and disability speaks to the accessibility of the environments across the groups observed. For practice, designing digital environments "to the child's measure" means designing for the moving, feeling, relating body—not for the screen alone—and treating the digital as a relational, exploratory and symbolic environment in which young children co-construct meaning. Confirming these patterns, and testing their direction, will require the multilevel, longitudinal and multi-rater work outlined above.

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