

Grasping Letters in Space: Embodied and Digital Ecologies for Inclusive Reading

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Abstract: The Dual Route Cascaded (DRC) model (Coltheart et al., 2001) remains a foundational framework for understanding reading processes and developmental dyslexia, linking reading difficulties to the efficiency and automatization of phonological and lexical pathways. While the DRC provides a robust account of decoding mechanisms, recent research invites a broader reflection on the conditions under which these processes are enacted. This paper offers a theoretical contribution that integrates cognitive models of reading with perspectives from embodied, extended, and ecological cognition. Within this framework, phonological and morphological decoding are discussed as dynamic coordination processes involving visual, auditory, and action-related information. Embodied and digitally mediated environments are examined as ecological contexts that may support the stabilization and integration of decoding processes by making linguistic structures perceptible, manipulable, and spatially organized. Embodied and digital ecologies are not discussed as corrective tools, but as conditions that may expand the range of viable reading experiences while remaining grounded in established theories of reading development.

Keywords: Dyslexia, Neurodiversity, Embodied cognition, Extended cognition, Immersive Technologies.

1. Introduction

Reading proficiency represents a fundamental competence for active participation in social, cultural, and democratic life. The *Italian National Guidelines for the Curriculum* (MIUR, 2012; MIM, 2025) emphasize that the development of solid linguistic competences is an essential condition for personal growth, citizenship, and critical access to knowledge.

Psychological and linguistic research has long demonstrated that reading relies on the integration of multiple components, including visual word recognition, phonological processing, access to the mental lexicon and semantic representations, as well as the coordination of attentional and memory resources (Coltheart et al., 2001;

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Dehaene, 2009; Snowling et al., 2022). These processes are shaped by experience, educational practices, and cultural tools (Snowling et al., 2022).

Dyslexia is defined as a neurodevelopmental profile characterized by persistent difficulties in the automatization of decoding processes, in the absence of general cognitive deficits or unfavorable sensory and environmental conditions (American Psychiatric Association, 2013; 2022; Peterson & Pennington, 2015).

Recent years have witnessed growing interest in approaches that conceptualize cognition as a process distributed across brain, body, artefacts, and environment. Embodied and extended cognition perspectives emphasize that cognitive functions emerge from the coupling of neural processes, bodily action, and material contexts (Clark, 2008). In educational research, these approaches have prompted a rethinking of digital technologies not as compensatory tools, but as components of learners' cognitive ecologies, where learning unfolds through interaction with material and symbolic environments (Magnani, 2008; Riva et al., 2019).

Building on the Dual Route Cascaded model of reading (DRC) (Coltheart et al., 2001) and integrating embodied and ecological perspectives, this paper offers a theoretical reflection on how letters and words may be experienced not only as static visual symbols, but as manipulable, spatialized, and multisensory entities within digitally mediated environments designed according to inclusive pedagogical principles.

2. Theoretical Framework: Reading Processes, Neurodiversity, and Embodied Cognition

2.1. *The Dual Route Cascaded Model of Reading*

The contemporary models of reading describe written language processing as the result of interactions among multiple cognitive mechanisms. Among these, the DRC model proposed by Coltheart et al. (2001) remains one of the most influential frameworks for understanding visual word recognition and reading aloud in alphabetic writing systems.

According to the DRC model, skilled reading relies on two partially independent yet interacting processing pathways. The lexical route enables readers to recognize familiar words as whole units, allowing direct access to stored orthographic representations and associated semantic information. This route supports fast and automatic word recognition, particularly for high-frequency and irregular words. In parallel, the sublexical (phonological) route converts graphemes into phonemes through rule-based processes, enabling the decoding of unfamiliar words and pseudowords by assembling their constituent sounds.

A key assumption of the DRC model is that these routes operate in parallel and in a cascaded manner, meaning that partial activation at one level of processing can influence subsequent stages before earlier processing is fully complete (Coltheart et al., 2001). Importantly, the model describes a universal functional architecture of skilled reading, rather than distinct reader types, and thus provides a general account of how written input may be transformed into spoken language.

2.2. *Dyslexia within the Dual Route Framework: Phonological and Morphological Decoding*

Within the DRC framework, developmental dyslexia (henceforth dyslexia) has traditionally been interpreted as a difficulty in the efficiency and automatization of specific components of the reading system, most frequently those involved in phonological processing (Snowling, 2000; Peterson & Pennington, 2015). Dyslexia is now widely understood as a neurodevelopmental profile characterized by variability in how reading-related processes are organized and stabilized over time.

Converging evidence consistently identifies phonological processing as a central locus of difficulty in dyslexia. Vellutino et al. (2004) demonstrated that persistent reading difficulties are most reliably associated with deficits in phonological awareness and alphabetic coding, rather than with visual, semantic, or general learning impairments. Dyslexia is thus primarily linked to difficulties in establishing stable and efficient grapheme–phoneme mappings, leading to reduced automatization of word identification and decoding processes. Weakly specified phonological representations constrain the consolidation of orthographic knowledge and the development of fluent reading, while not implying global cognitive deficits.

Hence, phonological decoding can be reconceptualized as a process of temporal and multisensory coordination rather than a purely symbolic conversion of graphemes into phonemes. Efficient decoding requires the alignment of visual letter forms, auditory speech sounds, and articulatory patterns within constrained temporal windows. Difficulties observed in dyslexia—such as unstable grapheme–phoneme correspondences or slow, effortful decoding—may therefore reflect reduced efficiency in stabilizing coordinated representations rather than an absence of phonological knowledge.

Notably, phonological decoding does not operate in isolation. Systematic reviews highlight its interaction with additional linguistic dimensions, including morphological decoding (Peterson & Pennington, 2015). Morphological parsing—the ability to recognize and manipulate meaningful sublexical units such as roots, prefixes, and suffixes—provides a complementary pathway for linking written forms to meaning, particularly in later stages of reading development or in morphologically rich languages.

From a dual-route perspective, morphological decoding contributes to both routes: supporting lexical access through reinforced form–meaning mappings and scaffolding sublexical processing by chunking complex words into meaningful units. Both phonological and morphological decoding rely on the stabilization of relationships among visual, auditory, and semantic representations, underscoring the centrality of integration processes rather than isolated skills.

Variability in phonological and morphological decoding is understood as part of a broader spectrum of cognitive styles shaped by linguistic experience, neural organization, and environmental conditions.

2.3. *From Cognitive Models to Neural Networks*

Neurocognitive research has provided converging evidence that reading relies on the functional specialization of visual and language-related brain regions. In particular, neuroimaging studies have identified the Visual Word Form Area (VWFA), located in the left occipito-temporal cortex, as a key region involved in the visual recognition of written words and letter strings (Dehaene, 2009).

The VWFA's activity reflects learned sensitivity to the statistical regularities of a writing system and its functional integration with phonological and semantic representations (Dehaene et al., 2015).

Although reading-related activity involves a broader left-lateralized network, including temporo-parietal and frontal regions, the VWFA provides a crucial neural interface between visual input and language processes, supporting the rapid identification of letter sequences that feed phonological and lexical decoding. Importantly, the heterogeneity documented in multiple-case studies of adults with dyslexia suggests that reading difficulties emerge from complex interactions among phonological, perceptual, and cognitive factors rather than from a single underlying condition (Ramus et al., 2003). This variability underscores the relevance of ecological and embodied approaches that focus on how reading-related processes are coordinated within specific learning environments.

2.4. Embodied and Extended Perspectives on Reading

While cognitive and neurocognitive models such as the DRC framework provide essential insights into the functional architecture of reading, they offer a limited account of how decoding processes are shaped by interaction with the body, artefacts, and environment.

Linguistic representations are not detached symbols, but are shaped by patterns of perception, articulation, and interaction.

Indeed, theories of extended cognition propose that cognitive processes may extend beyond the boundaries of the individual brain to include artefacts, technologies, and environmental structures that actively participate in thinking (Clark, 2008).

Applied to reading, these perspectives suggest that phonological and morphological decoding are not solely internal operations, but processes enacted within specific material and spatial conditions. The coordination of visual symbols, speech sounds, and articulatory routines is influenced by how letters and words are presented, manipulated, and temporally structured within an environment. From this perspective, embodiment does not replace symbolic processing, but highlights the ecological dimension of decoding—namely, the conditions under which phonological stabilization and form–meaning integration become achievable.

Attempts to modify the perceptual conditions of reading have also been proposed, such as optical or spectral filtering devices. However, some of these approaches remain highly controversial, as their theoretical assumptions and empirical validation have been questioned by independent scholars.²

These perspectives suggest that reading processes are shaped not only by internal cognitive mechanisms, but also by the ecological conditions under which phonological and morphological decoding are enacted—a premise that informs the design-oriented studies discussed in the following section.

² For instance, the hypothesis linking developmental dyslexia to ocular symmetry and visual mirror perception (Le Floch & Ropars, 2017) has been widely criticized on methodological and ethical grounds, and subsequent commentaries and independent trials have failed to provide robust evidence of efficacy (Naudet et al., 2024). These debates highlight the importance of grounding ecological and perceptual interventions within established models of language and reading development.

3. Embodied and Digital Ecologies for Reading

Recent research in educational technology and inclusive pedagogy has explored how embodied, tangible, and immersive environments may support reading and language-related processes by reshaping the ecological conditions in which they are enacted. Rather than proposing alternative models of reading, these approaches investigate how multisensory interaction, spatial organization, and learner agency can facilitate access to linguistic structures, particularly for neurodivergent profiles.

3.1. Embodied and Tangible Interfaces for Linguistic Structuring

One prominent line of work concerns tangible and embodied interfaces for language learning and morphosyntactic awareness. Beccaluva et al. (2022) present Moovy, a tangible user interface designed to support linguistic skills through physical manipulation and spatial arrangement. By allowing learners to interact with grammatical and lexical units through bodily action, the system externalizes abstract linguistic relations and supports learning through sensorimotor coordination. Although originally developed for grammar training, Moovy exemplifies how embodied interaction can render linguistic structures perceptible and manipulable, fostering active engagement and supporting the organization of linguistic processes.

3.2. Immersive Digital Environments, Agency and Neurodiversity

Immersive environments may reshape the experiential conditions of reading. A qualitative study by O'Neil et al. (2025) examined the use of immersive virtual reality (IVR) with students with dyslexia, highlighting how multisensory and spatial interaction can support letter recognition and phonological awareness while simultaneously strengthening learners' perceptions of themselves as competent readers. Rather than framing IVR as a remedial tool, the study emphasizes its role in agency, confidence, and engagement, suggesting that embodied interaction allows learners to develop personalized strategies for coordinating visual and phonological information.

A broader theoretical grounding for these design-oriented approaches is provided by research on digitality and neurodivergence. Blume and Bündgens-Kosten (2023) argue that digitally mediated environments can function as spaces of epistemic legitimacy for neurodivergent learners, supporting alternative modes of interaction, representation, and participation that move beyond deficit-oriented frameworks. Although situated beyond early literacy, this perspective offers a relevant lens for understanding how digital ecologies may support learners' identities as competent language users—an aspect increasingly recognized as central to inclusive literacy practices.

3.3. Immersive Educational Environments and XR Research in Language Learning

XR-based educational environments can support language learning through multisensory integration and spatialized interaction. In this regard, converging evidence from Immersive Educational Environments (IEEs) suggests that immersive, multisensory settings may support not only specific linguistic subskills but also broader dimensions of accessibility and engagement. In a mixed-method study with university students with dyslexia learning English as a foreign language, Staggini (2025) compared an online course delivered through interactive IEEs with a control

condition based on traditional non-immersive materials. Results indicate higher overall progress in the immersive condition, alongside more robust patterns in lexical performance for tasks requiring contextual inference and word use, as well as higher engagement and completion rates. Despite limitations related to sample size, these findings support the interpretation of immersive environments as ecological scaffolds: they do not replace linguistic instruction, but reorganize learning conditions by coupling multimodal input, navigable space, and structured feedback in ways that can support participation and stabilization of language processes for neurodivergent learners.

Beyond formal studies, a growing number of XR/AR design explorations investigate how spatialized and interactive representations of letters and words may support multisensory coordination and learner agency (see VerbaVision³ as an example for letters manipulation). While such prototypes require further empirical validation, they contribute to articulating design hypotheses aligned with ecological and neurodiversity-informed perspectives on literacy.

Taken together, these research lines suggest that immersive and interactive environments may enhance accessibility by strengthening engagement, participation, and learners' sense of competence.

4. Discussion

Rather than proposing alternative models of reading or technological solutions to reading difficulties, the contribution adopted an ecological perspective that situates phonological and morphological decoding within distributed systems involving cognition, bodily action, and environment.

Integrating the DRC model with embodied and extended cognition perspectives allows for a productive dialogue between cognitive and pedagogical approaches. While the DRC model provides a robust account of the functional architecture underlying skilled reading, embodied and ecological perspectives foreground the conditions in which decoding processes are enacted and stabilized. This integration does not challenge established cognitive models but complements them by shifting attention from internal mechanisms to contextual coordination.

Existing projects and research lines suggest that embodied and digital ecologies support reading-related processes by reshaping the environments in which decoding occurs. Across tangible interfaces, immersive environments, and design-oriented educational projects, a shared assumption emerges. Indeed, linguistic structures may become more accessible when they are made perceptible, manipulable, and embedded in meaningful action and space. Such approaches appear particularly relevant for readers whose interaction with conventional text-based contexts is effortful or unstable. From an ecological perspective, embodied and digital environments should therefore be understood not as corrective tools, but as contextual supports that facilitate the enactment and stabilization of existing cognitive processes.

³ An immersive learning tool designed to support individuals with dyslexia through augmented and virtual reality.
<https://urly.it/31dfnb>

5. Conclusions

Overall, this contribution argues that embodied and digital technologies do not introduce new models of reading, but rather offer new ecological conditions for the organization of reading processes. Adopting an ecological perspective shifts the focus of inclusion from remediation toward the design of learning environments that accommodate variability in how readers coordinate linguistic information. Future research should continue to investigate embodied and digital ecologies of reading through interdisciplinary and methodologically rigorous approaches, maintaining a dialogue between cognitive models, pedagogical theory, and design-based research.

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