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Robot-assisted language learning for students with and without dyslexia: a mixed-methods investigation on learning motivation in Cantonese-medium education

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ABSTRACT

Background and Aims: Students with dyslexia face challenges in reading and writing, particularly when learning Traditional Chinese. This study designs and implements *LexiBo*, a supplementary robot-assisted language learning (RALL) system tailored to Cantonese instruction students, informed by self-determination theory (SDT) and expectancy-value theory (EVT), and assesses using SDT, EVT, and intrinsic motivation inventory (IMI) questionnaires to foster learning motivation.

Sample: This is a 30-week experiment with sixty-eight participants, including control (dyslexia: N = 18, without dyslexia: N = 18) and experimental groups (dyslexia: N = 16, without dyslexia: N = 16).

Methods: A mixed-methods analysis of questionnaires, proficiency tests, and interviews is employed.

Results: Students with dyslexia demonstrate statistically significant improvement in emotional engagement, intrinsic motivation, and learning performance over time. RALL also appears to reduce affective barriers in intervention while supporting students' ability and expectancy beliefs.

Originality: This study integrates SDT and EVT into RALL for Cantonese-speaking students. The system addresses the under-researched cognitive and affective barriers of acquiring a tonal and logographic language through a comprehensive longitudinal design.

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Robot-assisted language learning (RALL); dyslexia; motivation and engagement; self-determination theory (SDT); expectancy-value theory (EVT); intrinsic motivation inventory (IMI)

1. Introduction

Individuals with dyslexia face compounded cognitive challenges when acquiring Traditional Chinese within Hong Kong's multilingual environments (Yin and Weekes 2003). Traditional Chinese operates as a morphosyllabic writing system characterised by visually dense logograms. It requires visual-spatial processing skills to decode intricate stroke orders and radical components (Dong et al. 2026; Fung et al. 2022; Han et al. 2007; Snow 2004; Tafti, Boyle, and Crawford 2014). For learners with dyslexia, the visual processing demands are inherently challenging (Stein 2014). The difficulty is further exacerbated by the phonological complexity of Cantonese. This is a tonal language that requires

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phonetic retrieval to distinguish homophones (So 1996). For example, '孩子' (children) and '鞋子' (shoes) both share the same pronunciation 'haai4 zi2', but have different meanings. Furthermore, sentence construction is complicated by a distinct diglossic relationship (Tang and Cheng 2014). Although Cantonese serves as the vernacular mother tongue, it may encompass different written and spoken forms. The written form is generally used in official publications, news media, and textbooks (Olson 1980), whereas the spoken form is primarily used in daily communication (Bauer 1982). Consequently, learners are required to navigate parallel linguistic structures depending on the context. For example, the phrase 'We go to class today' translates to the written form '我們今天去上課' but takes the spoken form '我哋今日去上堂'. These factors induce cognitive overload in those with dyslexia. They need to simultaneously juggle the visual-spatial decoding of morphosyllables, tonal-phonological mapping, and translation from spoken vernacular to written structures. Existing pedagogical practices often prioritise rote memorisation, which is less favourable for neurodiverse learners (George 2023; Rao and Chan 2009). While research has focussed extensively on dyslexia in English and STEM education (Knoop-van Campen, Segers, and Verhoeven 2020; Vasalou et al. 2017), there is a lack of studies examining how to effectively scaffold this unique intersection of orthographic, tonal, and diglossic barriers in non-alphabetic vocabulary acquisition and short-sentence construction.

Learners with dyslexia are often affected by inherent cognitive constraints, such as deficits in working memory and rapid automatised naming (Smith-Spark and Gordon 2022; Snowling 1998). These difficulties are frequently compounded by affective barriers, such as anxiety, stemming from repeated failures in traditional classrooms (Riddick 2009). Conventional pedagogical approaches often rely on one-way delivery and teacher-led instruction (Amirova 2025). Those with dyslexia are unwilling to raise questions or seek help in the classroom as they are afraid of negative evaluation by peers (Wilmot et al. 2023). In contrast, robot-assisted language learning (RALL) systems have demonstrated promising outcomes in engagement and motivation (Fung et al. 2024; Liang and Hwang 2023; Zhang et al. 2025). RALL can engage learners with interactive, multisensory design and technological advancements. These functions serve as essential scaffolds for learning (Chang et al. 2022; Chit, Yap, and Ahmad 2024). However, the field of RALL remains underdeveloped in some areas, such as disadvantaged groups. Most existing research focuses on general student populations, Western educational settings, or STEM subjects (Alghabban and Hendley 2020). For example, Van den Berghe et al. (2019) conducted a review of social robots for language learning. Among 13 robots used in various studies, none of them was specifically targeting those with dyslexia. Another example, Randall (2019) surveyed 79 RALL-related papers. One of the findings mentioned that robots could help individuals of all ages learn language. Researchers often overlook the cultural and linguistic specificity of contexts for the special or niche group (Atman, Yavuz, and Kocak Usluel 2023; Ouyang and Xu 2024; Zhao et al. 2024). Importantly, there is a lack of longitudinal RALL studies focussing on students with dyslexia. Additionally, a few studies integrate the theoretical frameworks necessary to explain why these technologies are successful. Specifically, while physical feedback addresses competence, designs often fail to foster the full spectrum of self-determination theory (SDT) constructs: autonomy (allowing choice in interactions) and relatedness (peer collaboration or cultural connection) (Ryan and Deci 2020).

To address these gaps, our investigation developed and tested (*LexiBo*) – an RALL system theoretically informed by SDT and expectancy-value theory (EVT). The Intrinsic Motivation Inventory (IMI) is used to assess learners' motivational experiences. The mixed-methods investigation addressed four research questions (RQs):

(1) What is the effect of *LexiBo* on the satisfaction of basic psychological needs of students with and without dyslexia?
(2) What is the effect of *LexiBo* on the intrinsic motivation of students with and without dyslexia?
(3) What is the effect of *LexiBo* on learning performance of students with/without dyslexia?
(4) How does *LexiBo* influence students' ability, expectancy beliefs, and interest/value in learning?

2. Literature review

Dyslexia is a reading and writing disability (Vellutino et al. 2004). Individuals with dyslexia often encounter cognitive and affective constraints (Snowling 1989), including phonological, working memory (WM), and rapid automatised naming (RAN). These disadvantages create barriers to literacy learning in a tonal logographic language. Multisensory, embodied, and adaptive RALL designs can scaffold these cognitive constraints by distributing processing across visual, auditory, kinesthetic, and tactile (VAKT) channels (Kelly and Phillips 2022; Rappolt-Schlichtmann, Boucher, and Evans 2018). AI-driven personalisation (e.g. automatic speech recognition (ASR), large language models (LLMs), and haptic guidance) provide individualised and contingent feedback (Stamper, Xiao, and Hou 2024; Wang and Young 2015; Durak and Onan 2025). Building on SDT and EVT, we proposed that such designs that support basic psychological needs can enhance ability, expectancy beliefs, and interest/value, which, in turn, foster intrinsic motivation as measured by the IMI.

2.1. The learning challenges and motivational problem space for special education needs

Learners with dyslexia often face significant challenges in language learning, such as deficits in phonological awareness, reading fluency, handwriting, and working memory capacity (Fung et al. 2021; Fung et al. 2022; Kiss et al. 2024). These difficulties are particularly salient when those with dyslexia learn a tonal and morphosyllabic writing system. The cognitive constraints are often accompanied by slow RAN, making it harder for learners to establish efficient orthography-phonology mappings and to automatise character recognition (Liao et al. 2015). As a result, they always suffer from low confidence and anxiety in literacy tasks, and negative school experiences that undermine their expectancy beliefs and perceived interest/value of reading and writing activities.

EVT is a framework for conceptualising these affective barriers mentioned above. Expectancy is the level of students' willingness to engage and persist, which depends on their beliefs about the likelihood of success (Andersen and Ward 2014). Value is the perceived importance, usefulness, and enjoyment of the task (Chan and Zhou 2023).

For many learners with dyslexia, repeated failure experiences depress both expectation and value, resulting in the avoidance of literacy tasks even when appropriate support is available (Tanner 2009). SDT complements EVT by emphasising that motivation and engagement depend on the satisfaction of three basic psychological needs: autonomy, competence, and relatedness (Yue and Lu 2022). These needs can be thwarted by highly performance-oriented instruction, which can make learners feel controlled, incompetent, and socially isolated (Earl et al. 2019; Vansteenkiste, Ryan, and Deci 2006). EVT and SDT frame the central problem this study addresses: designing RALL interventions that scaffold cognitive processes such as working memory and RAN while simultaneously rebuilding learners' expectancy beliefs, sense of competence, autonomy, and relatedness.

These cognitive constraints are amplified by the properties of the writing (Traditional Chinese) and sound (Cantonese) systems. Chinese characters (Figure 1) are visually dense, composed of multiple strokes and embedded radicals (Feldman and Siok 1999). So, learners are required to maintain complex orthographic forms in WM while mapping them onto syllables and tones. RAN is especially critical because fluent character reading relies on quickly accessing tightly bound orthography–phonology–semantics associations (Williams 2013). RAN deficits are an early marker of Chinese developmental dyslexia (Zhang et al. 2023), alongside weaknesses in orthographic knowledge, short-term memory, and visual–motor skills (X. Li, Hu, and Liang 2022). For Cantonese-speaking learners, tone adds another layer of processing (Figure (1a) and (1b)), as inaccurate or slow retrieval of tone patterns can disrupt both oral reading fluency and character–sound mapping, making WM and RAN weaknesses particularly detrimental for literacy acquisition (Li and Ho 2011; Tong, Tong, and King Yiu 2018).

2.2. Multisensory designs and embodied intervention in RALL for dyslexia

RALL systems have emerged as promising interventions in special educational needs (SEN) contexts, providing adaptive instruction tailored to individual learner profiles. Social robots can deliver adaptive and repetitive practice with fine-grained control over pacing and task difficulty (Chen et al. 2023), while maintaining a non-judgmental support and emphathetic interaction that reduces anxiety and supports persistence (Darmudas, Sobolewska, and Strathearn 2025; Matheus, Vázquez, and Scassellati 2025). From a design perspective, effective RALL for learners with dyslexia is grounded in multisensory learning principles, such as VAKT (Ali et al. 2024), which recommend engaging multiple sensory modalities to strengthen the mapping between spoken and written language. For Traditional Chinese character acquisition, the multisensory approach requires the RALL system to simultaneously integrate visual modalities (character presentation),



Figure 1. Three Traditional Chinese characters with similar radicals but different syllables or tones.

auditory cues (tones and pronunciations), kinesthetic interaction (guided stroke-order practice with haptic feedback), and tactile engagement (physical handwriting practice) (Fung, Fung, and Wan 2019; Prasetyaningrum and Faradila 2019). These multisensory and embodied design features are not only technical embellishments they also target the cognitive constraints. By coupling visual and auditory cues with physical enactment, RALL can offload WM demands (Ball et al. 2022; Berry et al. 2019), support phonological encoding (Van den Berghe et al. 2021), and facilitate automatisation of orthographic patterns (Reflinda, Roza, and Firdaus 2024), thereby addressing WM and RAN deficits. Simultaneously, the social robot and its ability to display contingent non-verbal behaviours (e.g. gaze, gestures, and encouragement) can create a supportive interactional climate (Saunderson and Nejat 2019) that reinforces learners' sense of competence and relatedness (Fung et al. 2024), aligning with SDT's motivational mechanisms.

Recent studies indicate that computerised and self-adaptive training can strengthen executive functions and RAN in children with specific learning or language disorders. For example, Suneesh, Pasupuleti, and Garate (2023) developed an interactive game-based application embedded in a social robot to support learners with dyslexia. In contrast, Fung et al. (2024) showed that dyslexia is associated with pronounced deficits in WM and RAN among Cantonese-speaking students learning Traditional Chinese. In addition, the online training programme *MemoRAN* improved inhibition, working memory, verbal fluency, and RAN performance in children with specific learning disorders by systematically targeting executive control during visual–verbal integration tasks (Capodieci et al. 2022). Similarly, a multimodal embodied robot for English as a second language (ESL) learning in preschoolers enhances lexical retention through rich, multisensory interaction (Rybakova and Choi 2025). These findings suggest that RALL can help learners with WM and RAN processing deficits by providing multisensory scaffolding and tightly controlled pacing, thereby reducing cognitive load during intensive practice.

Beyond these cognitive effects, the novelty and interactivity of social robot platforms can enhance task persistence and motivation. They may reduce anxiety and stress relative to conventional teacher- or tablet-based instruction (Fung et al. 2025a). However, although many assistive technologies can be customised to user profiles, they often provide limited contextual and social support in real-time learning situations (Svensson et al. 2021). Effective RALL interventions are, therefore, needed that simultaneously reinforce core literacy processes and create emotionally supportive and motivating learning environments for learners with special educational needs.

Compared with purely screen-based systems, embodied RALL systems may better address Chinese-specific literacy challenges by physically modelling stroke order, synchronising gestures with tonal pronunciation, and linking these cues to haptic guidance for handwriting. This multimodal coupling can reduce WM demands by distributing attention across visual, auditory, and motor channels, which is especially relevant for learners struggling with complex character forms and tones. Also, robots' learning advantages over screen-based tools are modest in cognitive terms. Their advantage may lie in making practice more engaging, attention-grabbing, and socially responsive. In addition, human-like robots can enact vocabulary meanings through gesture and body movement, e.g. 'breathe' (Figure 2). The use of human-like gestures and bodily enactment makes abstract vocabulary more concrete and memorable.



Figure 2. (a) is a purely screen-based system. (b) is a robot-based system.

2.3. Operationalising RALL through AI and embodied robotics

Recent advances in artificial intelligence (AI) and robotics provide concrete mechanisms through which the multisensory and embodied framework can be operationalised in RALL systems (Barua et al. 2022; Kaswan, Dhatterwal, and Ojha 2024). ASR enables real-time analysis of learners' pronunciation and tonal accuracy (Bashori et al. 2024), which is crucial in Cantonese, where prosodic differences signal lexical contrasts. Immediate and non-judgmental feedback allows learners to experiment with tone patterns, receive precise corrections, and gradually calibrate their phonological representations without the social pressure that often accompanies teacher-led correction (Abar, Pong, and Som 2025). This form of contingent feedback contributes to competence support in SDT terms and can incrementally strengthen learners' expectancy beliefs as conceptualised by EVT.

LLMs and adaptive learning algorithms further extend personalisation by modelling learners' performance trajectories and adjusting task difficulty, content sequencing, and feedback type in real time (Shukla et al. 2026). Such adaptivity helps maintain an optimal challenge–support balance, preventing both boredom and overload, and thereby supporting autonomy and competence needs (Sharma et al. 2025). Embodied agents and haptic interfaces translate abstract multisensory principles into tangible experiences (Iqbal and Campbell 2023; Z. Li et al. 2024; Muñoz and Dautenhahn 2021). For example, human-like robots can model stroke order and synchronise speech with gesture, and coordinate with haptic devices that guide learners' handwriting movements (Hood, Lemaignan, and Dillenbourg 2015). These interactions distribute cognitive load across sensory channels while providing rich multimodal cues, a combination that is particularly beneficial for learners with dyslexia and related SEN profiles (Othman and Ching 2024).

2.4. Motivational mechanisms and measurement in RALL

SDT-informed studies of educational technology and RALL consistently show that when tools provide meaningful choices, optimally challenging tasks, and responsive feedback, they are more likely to satisfy learners' basic psychological needs (Fung et al. 2025b; Lu et al. 2023). For example, a Positive Computing-oriented field study with social robots in public libraries found that user-controlled interaction flow, contingent responses, and human-like appearance and gestures received above-midpoint levels of autonomy and relatedness (Finkel et al. 2026). Simultaneously, those multisensory functions can address autonomy, competence, and relatedness, producing stronger task engagement than targeting single needs in isolation. AI-mediated language learning further indicates

that AI systems can bolster competence through diagnostic feedback and adaptive practice, and support autonomy through self-paced and choice-rich activities (Hong and Guo 2025; Mohebbi 2025). However, if the feedback is perceived as overly controlling or socially disconnected, there is a risk of undermining motivation (Ma and Chen 2025).

In AI education, SDT-based designs that explicitly support autonomy, competence, and relatedness enhance students' perceptions of AI learning, increase need satisfaction, and reduce achievement and gender gaps (Xia et al. 2022). From a psychological need-fulfilment perspective, recent HRI work argues that social robots designed to support autonomy, competence, and relatedness across the interface, task, behaviour, and life spheres can foster intrinsic motivation, improve engagement, and well-being (Janssen and Schadenberg 2024). Consistently, an L2 word-learning study with a social robot tutor reported that strategies explicitly supporting all three needs increased the strength and duration of children's task engagement relative to conditions where needs were only partially addressed (Van Minkelen et al. 2020). Integrating SDT with the Community of Inquiry framework in online education likewise shows that cognitive and social presence can strengthen autonomy, competence, and relatedness, with autonomy and competence, in particular, exerting significant positive effects on perceived learning and engagement (Yuerong et al. 2024). As mentioned above, need-supportive designs can enhance autonomy and competence, thereby promoting more self-determined forms of motivation. Accordingly, SDT guided the design of need-supportive interaction features, whereas EVT guided the design of meaningful, attainable, and progressively challenging learning tasks.

EVT emphasises learning motivation and persistence (Jin and Jue 2026). They are determined by the synergy between expectancy beliefs and the interest/value of the task (Eccles and Wigfield 2024). Learners are more likely to invest effort when they view RALL tasks as interesting, useful, aligned with their goals, and when they believe they can succeed with reasonable effort. To capture these motivational dynamics empirically, the present study utilises SDT, EVT, and IMI questionnaires. Specifically, the IMI serves as a multidimensional instrument grounded in SDT that assesses interest/value, perceived competence, effort/importance, pressure/tension, perceived choice, and relatedness (Ryan and Deci 2020). Some IMI dimensions conceptually overlap with SDT and EVT constructs, particularly perceived competence and task value. These overlaps are treated as complementary indicators of learners' motivational experience rather than as separate theoretical mechanisms. They allow us to examine whether the proposed RALL design, through its multisensory, adaptive, and socially supportive features, enhances learners' intrinsic motivation, perceived competence, and task value, while reducing pressure and tension (Deci and Ryan 2013; Y. Li et al. 2022).

The contribution of this study includes: (1) We designed and implemented *LexiBo*, an RALL system specifically adapted to support students in a Cantonese-speaking educational context. (2) We empirically examined the theoretical integration of SDT and EVT, demonstrating how RALL mechanisms foster intrinsic motivation and reduce affective barriers in dyslexia intervention. SDT, EVT, and IMI questionnaires were used to assess learners' learning motivation experience. (3) We conducted a 30-week study to demonstrate improvements in engagement and academic performance.

3. System design

Guided by the SDT–EVT framework outlined in Section 2, *LexiBo* is designed so that specific features of the human-like robot, multisensory elements and personalised design, interaction flow, pedagogy, and curriculum would support learners' autonomy, competence, and relatedness. Ultimately, the system can strengthen its expectancy beliefs and increase the interest/value of literacy practice.

3.1. Interactive design

3.1.1. Robotic platform and system architecture

LexiBo is implemented on an interactive and human-like robot, Kebbi (NA 2022). As shown in Figure 3. Kebbi has seven motors, two swivels, and one auxiliary wheel to be programmed to control its movement and gestures. From an SDT perspective, *LexiBo* provides a low-pressure and self-paced interaction intended to satisfy autonomy (by allowing learners to proceed without time pressure) and reduce tension (Pfenninger 2016). Also, its supportive and non-judgmental persona is designed to protect perceived competence and expectancy of success.

The movement controller (Table 1) provides nine pre-defined motion patterns grouped by interaction outcome: 'correct', 'incorrect', and 'no-response' patterns. Each pattern combines up to two forward or backward rolls with two 30° turns to the left or right, enabling short, expressive movements without disrupting the learning task. A parallel facial-expression controller provides nine corresponding face patterns (e.g. smiling eyes, neutral face), which are synchronised with the movement and song patterns to create consistent multimodal feedback (Table 2).

LexiBo follows a modular speech and dialogue pipeline. Learners' oral responses are captured by the robot's microphone and sent to a Google Cantonese speech recognition API, which converts speech to text in real-time. The recognised text is then processed by a dialogue manager with two modes: (1) for vocabulary recognition and picture–vocabulary, a rule-based module matches the learner's response against expected keywords and determines correctness; (2) for short-sentence, an LLM-based module evaluates the semantic appropriateness of the learner's input and generates short responses with suggested answers as a reference. The dialogue manager then triggers a text-to-speech



Figure 3. Kebbi has seven motors, two swivel and one auxiliary wheels to be programmed to control its movement, including fists (#1), elbows (#2), joints (#3) and a neck (#4).

Table 1. The design of the movement controller.

Movement controller	Action	Requirement
Forward	Full wheel rotation	Maximum 2 times
Backward	Full wheel rotation	Maximum 2 times
Turn left	30° turns	Maximum 2 turns
Turn right	30° turns	Maximum 2 turns

Table 2. The design of the expression, song and gesture.

Module	Correct	Incorrect	No response
Facial expression	3	3	3
Song	3	3	3
Gesture	3	3	3
Combination	27	27	27

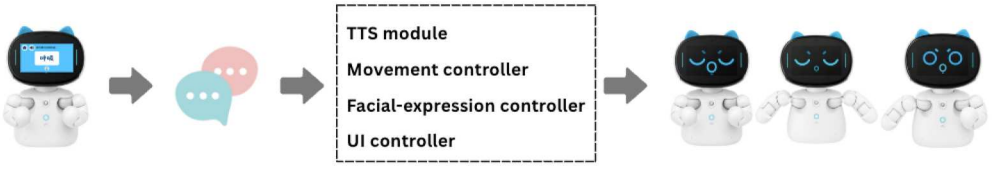


Figure 4. The overview of dialogue flow.

(TTS) engine to synthesise *LexiBo*'s spoken output (Figure 4), while the movement and facial-expression controllers randomly select one of the pre-defined motion–expression patterns based on the evaluation result. At the same time, the UI controller updates on-screen elements (question text, images, and recap screens), and all interaction events (ASR transcripts, learners' input, and correctness) are logged for analysis.

3.1.2. Multi-sensory elements

RALL can engage students through its interactive and dynamic elements. Incorporating multi-sensory elements, such as auditory, animations, and music, can cater to various learning styles and enhance motivation (Saborío Taylor 2025). *LexiBo*'s multisensory features operationalise competence support through immediate, non-punitive feedback (e.g. facial expressions indicating correctness and simple verbal prompts). This is expected to strengthen learners' perceived competence and expectancy for success, and to contribute to IMI subscales such as perceived competence and enjoyment.

3.1.3. Personalised design approach

We co-designed the *LexiBo* user interface (UI) and functions with a professional designer specialising in user experience (UX), a computer engineer with nine years of industry experience, and five students who were potential users. *LexiBo* offers customisable functions: (1) learners can adjust speech rate (−2 to +2) to adapt to their learning pace, and (2) *LexiBo* provides home button (Figure 5 #a1), question display (Figure 5 #a3), audio replay (Figure 5 #a2), answer recording (Figure 5 #a4), and recap functions (Figure 5 #b5) to empower learners to control their learning modality. The multimodal representation



Figure 5. The overview of system UI: (a) #1 home button, #2 audio replay, #3 question display, #4 recording, and (b) #5 recap functions.

ensures that learners fully comprehend questions before responding, thereby sustaining effort throughout the intervention.

These customisation options operationalise autonomy support by giving learners meaningful control over pace, modality (listening again vs reading), and when to progress or repeat. These designs can increase perceived choice and reduce pressure. From the EVT perspective, the ability to regulate challenge is expected to sustain expectancy beliefs. At the same time, multimodal question displays can make the task tractable and worth the effort (value and effort).

3.2. Pedagogy design

We co-designed a systematic pedagogy with a professional specialising in curriculum development. By integrating SDT, the pedagogy addresses students' strengths and weaknesses while providing scaffolded support to build competence and expectancy for success. Building on universal design for learning (UDL) principles, the design incorporates autonomy support through learner choice, multiple means of representation, and immediate feedback. In addition, scaffolded progression and explicit verbalisation of correct answers are intended to support competence and expectancy of success. In contrast, built-in opportunities for learner choice (e.g. acceptable alternative responses) provide autonomy support and reduce controlling pressure. Embedding tasks in familiar Hong Kong contexts is designed to enhance EVT task value (utility and attainment value), making RALL activities feel both relevant and meaningful.

LexiBo systematically replicates evidence-based teaching practices by verbalising correct answers before displaying written responses on screen, thereby supporting multi-sensory learning for students with dyslexia. *LexiBo* comprises three question types: (1) vocabulary recognition (Figure 6(a)), (2) picture-vocabulary Connection (Figure 6(b) and 6(c)), and (3) short sentence (Figure 6(d) and 6(e)). The questions were embedded within culturally relevant Hong Kong contexts to enhance interest/value and intrinsic motivation. *LexiBo* also allows acceptable response options. For example, as illustrated in Figure 6, when prompted with 'What are the children doing', students may respond with 'playing with friends' or 'building a sand castle', fostering autonomy while maintaining pedagogical rigour.



Figure 6. The overview of game flow: (a) vocabulary recognition, (b,c) Picture-Vocabulary Connection, and (d,e) short sentence.

These designs map directly onto the IMI perspective. Contextually meaningful content and flexible response formats are expected to increase enjoyment, value, and perception, while calibrated difficulty is intended to bolster perceived competence and reduce stress.

3.3. Curriculum design

The curriculum is designed for junior primary school students based on three key design criteria (CR). The selected vocabulary was sourced from 'A Study of Chinese Characters Recommended for the Subject of Chinese Language in Primary Schools' (Pan Huiru 2021) (CR 1), the 'Hong Kong Primary School Learning Vocabulary List Supplementary for Special Learning Disabilities' (Institute 2023) (CR 2). Furthermore, the designs of the picture-vocabulary and short sentences were referenced from the 'Territory-wide System Assessment (TSA) for primary school students' (Examinations and Authority 2023) (CR 3). The structured curriculum is shown as follows. Aligning lexical items and task formats with official Hong Kong learning lists and assessments is also intended to increase the value of EVT tasks, as learners and teachers can see a direct connection between RALL activities and learning outcomes.

3.3.1. Type 1) vocabulary recognition

Vocabulary size is the foundation of language acquisition (Fung et al. 2023). Most junior students do not have sufficient vocabularies, which hinder their expression, communication, and writing ability. As shown in Figure 6(a), '沙灘' only has one form (literally: beach; pronunciation: saa1 taan1).

3.3.2. Type 2) picture-vocabulary connection

Building on the foundation of vocabulary recognition, picture-vocabulary connection requires students to map a learned word to its corresponding visual representation (Fitriani, Erdiana, and Samad 2019). This approach leverages dual-coding theory, strengthening memory recall by creating associative links between verbal and visual information (Hodes 1994). As shown in Figure 6(b), students are required to identify an image of '沙城堡' (literally: sand castle; pronunciation: saa1 sing4 bou2) depicting a sand castle.

3.3.3. Type 3) short sentence construction

The final step involves synthesising vocabulary into simple and grammatically correct sentences. This task draws on the understanding that moving beyond word-level recognition to constructing phrases is critical for language development (Osgood 1963). As shown in Figure 6(d) and 6(e)), using the known word '沙灘' & '沙城堡', students can formulate the sentence: '家人和我在沙灘' (literally: My family and I are on the beach; pronunciation:

gaa1 jan4 wo4 ngo5 zoi6 saa1 taan1; nature: written form); '屋企人同我在喺沙灘' (literally: My family and I are on the beach; pronunciation: uk1 kei2 jan4 tung4 ngo5 hai2 saa1 taan1; nature: spoken form). The stepwise progression from vocabulary recognition to picture–vocabulary connection, and finally short sentence construction was deliberately chosen to provide an 'optimal challenge' trajectory that builds competence and expectancy beliefs over time. This design can gradually support self-determined motivation to engage with increasingly complex Traditional Chinese materials.

3.4. Learning procedure

Each student had a personal account. All students followed the curriculum in order, starting with vocabulary (N = 3), picture vocabulary (N = 5), and short sentence construction (N = 5). For the interaction procedure, first, students logged in to *LexiBo* with their personal login ID and password. Second, students pressed the required learning set (other irrelevant sets were locked) to start learning (Figure 7(a)). Third, the screen displayed a home button, a question, and its corresponding vocabulary/image. *LexiBo* read the question automatically. Fourth, a re-listening button appeared (Figure 7(b)). Students can press to re-listen if needed. Fifth, a recording button popped up (Figure 7(c)). Students were required to press the record button. If students did not have any interaction with the screen, *LexiBo* would ask, 'Are you thinking the answer?' to raise their awareness. Students had a maximum of three attempts, each lasting 10 s, to answer the question. *LexiBo* would interact with students by notifying them of correctness through animations, gestures, and voice. Six, no matter the correctness of students' answer, a suggested answer was displayed (Figure 7(d)) in written form but read in spoken form. *LexiBo* helped students interchange between two forms to adapt to the local culture. Finally, a next button appeared (Figure 7(e)) to guide students to proceed to the next question.

3.5. Theory integration

The integration of SDT and UDL principles operationalises the EVT framework throughout the whole system architecture (Figure 8). Personalised challenge regulation and multimodal displays sustain students' expectancy beliefs by making tasks tractable. Concurrently, EVT task value is enhanced through local pedagogical contexts and the direct alignment of lexical items with curricula and connecting interactive activities to educational outcomes.



Figure 7. *LexiBo* employed visual displays to guide students to interact with the system independently.

3.5.1. Self-determination theory

When basic psychological needs are satisfied, intrinsic motivation and sustained engagement are cultivated, with motivation acting as the psychological driver for engagement (Ryan and Deci 2020). SDT identifies three core needs: autonomy (perceived choice), competence (the capacity to master), and relatedness (a meaningful connection). Engagement comprises behavioural, emotional, and cognitive dimensions (Sun et al. 2019). The design of *LexiBo* addresses each need: students control the pace of their answers (autonomy), progress from vocabulary to sentences and receive responsive feedback (competence), and interact with a supportive conversation (relatedness). These design features align with evidence that robot responsiveness enhances cognitive engagement and learning gains. Figure 9 showed the theoretical design of *the LexiBo*.

3.5.2. Universal design for learning

UDL is an essential pedagogical framework for mixed-ability classrooms (Lieberman, Bean, and Grenier 2024). The aim is to promote learning equity by simplifying complex tasks and offering flexible instructional approaches (Mackey et al. 2023). The framework addresses three interconnected dimensions of learning: engagement (the affective dimension, addressing motivation and 'why to learn'), representation (the recognition dimension, addressing 'what to learn'), and action and expression (the strategic dimension, addressing 'how to learn') (Bray et al. 2024).

LexiBo operationalises these UDL principles through strategically designed affordances. *LexiBo* supports *representation* via multisensory scaffolding that integrates animation, sound effects, and auditory guidance. The purpose is to facilitate information processing in diverse sensory modalities. *Action and expression* are enabled through gesture- and movement-based interactions. The aim is to allow learners to demonstrate understanding

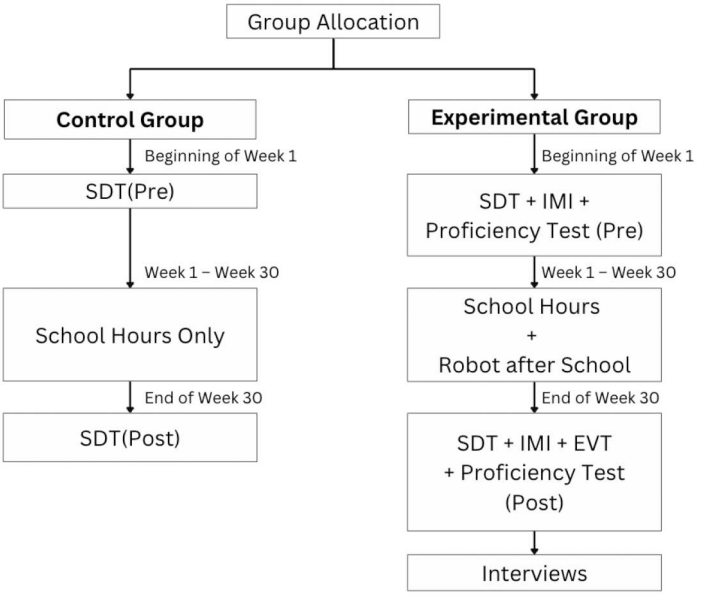


Figure 8. The overview of study flow.

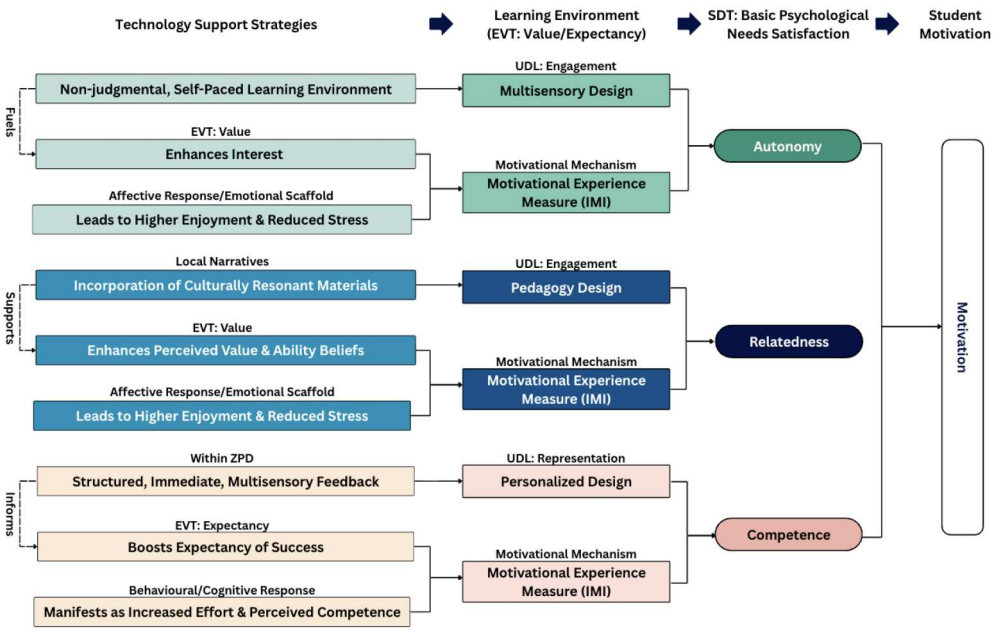


Figure 9. The proposed model of student motivation in RALL.

through embodied responses. *Engagement* is fostered through learner autonomy (customisable learning pace and adjustable speech rate) and culturally sustaining content (relatedness). They are central to intrinsic motivation.

4. Methods

This study employed an empirical experiment with a mixed-method approach. Quantitative data were collected through pre- and post-intervention surveys and proficiency tests, followed by qualitative interviews designed to explain and contextualise observed changes in motivation and performance. Participants were allocated to one of two groups: the experimental group, which received the *LexiBo* RALL intervention after school hours, and the control group, which received only standard instruction during school hours. The intervention lasted 30 weeks, a duration chosen to assess long-term learning effects and motivational shifts. Data collection for the experimental group included pre-, post-tests and interviews.

4.1. Study design

4.1.1. Inclusion criteria

The criteria for student inclusion in this study were as follows: (1) Participants are in Grades 2 to 5, (2) Participants should be able to read Traditional Chinese characters and speak Cantonese, (3) Participants with dyslexia must provide a valid report to their school. (4) Participants do not have any medical or physical disabilities that could affect their interaction with robots or their ability to read aloud and (5) Prior experience with

digital tools is needed, such as tablets. As only authorised personnel can review the report, school teachers select the students based on the inclusion criteria.

4.1.2. Regulations

The University's Institutional Review Board (IRB) approved the experimental protocol. We obtained informed consent from the students' guardians before the experiment began. We also received individual consent from students at each learning session. Students were allowed to change their learning schedule or withdraw from the experiment at any time. Participation was entirely voluntary.

4.1.3. Participants

To ensure a fair comparison, school teachers selected four groups of students (N = 68) based on specific inclusion criteria, comprising a control group (N = 36) and an experimental group (N = 32) (Table A.2). Two groups of students were from the same primary school. All students received regular classroom instruction led by registered Chinese teachers with several years of experience in inclusive education. The learning materials for the control group were on the same level as those of the experimental group. Two experienced teachers reviewed our learning materials to ensure that the difficulty level aligns with that of the traditional materials. They did not independently score the tests in this study.

For the control group, we have two sub-groups – dyslexia (M = 9.38-year-old, SD = 1.07-year-old, Male: N = 9; Female: N = 9), non-dyslexia (M = 9.30-year-old, SD = 1.20-year-old, Male: N = 8; Female: N = 10). The participants were required to complete pre- and post-questionnaires at the first and twenty-eighth weeks, respectively. For the experimental group, we have two sub-groups – dyslexia (M = 9.60-year-old, SD = .69-year-old, Male: N = 9; Female: N = 7), non-dyslexia (M = 8.86-year-old, SD = .80-year-old, Male: N = 13; Female: N = 3). They also administered pre- and post-questionnaires at the first and twenty-eighth weeks and played with *LexiBo* for 30 consecutive weeks. From Weeks 1 to 30, students were required to complete Set 1 (pre-test) through Set 30 (post-test), with increasing difficulty over time. A language proficiency test was used to evaluate efficacy. Each time, a student learned in a classroom (15 min per week) (Figure 10), a teaching assistant (TA) was in the classroom to provide technical support.



Figure 10. A student was interacting with Kebbi & *LexiBo* in the classroom.

A sample-size calculation was conducted in G*Power 3.1 (Faul et al. 2009) to assess the adequacy of the available sample, specified as a repeated-measures analysis of variance (ANOVA) with a within-between interaction. The calculation reflected the four study groups (experimental group with/without dyslexia, and control group with/without dyslexia) assessed at two time points (pre- and post-test). Assuming a medium effect size (f = .25), an alpha level of .05, a statistical power of .90, a correlation of .50 between repeated measurements, and a non-sphericity correction of 1.00, the analysis indicated the required sample size of 64 participants. The calculation assumption aligns with standard statistical conventions for behavioural and educational research (Cohen 2013).

The *LexiBo* intervention was held for 30 consecutive teaching weeks. Students in the experimental group used the system once per week for approximately 15 min, completing one set per session. This resulted in a total exposure of about 450 min (7.5 h) of *LexiBo* practice across the study period. Session attendance was monitored by the TA. All participating students completed all 30 sets, and no sessions were dropped due to technical failure. The school timetable, class size, and allocation of teaching staff were comparable across conditions. We did not implement additional structured after-school programmes during the study. According to the school teacher's report, the participating students came from low-income families living in public housing estates, where private tutoring and commercial enrichment classes are uncommon.

4.2. Measures

4.2.1. Quantitative measurement

All questions were written in Traditional Chinese and reviewed by two Chinese teachers to ensure readability. A five-point Likert scale was used to evaluate each variable. In this section, we provide a detailed discussion of each measure.

4.2.1.1. Questionnaires of self-determination theory construct. The questionnaires were administered to both experimental and control groups with two time points: pre- and post-intervention. The questionnaire assessed learning engagement and motivation, addressing RQ1. This work adopted validated questionnaires (Chen et al. 2015; Maroco et al. 2016; Vallerand et al. 1992) and a previous study conducted in the same region (Fung et al. 2024).

The control group completed the same 12-item questionnaires (measuring four variables with three items each) at both pre- and post-test. The experimental group completed this identical 12-item pre-test, but their post-test was expanded to 21 items (measuring seven variables with three items each). All items utilised a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). To calculate the final scores, we computed the mean item score for each construct and subsequently transformed the mean into a 0–100 percentage scale to facilitate interpretation. All students completed the SDT questionnaires. The scales did not include any reverse-coded items.

For the first 12-item with variables (1)–(4), to accommodate the different learning conditions, the questionnaire wording was contextually adapted. For both the pre- and post-tests in the control group, as well as the pre-test in the experimental group, the items referenced learning with 'teachers' (e.g. I feel very comfortable when I interact with teachers). For the experimental group's post-test, the referent was changed to *LexiBo*.

The pre- and post-questionnaires included seven variables: (1) behavioural ($\alpha = .74$) (e.g. I participate in all the learning activities when learning with *LexiBo*/teachers), (2) emotional ($\alpha = .88$) (e.g. I feel very comfortable when I interact with *LexiBo*/teachers), (3) cognitive engagement ($\alpha = .82$) (e.g. When learning with *LexiBo*/teachers, I try different methods to learn Chinese), (4) motivation ($\alpha = .81$) (e.g. Learning Chinese makes me happy), (5) autonomy ($\alpha = .78$) (e.g. I feel a sense of freedom learning with *LexiBo*), (6) competence ($\alpha = .81$) (e.g. I feel capable of completing the Chinese tasks when learning with *LexiBo*), and (7) relatedness ($\alpha = .74$) (e.g. I feel a sense of connection when learning with *LexiBo*).

4.2.1.2. Questionnaires of intrinsic motivation inventory construct. The questionnaires were administered exclusively to the experimental group and were intervention-specific to capture the experience related to the *LexiBo* system. All questionnaires were adapted from McAuley, Duncan, and Tammen (1989); Monteiro, Mata, and Peixoto (2015); Wigfield and Eccles (2000) and administered post-intervention. The IMI is a multidimensional tool assessing subjective experience, answering RQ2: (1) enjoyment ($\alpha = .78$) (e.g. I really enjoy implementing *LexiBo* to learn Traditional Chinese), (2) perception ($\alpha = .80$) (e.g. I think I have performed well in *LexiBo*), (3) effort ($\alpha = .84$) (e.g. I put a lot of effort into *LexiBo* to learn Traditional Chinese), (4) stress ($\alpha = .68$) (e.g. I felt very nervous when I was learning with *LexiBo*), and (5) value ($\alpha = .91$) (e.g. I think *LexiBo* can help me improve my Traditional Chinese.).

The instrument consisted of 29 total items distributed across five constructs. To ensure response reliability, several constructs included reverse-coded items:

- Enjoyment: 6 items (including 2 reverse-coded items)
- Perception: 6 items (including 1 reverse-coded item)
- Effort: 5 items (including 2 reverse-coded items)
- Stress: 5 items (including 3 reverse-coded items)
- Value: 7 items (no reverse-coded items)

All items utilised a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). During data processing, scores for all reverse-coded items were mathematically inverted. Following this inversion, we computed the mean item score for each construct. To facilitate straightforward interpretation alongside our other measures, these mean scores were subsequently transformed into a 0–100 percentage scale. All questionnaires were completed in full.

4.2.1.3. Measurement of proficiency tests. The proficiency tests were administered to the experimental groups and intervention-specific. The test comprised 13 items, including vocabulary recognition (three items), picture-vocabulary connection (five items), and five short sentence construction (five items). Each item is worth 1 point, for a maximum total score of 13 points. Clear target answers and acceptable semantic/lexical variants were pre-defined to eliminate scoring bias. The test took approximately 15 min and was administered automatically via *LexiBo*, with the TA presented only to provide technical support. The pre- and post-tests utilise the identical structural framework, item distribution, duration, and scoring metrics. To ensure content validity and appropriate difficulty control,

two senior teachers reviewed the test content, scoring method and validated that the items were aligned with the curriculum and instructional materials.

In the vocabulary recognition section, students were required to provide the exact Cantonese pronunciation of the target vocabulary (e.g. target character: 沙灘; required pronunciation: saa1 taan1). In the picture-vocabulary connection section, students named the object based on visual prompts, with a fewer acceptable responses permitted when they conveyed the same intended meaning. For example, given an image of a sand castle, the primary target answer is '沙城堡'. However, calibrated variants such as '堆沙城堡' and '沙堡壘' are explicitly accepted. In the short sentence construction section, students wrote a sentence based on the pictured context. An LLM-based module evaluated the semantic appropriateness of the learner's inputs by assessing whether they preserved the target meaning. For example, when shown an image of a family on a beach and asked 'Who is on the beach?', the baseline target response is '家人和我在沙灘'. In contrast, semantically accurate variations detailing family members (e.g. '一家人' (literally: whole family), '父母' (literally: parents), '爸爸媽媽哥哥姐姐' (literally: father, mother, elder brother and sister)) receive full credit. This test was not a separate external examination. It was embedded in the intervention through the training exercises administered in Weeks 1 and 30. Sets 1 and 30 were treated as the pre-/post-test, respectively. These tests provide an objective pre-/post score analysis that measures the intervention's effect on learning performance, addressing RQ3.

4.2.1.4. Questionnaires of expectancy-value theory construct. The questionnaires were administered exclusively to the experimental group and intervention-specific, addressing RQ4. All questionnaires were adapted from Eccles and Wigfield (2016), administered pre- and post-intervention. This measure assessed three EVT factors: (1) ability beliefs ($\alpha = .92$) (e.g. How good in Chinese are you), (2) expectancy ($\alpha = .92$) (e.g. How well do you expect to do in Chinese), and (3) interest/value ($\alpha = .68$) (e.g. Compared to most of other activities, how useful is what you learn in Chinese).

The instrument comprised of nine items across three constructs: ability beliefs (two items), expectancy (two items), and interest/value (five items). Responses were recorded on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). To standardise our reporting, we calculated the mean item score for each construct and subsequently transformed this mean into a 0–100 percentage scale. All participants completed all items. Additionally, the EVT scale did not include any reverse-coded items.

4.2.2. Qualitative measurement

The qualitative phase involved interviews conducted with students from the experimental group after the intervention period. These interviews underwent thematic analysis. Following the six-phase approach described in Braun and Clarke (2006), we systematically coded the interview transcripts to identify recurring patterns and themes in the participants' responses. The analysis involved: (1) familiarisation with the data, (2) initial coding of meaningful segments, (3) searching for themes by grouping related codes, (4) reviewing and refining themes, (5) defining and naming final themes, and (6) producing the analytical report. This process identified key themes in our findings, including students' perspectives on difficulty and challenges, scenario design and attention, time perception and fatigue, and improvements.

The first author documented the interview responses using pen and paper, and later collaborated with other research team mates to conduct a thematic analysis. The first author performed the initial coding to develop preliminary codes. Following this, two rounds of discussions were held to categorise and refine these codes, ensuring a thorough interpretation of the collected feedback.

In total, 361 responses were received in the interviews. The author conducted the initial coding of all transcripts and developed preliminary codes by identifying meaningful segments in participants' responses. Subsequently, two rounds of structured discussions were held with research team members. These discussions focussed on reviewing preliminary codes, considering alternative interpretations, grouping related codes, and refining candidate themes. Independent double-coding of the transcripts was not conducted. Consequently, a formal inter-coder reliability metric was not calculated.

4.3. Results

In this section, we analysed students' learning motivation and efficacy qualitatively and quantitatively. Aminu and Shariff (2014) suggested that normally distributed data have skewness and kurtosis values within the acceptable range of <3 and <10, respectively. Cohen (2013) that partial eta squared (η_p^2) was used to measure effect size, and .01, .06, and .14 were designated small, medium, and large effect sizes, respectively. Descriptive statistics were used, and SPSS[1] version 30.0.0.0 was employed.

4.3.1. Quantitative analysis

The statistical analysis, following the 30-week intervention, revealed several key differences between the experimental and control groups, particularly among students with dyslexia.

4.3.1.1. Analysis of self-determination theory construct. To answer RQ1, a one-way repeated-measures ANOVA was conducted for the experimental group. From the quantitative analysis, *LexiBo* performed better than those using conventional learning methods. Additionally, students with dyslexia showed greater improvement in engagement and motivation than those without dyslexia. The analysis is shown below.

For the experimental group (Tables 3 and 4), students with dyslexia showed the largest improvement in emotional engagement ($F(1, 15) = 8.53$, $p<.01$, $\eta_p^2 = .22$) and intrinsic

Table 3. Experimental group. Pearson correlations among post-test motivational and engagement variables.

Variable	1	2	3	4	5	6	7
1. Autonomy	1						
2. Competence	.808**	1					
3. Relatedness	.739**	.649**	1				
4. Behavioural Engagement	−.155	−.308	−.288	1			
5. Emotional Engagement	−.251	−.104	−.251	.568*	1		
6. Cognitive Engagement	−.202	−.105	−.235	.738**	.800**	1	
7. Intrinsic Motivation	−.095	−.059	−.420	.434	.368	.231	1

Note: $N = 32$. $^*p < .05$, $^{**}p < .01$.

Table 4. The SDT overview of ANOVA for the experimental group.

	Group	% Change	Pre: *M*(*SD*) [95% CI]	Post: *M*(*SD*) [95% CI]	*p*-value	η_p^2	*F*-value
BE	Dyslexia	+6.05	75.83 (17.36) [66.58, 85.09]	80.42 (11.54) [74.27, 86.56]	.39	.03	.77
	Non-Dyslexia	+1.95	85.83 (14.17) [78.28, 93.38]	87.50 (11.64) [81.30, 93.70]	.72	.004	.13
EE	Dyslexia	+32.20	60.83 (22.29) [48.95, 72.71]	80.42 (14.90) [72.48, 88.36]	.0067**	.22	8.53
	Non-Dyslexia	+7.32	85.42 (14.03) [77.94, 92.89]	91.67 (10.18) [86.24, 97.09]	.16	.07	2.08
CE	Dyslexia	+10.56	75.00 (18.62) [65.08, 84.92]	82.92 (14.80) [75.03, 90.80]	.19	.06	1.77
	Non-Dyslexia	+9.80	80.83 (14.17) [73.28, 88.38]	88.75 (8.33) [84.31, 93.19]	.064	.11	3.71
IM	Dyslexia	+27.53	62.08 (25.15) [48.68, 75.48]	79.17 (18.99) [69.04, 89.29]	.0038*	.14	4.70
	Non-Dyslexia	+2.00	83.33 (10.89) [77.53, 89.13]	85.00 (15.30) [76.85, 93.15]	.73	.004	.13

Note: The acronyms BE, EE, CE and IM denote Behavioural, Emotional, Cognitive Engagement, and Intrinsic Motivation, respectively. '**' and '*' represent $p < .01$ and $p < .05$, respectively.

motivation ($F(1, 15) = 4.70$, $p < .05$, $\eta_p^2 = .14$). However, behavioural and cognitive engagement improved more modestly.

For the control group (Tables 5 and 6), students with dyslexia showed the largest declines in behavioural ($F(1, 17) = 98.58$, $p < .001$, $\eta_p^2 = .74$), emotional ($F(1, 17) = 27.74$, $p < .001$, $\eta_p^2 = .45$), cognitive engagement ($F(1, 17) = 20.45$, $p < .001$, $\eta_p^2 = .38$), and intrinsic motivation ($F(1, 17) = 1.31$, $p < .001$, $\eta_p^2 = .04$). By contrast, students without dyslexia showed only small and non-significant changes in emotional, cognitive engagement, and intrinsic motivation, despite a substantial decline in behavioural engagement ($F(1, 17) = 39.25$, $p < .001$, $\eta_p^2 = .54$).

Table 5. The SDT overview of ANOVA for the control group.

	Group	% Change	Pre: *M*(*SD*) [95% CI]	Post: *M*(*SD*) [95% CI]	*p* -value	η_p^2	*F*-value
BE	Dyslexia	−47.28	81.48 (13.63) [74.70, 88.26]	42.96 (9.21) [38.38, 47.55]	7.70E−8***	.74	98.58
	Non-Dyslexia	−25.57	81.11 (12.58) [74.86, 87.37]	60.37 (6.25) [57.26, 63.48]	1.4E−13***	.54	39.25
EE	Dyslexia	−29.31	85.93 (10.94) [80.49, 91.36]	60.74 (17.09) [52.24, 69.24]	3.9E−9***	.45	27.74
	Non-Dyslexia	+4.34	76.67 (11.49) [70.95, 82.38]	80.00 (20.07) [70.02, 89.98]	7.78E−6***	.01	.37
CE	Dyslexia	−25.45	81.48 (12.64) [75.20, 87.77]	60.74 (14.80) [53.39, 68.10]	7.1E−7***	.38	20.45
	Non-Dyslexia	+6.69	77.41 (13.36) [70.76, 84.05]	82.59 (14.84) [75.21, 89.97]	.366	.03	1.21
IM	Dyslexia	−26.78	82.96 (14.14) [75.93, 89.99]	60.74 (14.44) [53.56, 67.93]	4.7E−7***	.04	1.31
	Non-Dyslexia	+8.45	74.45 (13.96) [67.51, 81.39]	80.74 (18.70) [71.44, 90.04]	.35	.14	21.75

Note: The acronyms BE, EE, CE and IM denote Behavioural, Emotional, Cognitive Engagement, and Intrinsic Motivation, respectively. '***' represents $p < .001$.

Table 6. Control group. Pearson correlations among post-test motivational and engagement variables.

Variable	1	2	3	4	5	6	7
1. Autonomy	1	–	–	–	–	–	–
2. Competence	.570*	1	–	–	–	–	–
3. Relatedness	.417	.701**	1	–	–	–	–
4. Behavioural Engagement	.037	.503*	.357	1	–	–	–
5. Emotional Engagement	.050	.431	.650**	.237	1	–	–
6. Cognitive Engagement	.046	.085	.310	.072	.498*	1	–
7. Intrinsic Motivation	−.122	.085	.410	.358	.552*	.633**	1

Note: $N = 36$. *$p < .05$, **$p < .01$.

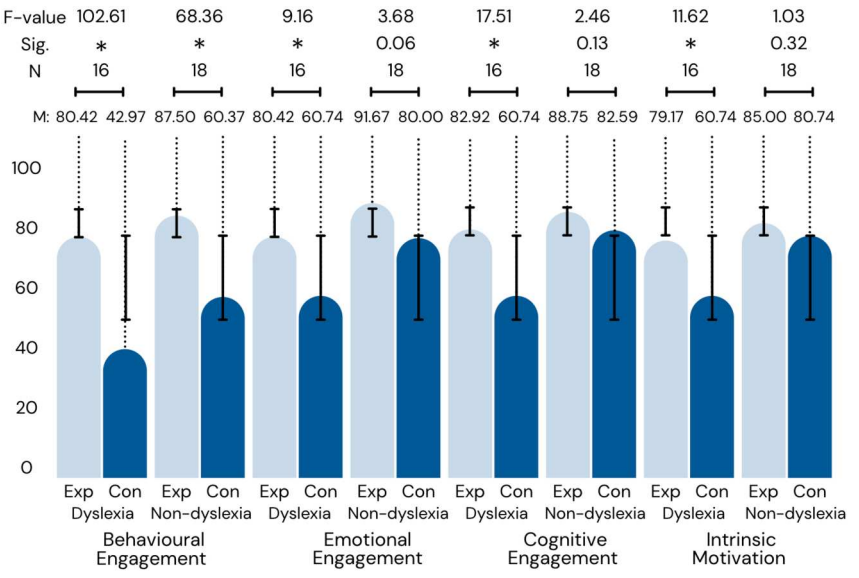


Figure 11. Overview of analysis of covariance (ANCOVA) for SDT. Error bars showed standard deviation. '*', Exp and Con denoted $p < .05$, experimental, and control group.

We also compared the effects of learning with/without *LexiBo*. The analysis of covariance (ANCOVA) was used (Figure 11), with *LexiBo* as pre-test. Students with dyslexia demonstrated greater improvement than those without dyslexia over 30 weeks. For students with dyslexia, the range of skewness was within −.05 to.13 and kurtosis was within −.87 to 1.33. For those without dyslexia, the range of skewness was within −2.06 to .24 and kurtosis was within −1.37 to 5.99.

For students with dyslexia, behavioural engagement exhibited statistically significant improvement (p<.001, $F(1, 31) = 102.61$; experimental group: $M = 80.42$; control group: $M = 42.97$); emotional engagement manifested statistically significant improvement ($p = .005$, $F(1, 31) = 9.16$; experimental group: $M = 80.42$; control group: $M = 60.74$); cognitive engagement revealed statistically significant improvement ($p < .001$, $F(1, 31) = 17.51$; experimental group: $M = 82.92$; control group: M =60.74); intrinsic motivation presented statistically significant improvement ($p = .002$, $F(1, 31) = 11.62$; experimental group: $M =$ 79.17; control group: $M = 60.74$).

For students without dyslexia, behavioural engagement exhibited statistically significant improvement ($p < .001$, $F(1, 31) = 68.36$; experimental group: $M = 87.50$; control group: $M = 60.37$); emotional engagement manifested improvement ($p = .064$, $F(1, 31) = 3.68$; experimental group: $M = 91.67$; control group: M = 80.00); cognitive engagement revealed improvement ($p = .127$, $F(1, 31) = 2.46$; experimental group: $M = 88.75$; control group: $M = 82.59$); intrinsic motivation presented improvement ($p = .318$, $F(1, 31) = 1.03$; experimental group: $M = 85.00$; control group: $M = 80.74$).

Table 7 presents the descriptive and ANOVA analysis of autonomy, competence, and relatedness for the experimental group in the post-test. The predictors were BE, EE, CE, and IM, and the dependent variables were autonomy, competence, and relatedness. In general, students without dyslexia reported higher mean scores across all three SDT

Table 7. The descriptive and ANOVA analysis of autonomy, competence and relatedness for the experimental group.

	Group	Post: *M*(*SD*) [95% CI]	Skewness	Kurtosis	*p*-value	η_p^2	*F*-value
Autonomy	Dyslexia	79.58 (12.99) [72.66, 86.50]	−.83	.60	.659	.18	.62
	Non-Dyslexia	87.08 (9.88) [81.82, 92.35]	.44	−1.65	.921	.07	.22
Competence	Dyslexia	78.33 (17.64) [68.93, 87.73]	−.75	.37	.482	.25	.93
	Non-Dyslexia	88.33 (10.75) [82.60, 94.06]	.19	−2.08	.939	.06	.19
Relatedness	Dyslexia	81.25 (14.24) [73.66, 88.84]	−.65	.18	.796	.13	.41
	Non-Dyslexia	90.00 (10.33) [84.50, 95.50]	.00	−2.31	.661	.18	.62

dimensions: autonomy ($M = 87.08$, $SD = 9.88$, $p = .921$, $\eta_p^2 = .07$, F-value = .22) compared with students with dyslexia ($M = 79.58$, $SD = 12.99$, $p = .659$, $\eta_p^2 = .18$, F-value = .62), competence ($M = 88.33$, $SD = 10.75$, $p = .939$, $\eta_p^2 = .06$, F-value = .19) compared with students with dyslexia ($M = 78.33$, $SD = 17.64$, $p = .482$, $\eta_p^2 = .25$, F-value = .93); and relatedness ($M = 90.00$, $SD = 10.33$, $p = .661$, $\eta_p^2 = .18$, F-value = .62) compared with students with dyslexia ($M = 81.25$, $SD = 14.24$, $p = .796$, $\eta_p^2 = .13$, F-value = .41). However, the predictive ANOVA models were not statistically significant for either group in any dimension.

4.3.1.2. Analysis of intrinsic motivation inventory. To address RQ2, we examined inter-item correlations and evaluated the descriptive statistics of the IMI. Participants' intrinsic motivation was assessed using the IMI. the range of skewness was from −2.70 to −1.11 and kurtosis was from .42 to 8.10. Descriptive statistics revealed that participants reported high levels of enjoyment ($M = 86.46$, $SD = 22.02$, $\alpha = .94$), perception ($M = 87.32$, $SD = 15.19$, $\alpha = .84$), effort ($M = 90.71$, $SD = 9.98$, $\alpha = .71$), value ($M = 77.14$, $SD = 26.10$, $\alpha = .95$), and relatively lower stress ($M = 89.03$, $SD = 15.03$, $\alpha = .93$). All subscales demonstrated acceptable to excellent internal consistency, with Cronbach's alpha coefficients ranging from .71 (effort) to .95 (stress).

As shown in Table 8, inter-item correlations among the five IMI subscales ranged from .04 to .84. Strong positive correlations were observed between perception and value ($r = .84$), enjoyment and value ($r = .83$), and enjoyment and perception ($r = .72$), indicating substantial shared variance among motivational dimensions. Moderate correlations emerged between stress and value ($r = .63$), stress and perception ($r = .52$), and stress and effort ($r = .15$). The correlation suggests that participants can maintain engagement by minimising anxiety.

4.3.1.3. Analysis of expectancy-value theory. To address RQ3, a one-way repeated-measures ANOVA was conducted to measure EVT (Table 9). The one-way repeated-measures ANOVA revealed improvements in expectancy beliefs, with participants reporting higher expectations for success post-intervention ($M = 93.75$, $SD = 9.57$) compared to

Table 8. Overview of descriptive analysis of IMI subscales.

Variable	Enjoyment	Perception	Effort	Stress	Value
Enjoyment	1.00	.72	.04	.70	.83
Perception	–	1.00	.51	.52	.84
Effort	–	–	1.00	.15	.40
Stress	–	–	–	1.00	.63
Value	–	–	–	–	1.00

Table 9. Descriptive analysis and overview of ANOVA for EVT.

Variable		*M*	*SD*	Skewness	Kurtosis	Improvement	*F*-value	*P*-value	η_p^2
Ability	Pre	75.00	15.06	−.60	.56	17.50	10.48	**	.411
	Post	88.13	13.28	−.59	−.76				
Expect	Pre	74.38	13.65	−.03	−.60	26.05	27.35	***	.646
	Post	93.75	9.57	−.90	−1.39				
Interest/	Pre	82.75	11.66	−.35	−.48	9.67	5.05	.16	.252
Value	Post	90.75	8.97	−.16	−1.95				

Note: '***' and '**' denote $p < .001$ and $p < .01$, respectively.

pre-intervention ($M = 74.38$, $SD = 13.65$), representing a mean improvement of 26.05% ($F(1, 31) = 27.35$, $p<.001$). Similarly, perceived ability increased by 17.50% (pre-test: $M = 75.00$, $SD = 15.06$; post-test: $M = 88.13$, $SD = 13.28$, $F(1, 31) = 10.48$, $p<.01$). Interest/value showed modest improvement by 9.67% (pre-intervention: $M = 82.75$, $SD = 11.66$; post-intervention: $M = 90.75$, $SD = 8.97$; $F(1, 31) = 5.05$, $p = .16$).

4.3.1.4. Analysis of proficiency tests. To address RQ4, a one-way repeated-measures ANOVA was conducted on the proficiency test scores. Students with dyslexia showed greater improvement than those without dyslexia. The performance of students with dyslexia improved by 14.31% (Pre: $M = 80.75$, $SD = 18.61$; Post: $M = 92.31$, $SD = 10.51$; $p = .039$; $F(1, 15) = 4.68$). The performance of students without dyslexia improved by .51%, and the difference was less dispersed (Pre: $M = 80.83$, $SD = 17.27$; Post: $M = 81.25$, $SD = 15.38$, $p = .943$; $F(1, 15) = .01$).

4.3.2. Qualitative analysis

Thematic analysis of student interviews provided the explanatory depth for the quantitative results, articulating the mechanism of motivational change.

4.3.2.1. Theme A: Affective engagement and psychological need satisfaction. The qualitative findings complemented the quantitative results by explaining why students in the experimental group, particularly those with dyslexia, showed the largest improvement in emotional engagement and intrinsic motivation. Consistent with the SDT findings, students' responses and performance suggested that *LexiBo* supported relatedness and competence through its encouraging feedback, attractive appearance, and low-pressure interaction style. Over 90% of participants reported that they liked *LexiBo*. Many students described *LexiBo* as 'very fun', suggesting that the robot fostered positive emotional value and interest/value. Students highlighted the robot's aesthetic and interactive features, including its smiling face and music. Encouraging responses after failure appeared to reduce anxiety and reinforce willingness to continue learning. For example, one student noted, 'If I fail, *LexiBo* will also encourage me, and I feel very happy', indicating that the robot's feedback function may have supported emotional safety and competence development. However, one-third of students also reported that some tasks were difficult or occasionally boring, which explains why behavioural and cognitive engagement improved more modestly than emotional engagement and intrinsic motivation. Specifically, one student reported that the system became boring due to the extensive Chinese-language content. This student noted that the high volume of questions and

learning sets was overwhelming, suggesting that reducing the workload might improve the overall learning experience.

4.3.2.2 Theme B: Cognitive load, usability, and competence support. The qualitative findings also explain why behavioural and cognitive engagement improved more modestly than emotional engagement and intrinsic motivation in the quantitative results. Although *LexiBo* was generally perceived as easy to use, students reported that the linguistic complexity of some tasks, particularly short-sentence construction, increased cognitive load and sometimes hindered improvements in engagement. Over 60% of participants reported feeling stressed when using *LexiBo* as they did not know how to answer complex questions. For example, one student commented, '會壓力大, 因為有時候我不會那些題目' (lit., I feel great pressure because sometimes I do not know how to answer those questions). This finding suggests that while the *LexiBo* interface supported competence through simple, accessible operations, the difficulty of the content still challenged students' confidence and information processing. At the same time, most participants described *LexiBo* as '很容易' (lit., very easy), and one student explained, '因為操作 robot 的時候先開機，然後找那個登入按鈕，然後按就可以了。好簡單，好快。' (lit., When I use *LexiBo*, I turn it on. Then, I find the login button and press it. It is so simple and fast). These findings suggest that usability of *LexiBo* supported competence satisfaction. However, the higher cognitive demands of sentence-level tasks may have limited stronger gains in behavioural and cognitive engagement. However, one student reported difficulty keeping up with the pace of the activities, explaining that there was too much content to remember and that some items were challenging because they included unfamiliar Chinese characters (好困難, 太快跟不上; 題目有點難, 可能有字看不懂, 但懂得聽).

4.3.2.3. Theme C: Perceived interest/value of learning. Qualitative data further supported the EVT-related outcomes, illustrating that students viewed *LexiBo* as a highly valuable and meaningful resource for Chinese language acquisition. Students almost expressed positive responses of *LexiBo* and explicitly recognised its pedagogical value. Over 90% of participants agreed that the learning activities were useful as *LexiBo* enabled independent practice and supported preparation for school assessment. For instance, one student stated, '因為考試都要自己讀，機械人可以幫我預先練習' (lit., Because I have to study for the exam myself, *LexiBo* can help me practice in advance). Another student explained, '我喜歡, 因為我可以認識好多字' (lit., I like it because I can learn many vocabulary words). These responses suggest that students viewed *LexiBo* not merely as an enjoyable tool, but as a useful resource for vocabulary development and academic preparation. Students' feedback explained the observed improvements in expectancy beliefs, perceived ability, and learning value. On the other hand, one student reported feeling somewhat tired because the activities required extensive verbal responses. The student suggested converting some questions into multiple-choice items and reducing the total number of questions by one or two. Nevertheless, the student considered the Chinese learning materials appropriate for their proficiency level (有點點累。因為講的地方太多, 可以改為MC題, 寫出來。題目數量可以減少一兩題。但是, 現在的中文知識符合我的中文能力).

5. Discussion

5.1. Affective mechanisms of motivation in RALL

The experimental group showed statistically significant improvement in emotional and behavioural engagement. These improvements are consistent with the interpretation that *LexiBo* may support the three basic psychological needs emphasised in SDT (i.e. autonomy, competence, and relatedness), which are known to strengthen engagement and intrinsic motivation (Van Minkelen et al. 2020; L. Yang and Li 2025). This interpretation is also consistent with prior work, showing that robots can enhance well-being and engagement when they offer choice, provide feedback, and sustain interactive social behaviour (Janssen and Schadenberg 2024). The pattern suggests that the primary contribution of *LexiBo* lies in strengthening the affective dimension of learning. In addition, the post-test correlations showed that autonomy, competence, and relatedness were strongly interrelated, while behavioural, emotional, and cognitive engagement were also positively connected, indicating a coherent motivational structure in the experimental group.

This motivational effect appeared to be important for students with dyslexia. Prior research shows that these learners often experience anxiety, low self-esteem, and reduced confidence in academic and language-learning contexts (Abu Omar et al. 2024; Akter, Taisiq, and Munira 2025; Zuppardo et al. 2023), which may undermine persistence and willingness to participate (Almgren Bäck et al. 2024; Shahab et al. 2026). The control group findings align with this, suggesting that students with dyslexia were more vulnerable to losses in motivation and engagement over time. The post-test correlations showed that competence was positively associated with autonomy and relatedness, while emotional, cognitive, and intrinsic motivation variables were also positively connected, indicating a weaker but still coherent motivational structure in the control group. However, our findings suggest that *LexiBo* is able to act as an instructional tool and affective scaffold that helped reduce barriers to participation (Dignam, Smith, and Kelly 2025).

The qualitative findings help explain this pattern. In the interviews, students repeatedly described *LexiBo* as fun, visually appealing, and encouraging, especially when they made mistakes. These comments suggest that relatedness can be supported by *LexiBo's* friendly appearance and social presence, while immediate feedback, repeated attempts, and a low-pressure interaction format can also support competence. Its aesthetic design may also have made *LexiBo* feel less threatening and more approachable, thereby reducing the emotional cost of failure and helping students remain engaged in the tasks (Galindo 2025; Janssen and Schadenberg 2024; Koschate et al. 2016).

5.2. Explaining uneven improvement in engagement and motivation

An interesting finding of this study was that not all dimensions of engagement and motivation improved to the same extent. Emotional engagement and intrinsic motivation showed a significant improvement for students with dyslexia, whereas behavioural and cognitive engagement improved more modestly. The intervention may influence how students *feel* about learning. It may not substantially change how deeply they process learning content (Namaziandost, Çakmak, and Ashkani 2025; Nesbitt et al. 2025). In

other words, affective readiness may have developed before stronger behavioural regulation and cognitive investment became fully established (Guedes et al. 2023; Kelly, Yeigh, and Hudson 2024). This interpretation aligns with SDT, which suggests that need-supportive environments may first reduce resistance and foster willingness to participate, thereby creating conditions for later cognitive engagement (Kritz et al. 2023; Standage, Ryan, and Curran 2025; Wang et al. 2025).

Students described *LexiBo* as enjoyable, attractive, and easy to use. Their responses was able to explain the rise in emotional engagement. At the same time, they also reported that the short-sentence tasks were demanding. Moreover, the students sometimes felt pressure when they did not know how to answer. This suggests that although the UI and interactional design reduced emotional barriers, some tasks remain complex, especially for students with weak Chinese foundations. The phenomenon possibly indicated that students may have become more willing to engage in learning, even with a relatively higher cognitive load for higher-order language production.

5.3. Intrinsic motivation inventory and stress reduction

The IMI results provide evidence of robust affective engagement: strong enjoyment, perception, interest/value, and moderate stress. The strong correlations of motivational dimensions indicate tightly integrated affective experiences: enjoyment and value, competence and value, enjoyment and competence. These relationships suggest that emotional engagement became inseparable from learners' perception of task importance (Nakata, Nitta, and Tsuda 2022), a hallmark of intrinsic motivation (Wang and Xue 2022).

Immediate and personalised feedback mechanisms can address the need for competence (Yang, Shao, and Guo 2025). However, we found that many students reported experiencing stress related to task difficulty, particularly the short sentence task. Although stress was not entirely eliminated, it remained decoupled from 'effort'. The result suggested that emotional scaffolding moderated the anxiety associated with cognitive challenge. Research demonstrates that emotionally-scaffolded corrective feedback can reduce learning anxiety and improve achievement, particularly for learners with high initial anxiety (Alavi and Esmaeilifard 2021).

5.4. From motivation to proficiency development

Students with dyslexia showed substantial improvement in language proficiency compared with those without dyslexia. This finding revealed that the affective benefits of *LexiBo* were not only subjective impressions, but were accompanied by measurable language learning improvement. This pattern aligns with EVT and SDT. When learners perceive learning as valuable, feel more capable of success, and experience less emotional threat, they are more likely to persist in practice and benefit from repeated exposure (Englund et al. 2023; Lee and Song 2022).

Students described *LexiBo* useful for practising before exams, learning vocabulary, and reviewing tasks independently. Their responses suggest that *LexiBo* can be used as a structured rehearsal tool, enabling repeated exposure to vocabulary and sentence patterns. These features are specifically essential for learners with dyslexia, who often benefit from repetition, multimodal presentation, and reduced time pressure (Javed

et al. 2024; Rahmadhani and Damanik 2025). Also, the replay and recap functions may have supported memory consolidation for them (Radtke et al. 2025; Sabih and Kuyini 2024). These features may have made practice more accessible and more sustainable over time.

5.5. Implications for RALL and inclusive design

Our findings offer several implications for the design of RALL in inclusive education. First, *LexiBo* indicates that RALL could be conceptualised as a motivational intervention rather than as a purely technological delivery mechanism. The advantages of *LexiBo* were found in emotional engagement, intrinsic motivation, expectancy beliefs, and perceived interest/value. Qualitative evidence showed that these outcomes were linked to social responsiveness, attractive design, and non-judgmental feedback (Brandmo and Gamlem 2025; Clark 2012; Y. Li et al. 2026). This suggests that the success of RALL depends on the presence of hardware (i.e. robot) or novel technology (i.e. AI-empowered solutions) but also on a psychologically safe and meaningful learning environment.

Second, the mixed-methods evidence points to several practical design principles for future RALL systems. An effective system should incorporate multimodal representations, adjustable pacing, repeated listening and replay functions, immediate supportive feedback, and task sequences that progress from recognition to production (Cheng et al. 2025; Dritsas et al. 2025; Oviatt et al. 2000; Sarter 2006). However, positive effects alone may not produce a broad learning improvement. As mentioned in the qualitative analysis, cognitively demanding tasks (i.e. sentence-level tasks) may have constrained stronger growth in behavioural and cognitive engagement. Future RALL design should combine emotional support with adaptive difficulty and more fine-grained scaffolding. Therefore, inclusive AI-empowered robotic learning environments can move beyond novelty and become sustainable tools for equitable participation and language development.

5.6. Limitation

We acknowledge several limitations in this work. First, although the intervention spanned 30 weeks, the weekly dose of *LexiBo* use was relatively short (about 15 min). Over such a period, students were also exposed to ongoing classroom teaching and spoken language use and experience natural maturation. Consequently, the performance of *LexiBo* is associated with additional improvements in motivation and literacy outcomes. Second, although the sample size was relatively small, the longitudinal design strengthens confidence in the findings. Third, the sample focused on students with and without dyslexia. Students with other SEN or from different regions may show differential responses. Nevertheless, this work provides the 30-week examination of RALL motivation among students with dyslexia in Hong Kong, where Cantonese was the medium of instruction. Fourth, the gender distribution was skewed in favour of male participants. Future research should prioritise gender-balanced recruitment to investigate potential sex-specific responses to interventions. Finally, due to the limited sample size, we were unable to conduct a factor analysis, such as an exploratory factor analysis (EFA) (Tinsley and Tinsley 1987) to empirically confirm discriminant validity. Future research will scale up the participant pool to enable a more comprehensive measurement-model assessment.

6. Conclusion

This study demonstrated that a 30-week RALL intervention for students with and without dyslexia promoted their learning motivation and efficacy. In general, the experimental group exhibited a significant improvement in expectancy. Moreover, students with dyslexia in the experimental group demonstrated a significant improvement in emotional engagement and motivation following this additional instruction. This longitudinal study provides insights into aesthetic and anthropomorphic design for RALL. The application can contribute to the community by being translated into alternative languages, such as English and Mandarin. In the future, we will design experiments to explore which types of clothing, fabrics, or styles can enhance students' engagement in RALL. Additionally, we will design various human-centred animations, expressions, and actions to examine which combinations can further enhance students' motivation.

Note

1. SPSS version 30.0.0.0, https://www.ibm.com/products/spss-statistics

Disclosure statement

No potential conflict of interest was reported by the author.

Data availability statement

De-identified summary data may be made available from the corresponding author upon reasonable request and subject to further IRB approval.

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Appendix. Supplementary information

A.1. Lists of abbreviations

- ANCOVA: Analysis of covariance
- ANOVA: Analysis of variance
- ASR: Automatic speech recognition
- ESL: English as a second language
- EVT: Expectancy-value theory
- IMI: Intrinsic motivation inventory
- RALL: Robot-assisted language learning
- RAN: Rapid automatised naming
- SDT: Self-determination theory
- SEN: special education needs
- UDL: Universal design for learning
- UI: User interface
- VAKT: Visual, auditory, kinesthetic, tactile

A.2. Summary of statistical models, sample sizes, and degrees of freedom

Analysis / Construct	Sample size (N)	Degrees of freedom (df)
Pre- vs. Post-Test		
Experimental (Exp.) Group	N = 32	*df* = 31
Exp. Dyslexia Subgroup	n = 16	*df* = 15
Exp. Non-Dyslexia Subgroup	n = 16	*df* = 15
Control (Con.) Group	N = 36	*df* = 35
Con. Dyslexia Subgroup	n = 18	*df* = 17
Con. Non-Dyslexia Subgroup	n = 18	*df* = 17
EVT Measures		
Exp. Group (Pre/Post)	N = 32	*df* = 31