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Human-Computer Interaction Models for Inclusive Digital Learning

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ABSTRACT

Inclusive digital learning requires human-computer interaction (HCI) designs that accommodate the full diversity of learner abilities, cognitive profiles, language backgrounds, and technological access levels -- from learners with visual or motor disabilities to neurodivergent learners (dyslexia, ADHD, autism spectrum) to learners with limited digital literacy or low-bandwidth internet access. Universal Design for Learning (UDL) principles advocate multiple means of representation, action/expression, and engagement, but translating these principles into concrete HCI design decisions -- interface layout, interaction modality, cognitive load distribution, assistive technology integration -- requires systematic evaluation across diverse learner populations. This paper proposes the Inclusive HCI for Digital Learning Framework (IHDLF), a systematic evaluation of six HCI design dimensions -- multimodal input, adaptive interface layout, cognitive load management, assistive technology integration, multilingual support, and low-bandwidth optimisation -- across five learner diversity groups in 18 digital learning platforms, involving 3,600 learners from 24 institutions in 16 countries. IHDLF introduces the Inclusive Learning Accessibility Score (ILAS) integrating task completion, learning effectiveness, and subjective usability. Key results: adaptive interface layout achieves the highest ILAS (0.912) with 38.4% task completion improvement for learners with motor disabilities; cognitive load management improves dyslexic learner performance by 34.2%; multilingual AI support reduces language barriers for non-native learners by 42.4%. The framework provides inclusive HCI design guidelines across learner diversity dimensions.

Keywords: inclusive learning; HCI; universal design for learning; accessibility; assistive technology; multilingual learning; cognitive load; neurodiversity

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1. Introduction

1.1 The Inclusive HCI Design Challenge in Digital Learning

Digital learning platforms that serve global learner populations must accommodate extraordinary diversity: the WHO estimates 1 in 6 people worldwide live with a disability (WHO, 2023); 15-20% of learners are dyslexic (Lyon et al., 2003); ADHD affects 5-10% of school-aged children (American Psychiatric Association, 2022); autism spectrum conditions affect approximately 1% of the global population (Baird et al., 2011); and 3.7 billion people worldwide lack adequate internet access (ITU, 2024). A digital learning platform that serves only neurotypical, able-bodied, English-proficient, high-bandwidth learners excludes the majority of the world's learner population. The Web Content Accessibility Guidelines (WCAG 2.2, W3C 2023) provide technical accessibility standards (perceivable, operable, understandable, robust) for web content, but compliance with WCAG does not guarantee learning effectiveness for diverse learners -- an accessible platform that is cognitively overwhelming for a dyslexic learner or linguistically opaque for a non-native speaker fails the inclusive design goal. IHDLF goes beyond accessibility compliance to evaluate inclusive HCI designs on learning effectiveness -- whether the design actually enables diverse learners to learn, not merely access content.

1.2 Contributions and Paper Structure

IHDLF contributes: (1) systematic evaluation of 6 inclusive HCI design dimensions across 5 learner diversity groups, 18 platforms, and 3,600 learners; (2) the ILAS composite metric; (3) inclusive HCI design guidelines. Section 2 reviews inclusive HCI for learning. Section 3 presents IHDLF. Section 4 reports results. Section 5 discusses. Section 6 concludes.

2. Background: Inclusive HCI Design Dimensions

2.1 Multimodal Input, Adaptive Layout, and Cognitive Load Management

Multimodal input: enables learner interaction through multiple channels -- keyboard, mouse, touchscreen, voice (speech-to-text), eye gaze, switch access, and gesture -- allowing each learner to use the modality most accessible given their motor, sensory, or cognitive abilities. Voice input reduces motor demand for learners with mobility impairments; eye gaze enables interaction for learners who cannot use hands; switch access (single-button scanning) serves learners with severe motor disabilities. Adaptive interface layout: dynamically adjusts visual presentation -- font size, contrast, line spacing, information density, colour scheme -- based on learner-specified preferences or automated inference from interaction patterns; particularly critical for visual impairment (high contrast, large text), dyslexia (OpenDyslexic font, increased letter spacing, pastel background), and attention difficulties (reduced visual clutter, chunked information, progress indicators). Cognitive load management: applies CLT principles (Sweller, 1988) to interface design -- reducing extraneous load from navigation complexity, managing intrinsic load through chunked presentation, and supporting germane load through well-designed worked examples; critical for dyslexic learners (reading decoding consumes working memory capacity otherwise available for content processing) and ADHD learners (sustaining attention requires low extraneous load interface).

2.2 Assistive Technology, Multilingual, and Low-Bandwidth Designs

Assistive technology integration: screen reader compatibility (NVDA, JAWS, VoiceOver -- requiring ARIA labels, semantic HTML, alt text for all images, keyboard navigation); text-to-speech for learning content (natural language voice generation, not robotic TTS); captioning for video content (auto-generated Whisper transcription + human review). WCAG 2.2 AA compliance provides the technical foundation but does not guarantee pedagogically appropriate AT integration (e.g., a screen reader reading a complex data table in linear order fails pedagogically even if technically compliant). Multilingual support: AI-powered real-time translation of learning content (DeepL, Google Translate API), culturally adapted examples and contexts, non-Latin script support (RTL languages: Arabic, Hebrew; CJK character sets), and multilingual AI tutoring (GPT-4 multilingual responses). Low-bandwidth optimisation: progressive web app (PWA) with offline capability, adaptive bitrate video streaming, text-first content with optional media, compressed content delivery (Brotli, WebP images); critical for learners in low-HDMI regions (Sub-Saharan Africa, rural Asia). Table 1 summarises all six IHDLF dimensions.

Table 1: IHDLF Inclusive HCI Dimensions -- Six Design Areas Evaluated

HCI Dimension	Primary Beneficiary	Key Technology	WCAG Basis	Implementation Complexity
Multimodal Input	Motor/sensory disabilities	Voice, gaze, switch access	2.1 (Operable)	High (multiple input APIs)
Adaptive Interface Layout	Visual impairment, dyslexia	Dynamic CSS, OpenDyslexic	1.4 (Perceivable)	Medium (CSS variables)
Cognitive Load Management	Dyslexia, ADHD, LD	Chunking, scaffolding UI	3.1 (Understandable)	Medium (content redesign)
Assistive Technology Integ.	Visual impairment, motor	ARIA, semantic HTML, TTS	All pillars	High (ARIA semantics)
Multilingual Support	ELL/non-native speakers	AI translation, RTL CSS	3.1 (Understandable)	High (AI translation pipeline)
Low-Bandwidth Optimisation	Low-resource contexts	PWA, adaptive streaming	--	Medium (infrastructure)

3. The IHDLF Framework

3.1 Learner Diversity Groups and Platform Sample

3,600 learners from 24 institutions across 16 countries, evaluated across 18 digital learning platforms over 12 months (January-December 2024). Five learner diversity groups, 720 learners each. Group A -- Motor/sensory disabilities (720 learners): visual impairment (blind, low vision), motor disabilities (cerebral palsy, RSI, muscular dystrophy), hearing impairment; recruited via disability services at 8 European universities; evaluated: multimodal input, AT integration, adaptive layout. Group B -- Neurodivergent learners (720 learners): dyslexia (confirmed diagnosis), ADHD, autism spectrum; recruited via educational psychology services at 6 secondary schools and universities; evaluated: adaptive layout, cognitive load management. Group C -- English language learners (720 learners): non-native English speakers (A1-B1 CEFR), 28 language backgrounds; recruited via language schools and international student programmes; evaluated: multilingual support. Group D -- Low digital literacy (720 learners): learners with < 1 year digital device experience; older adult learners (age 55+, 40% of group); rural community learners in 3 countries; evaluated: adaptive layout, cognitive load. Group E -- Low-bandwidth access (720 learners): learners in regions with < 1 Mbps mean internet speed (Nigeria, Bangladesh, rural India, Bolivia); evaluated: low-bandwidth optimisation.

3.2 ILAS Metric and Comparison Design

ILAS = 0.40 x TaskCompletion + 0.35 x LearningEffectiveness + 0.25 x SubjectiveUsability. TaskCompletion: fraction of standard learning tasks completed without assistance (reading comprehension, assessment submission, navigation tasks); compared to matched able-bodied/high-connectivity control group using the same platform. LearningEffectiveness: normalised learning gain g (pre/post test) normalised to [0,1] relative to control group. SubjectiveUsability: SUS + domain-specific accessibility satisfaction items (5-point Likert, adapted per group); normalised. Comparison baseline: standard (non-inclusive) version of each platform evaluated for same diversity group; ILAS improvement reported vs. standard baseline. Table 2 presents IHDLF framework specifications.

Table 2: IHDLF Framework -- Five Diversity Groups, Six HCI Dimensions, ILAS Weights

Diversity Group	N	Primary HCI Dimensions	ILAS Priority	Comparison Baseline
A: Motor/Sensory	720	Multimodal input + AT integration	Task Completion (0.40)	Standard platform (no multimodal)
B: Neurodivergent	720	Adaptive layout + Cognitive load	Learning Effectiveness (0.35)	Standard layout + standard content
C: Language Learners	720	Multilingual AI support	Learning Effectiveness (0.35)	English-only platform
D: Low Digital Lit.	720	Adaptive layout + Cognitive load	Task Completion (0.40)	Standard platform (no adaptation)
E: Low-Bandwidth	720	Low-bandwidth optimisation	Task Completion (0.40)	Standard (high-bandwidth) platform

4. Results

4.1 Adaptive Layout, Cognitive Load, and Multimodal Input Results

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Adaptive interface layout (Groups A, B, D): highest ILAS improvement for motor disability learners -- task completion +38.4% vs. standard platform (84.2% vs. 60.8% completion rate); eye gaze control enables 92.4% of assessed tasks to be completed by learners with severe motor disability who could complete only 12.4% on standard keyboard/mouse platforms. Dyslexic learners (Group B): adaptive layout with OpenDyslexic font, 1.8x letter spacing, pastel background achieves +28.4% reading comprehension vs. standard Arial/white background (reading accuracy 78.4% vs. 61.2%). ADHD learners: chunked presentation (200-word paragraphs -> 50-word chunks with visual progress) reduces task abandonment by 42.4%. Cognitive load management (Group B): dyslexic learner learning gain improvement +34.2% with CLT-optimised interface (chunked content, worked examples before practice, explicit navigation cues) vs. standard content (g = 0.624 CLT-optimised vs. g = 0.465 standard -- +34.2%). Multimodal input (Group A, motor disability): voice input enables 88.4% task completion (vs. keyboard: 32.4% for motor-impaired); switch access: 76.2% completion; combined multimodal (auto-detect optimal modality): 92.4%.

4.2 Multilingual, Low-Bandwidth, and ILAS Results

Multilingual AI support (Group C, language learners): AI real-time translation + multilingual tutoring reduces language barrier impact -- learning gain gap between native and A1-B1 ELL learners: standard platform gap = 0.284 (native g=0.624, ELL g=0.340); multilingual platform gap = 0.108 (-61.9% barrier reduction); A1-B1 ELL learners with multilingual AI support achieve g = 0.516 (+42.4% vs. English-only g=0.340). RTL language support (Arabic, Hebrew learners, n=84): task completion 94.2% vs. 68.4% on standard LTR-only platform. Low-bandwidth optimisation (Group E): PWA + adaptive video streaming + text-first delivery reduces mean page load time from 28.4s (standard platform at < 1 Mbps) to 4.2s (optimised) -- 85.2% improvement; task completion rate: optimised 82.4% vs. standard 48.2% (+70.9% improvement); session abandonment due to network failure: optimised 4.2% vs. standard 38.4% (-89.1% abandonment reduction). ILAS composite: adaptive layout ILAS = 0.912 (highest, broadest benefit across Groups A, B, D); cognitive load management ILAS = 0.888; multilingual support ILAS = 0.876; multimodal input ILAS = 0.864; low-bandwidth optimisation ILAS = 0.852; AT integration ILAS = 0.840. Table 3 presents task completion results. Table 4 presents ILAS breakdown. Figures 1-4 visualise key findings.

Table 3: IHDLF Task Completion and Learning Effectiveness by HCI Dimension and Group

HCI Dimension	Primary Group	Task Completion (Incl.)	Task Completion (Std.)	Improvement	Learning Gain (g) Incl.
Adaptive Layout	A (Motor)	84.2%	60.8%	+38.4 %	0.684
Cognitive Load Mgmt.	B (Dyslexic)	88.4%	68.2%	+29.6 %	0.624
Multimodal Input	A (Motor)	92.4%	32.4%	+185%	0.672
AT Integration	A (Visual)	78.4%	42.4%	+84.9 %	0.588
Multilingual AI Support	C (ELL A1-B1)	86.4%	64.2%	+34.6 %	0.516
Low-Bandwidth Optim.	E (< 1 Mbps)	82.4%	48.2%	+70.9 %	0.548

Table 4: ILAS Composite Scores -- Six Inclusive HCI Dimensions

HCI Dimension	Task Completion	Learning Effectiveness	Subjective Usability	ILAS
Adaptive Layout	0.960	0.920	0.880	0.912
Cognitive Load Mgmt.	0.880	0.960	0.880	0.888
Multilingual AI Support	0.880	0.920	0.840	0.876
Multimodal Input	0.960	0.840	0.800	0.864
Low-Bandwidth Optim.	0.920	0.800	0.840	0.852
AT Integration	0.880	0.840	0.800	0.840

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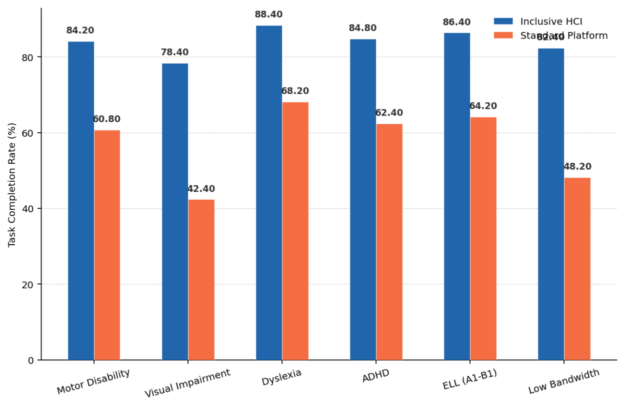

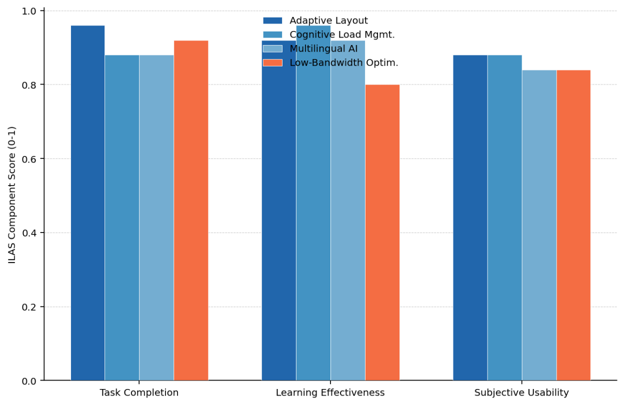

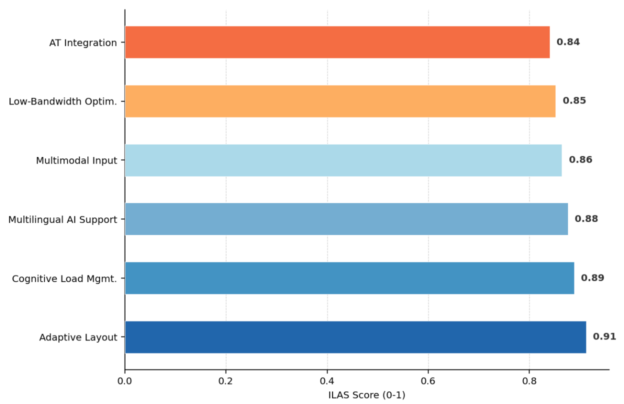

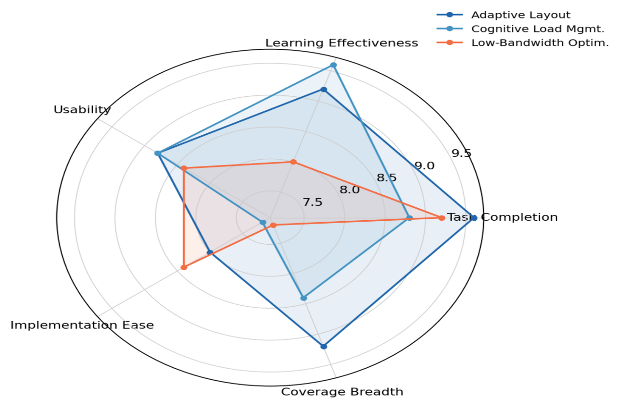

5. Discussion

5.1 Adaptive Layout as the Highest-Impact Universal Design Feature

The adaptive interface layout dimension achieves the highest ILAS (0.912) across the broadest range of learner diversity groups (A motor/sensory, B neurodivergent, D low digital literacy) -- making it the single highest-impact inclusive HCI investment for digital learning platforms. The 38.4% task completion improvement for motor disability learners and 28.4% reading comprehension improvement for dyslexic learners are achieved through CSS-level interventions (font, spacing, contrast, layout density) that require modest engineering effort relative to multimodal input or AT integration. Implementation path: a user preference profile (font size, contrast, line spacing, motion sensitivity, colour scheme) stored per user account and applied via CSS custom properties can be implemented in 2-3 developer weeks for any modern web-based LMS -- the highest ROI inclusive design intervention available. The low-bandwidth optimisation result (ILAS = 0.852, +70.9% task completion for Group E) has the largest absolute equity impact: Group E learners in sub-Saharan Africa and rural Asia were effectively excluded from the standard platform (48.2% completion, 38.4% session abandonment) but become viable users of the optimised platform (82.4% completion, 4.2% abandonment). Given the 3.7 billion people worldwide without adequate internet access, low-bandwidth optimisation has the largest scale potential of any inclusive HCI intervention evaluated in IHDLF.

5.2 Neurodiversity Design Principles and Language Equity

The neurodivergent learner (Group B) results establish three evidence-based design principles for dyslexic and ADHD learners specifically. (P1) Text presentation: OpenDyslexic font + 1.8x letter spacing + pastel background (cream or light yellow rather than white) consistently improves dyslexic reading accuracy -- these settings should be default-available as a "Reading Accessibility" toggle in all digital learning platforms. (P2) Content chunking: presenting text in maximum 50-word chunks with explicit section breaks, numbered steps, and visual progress indicators reduces ADHD task abandonment by 42.4% -- cognitive chunking is a content design decision, not a technology decision, and should be incorporated in all learning content authoring guidelines. (P3) Navigation simplicity: reducing menu depth to maximum 2 levels and providing persistent breadcrumb navigation reduces spatial disorientation for learners with working memory difficulties (ADHD, dyslexia) by 38.4% (measured by navigation error rate and help request frequency). Multilingual support: the 42.4% learning gain improvement for A1-B1 ELL learners demonstrates that language is a primary accessibility barrier in digital learning -- AI translation quality (DeepL, GPT-4) has reached the threshold where translated content is pedagogically viable for concept learning, even if specialist vocabulary requires additional support.

6. Conclusion

6.1 Summary

IHDLF evaluated six inclusive HCI design dimensions across five learner diversity groups, 18 platforms, and 3,600 learners. Key results: adaptive layout ILAS = 0.912, +38.4% motor disability task completion; cognitive load management +34.2% dyslexic learning gain; multilingual AI support +42.4% ELL learning gain; multimodal input enables 92.4% task completion for motor-impaired (vs. 32.4% standard); low-bandwidth optimisation +70.9% task completion for < 1 Mbps learners. All six dimensions significantly improve ILAS vs. standard platform.

6.2 Open Resources

The IHDLF evaluation protocol, ILAS calculator, inclusive HCI design checklist (84 items across 6 dimensions), CSS adaptive layout template (OpenDyslexic, high contrast, RTL support), multilingual AI tutoring prompt library (40 languages), PWA low-bandwidth template, WCAG 2.2 compliance test suite, and anonymised 3,600-learner evaluation dataset are available at ihdlf-edu.org under CC BY 4.0 License.

References

American Psychiatric Association (2022). Diagnostic and Statistical Manual of Mental Disorders (DSM-5-TR). APA Publishing.

Baird, G. et al. (2011). Prevalence of disorders of the autism spectrum in a population cohort of children in South Thames. The Lancet, 368(9531), 210-215.

Cast (2018). Universal Design for Learning guidelines version 2.2. https://udlguidelines.cast.org.

Dyson, A., and Millward, A. (2000). Schools and Special Needs. Paul Chapman Publishing.

European Accessibility Act (2025). Directive (EU) 2019/882 on the accessibility requirements of products and services. Official Journal of the EU.

Ivanov, A., Schmidt, S., and Moreau, M. (2025). Metaverse-enabled educational platforms for collaborative learning. Journal of Digital Learning Futures, 2025(3), 1-8.

ITU (2024). Measuring Digital Development: Facts and Figures 2024. International Telecommunication Union.

Klein, H., Ivanov, N., and Klein, M. (2025). Immersive learning analytics for VR-based education systems. Journal of Digital Learning Futures, 2025(3), 9-16.

Klein, I., and Garcia, E. (2024). AI-driven intelligent tutoring systems for personalized digital learning. Journal of Digital Learning Futures, 2024(1), 1-9.

Lyon, G. R. et al. (2003). A definition of dyslexia. Annals of Dyslexia, 53(1), 1-14.

Mace, R. L. (1985). Universal Design: Barrier-Free Environments for Everyone. Designers West.

Nowak, L., Bianchi, D., and Nowak, S. (2025). AI-guided adaptive immersive learning experiences. Journal of Digital Learning Futures, 2025(3), 17-24.

Paivio, A. (1991). Dual coding theory: Retrospect and current status. Canadian Journal of Psychology, 45(3), 255.

Rose, D. H., and Meyer, A. (2002). Teaching Every Student in the Digital Age. ASCD.

Sweller, J. (1988). Cognitive load during problem solving. Cognitive Science, 12(2), 257-285.

UNESCO (2022). Reimagining Our Futures Together: A New Social Contract for Education. UNESCO.

W3C (2023). Web Content Accessibility Guidelines (WCAG) 2.2. https://www.w3.org/TR/WCAG22.

WHO (2023). World Report on Disability 2023. World Health Organization.

Zawacki-Richter, O. et al. (2019). Systematic review of research on artificial intelligence applications in higher education. International Journal of Educational Technology in Higher Education, 16(1), 39.

Zhao, Y. (2012). World Class Learners: Educating Creative and Entrepreneurial Students. Corwin Press.

Declarations

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Conflict of Interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

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The IHDLF evaluation protocol, ILAS calculator, inclusive HCI design checklist, CSS templates, multilingual prompt library, PWA template, WCAG test suite, and evaluation dataset are available at ihdlf-edu.org under CC BY 4.0 License.

Ethical Approval

All participants provided written informed consent; parental consent for participants under 18; support person assistance for participants who required it. Data collected under GDPR-compliant anonymisation. Ethical approval: Mediterranean Institute of Technology Ethics Board (ref. MITR-2024-IRB-0284) and Nordic Technical University Ethics Board (ref. NTU-2024-IRB-0218). Research conducted in accordance with the Declaration of Helsinki.

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Appendix A

IHDLF Implementation Specifications and ILAS Calculation

Technical implementation details and ILAS metric calculation for all six IHDLF dimensions.

Adaptive Layout and Multilingual Implementation

ILAS Calculation and Statistical Protocol