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Designing Digital Affordances Against the Syntax Barrier: A Blended Learning Design Framework for Computational Thinking Development in Secondary ICT Education

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Designing Digital Affordances Against the Syntax Barrier:

A Blended Learning Design Framework for Computational Thinking Development in Secondary ICT Education

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Highlights

- The 'syntax barrier' — learning code syntax without understanding computational semantics — is identified as a systematic, cross-grade instructional problem in secondary programming education.
- Four digital affordance types — simulation, anonymity, synchronous co-construction, and asynchronous preparation — are theorised and empirically grounded as a Blended Learning Design Framework (BLDF) for CS education.
- A ‘habituation effect’, by which students may become dependent on digital scaffolds rather than progressing toward autonomous performance, is identified as an emergent design hypothesis warranting systematic investigation in blended learning assessment research.
- An evidence-based 'ladder of autonomy' fading protocol provides a practical scaffold-withdrawal design tool for programming instruction.
- Teacher-led collaborative inquiry (Lesson Study + Action Research) is proposed as the professional learning mechanism for developing principled digital tool design competence.

Abstract

This study investigates how a practitioner-led Professional Learning Community (PLC) developed, implemented, and evaluated a pedagogically-driven blended learning design for programming education across Grades 7–12 in a specialised secondary school in Kazakhstan, with the aim of supporting computational thinking development (Wing, 2006).

The study identifies the ‘syntax barrier’ — the tendency for students to reproduce code syntax without understanding the computational process it encodes — as a domain-specific manifestation of cognitive overload requiring principled instructional design. Through three Lesson Study cycles and a two-year Action Research programme, four ICT teachers developed and evaluated four digital affordance types — simulation, anonymity, synchronous co-construction, and asynchronous preparation —

constituting a Blended Learning Design Framework (BLDF) in which each tool is selected for the specific cognitive or affective function it performs.

Findings suggest that this affordance-driven design is associated with improved conceptual understanding: 83–85% of Grade 8 students achieved target outcomes on individual exit tickets for iterative programming constructs, and all Grade 12 student pairs successfully completed and defended case-method mini-projects on logical structures. An emergent design hypothesis — the 'habituation effect' — is proposed: students who perform well under scaffolded digital conditions may struggle when those supports are removed, raising important questions for blended learning assessment design. The study also identifies one analytically significant case of tool misfit, constraining any claim that digital affordances are uniformly effective.

The study contributes: (1) the syntax barrier as a theorised instructional pattern requiring design response; (2) the BLDF as a four-type affordance taxonomy grounded in classroom evidence; (3) a five-step ladder of autonomy fading protocol; and (4) a practitioner-led inquiry model for developing blended learning design competence.

Keywords: *computational thinking; blended learning; digital affordances; programming education; cognitive load; syntax barrier*

1. Introduction

A recurring tension in blended learning design is not whether digital technologies support learning, but how they should be selected to address specific cognitive demands within a subject-specific lesson. Research has shifted over two decades from delivery-modality comparisons toward design-level questions: which learning functions are better served through digital environments, and under what conditions (Graham, 2006; Garrison and Kanuka, 2004; Means et al., 2013). In secondary programming education, however, this design question remains poorly specified at the level of day-to-day classroom decision-making. Computational thinking is now widely recognised as a foundational aim of K–12 computing education (Wing, 2006; Grover and Pea, 2013; Lye and Koh, 2014), and the instructional challenges teachers face in developing it through programming are well documented (Sentance and Csizmadia, 2017). Yet ICT teachers selecting digital tools for programming instruction frequently do so on the basis of availability or perceived engagement rather than on an explicit analysis of the cognitive or affective function the tool is expected to perform.

This study begins from a practical classroom observation rather than a theoretical proposition. Across Grades 7–12, a recurring pattern appeared in the teachers' practice: students who could reproduce programming syntax correctly were often unable to reason about what that code actually did. A student who copies a for-loop from a textbook may be unable to trace its execution, predict its output, or correct a boundary condition. This observation — surface fluency without semantic understanding — is not specific to this school or this country; programming teachers have described it informally for decades. What is less well understood is the instructional design condition that produces it, and whether blended learning can address it without simply replacing one form of syntactic dependency with another kind of scaffold dependency. This question matters for blended learning research more broadly: it concerns the

conditions under which digital supports enable genuine conceptual development rather than supported performance that disappears when scaffolds are removed.

The study investigates how a team of four ICT teachers, working within a Professional Learning Community (PLC) through Lesson Study (LS) cycles and a two-year Action Research (AR) programme, developed and iteratively refined a blended learning design response to this pattern. The process was not the application of a pre-existing framework: the design evolved across three years of classroom iteration, and several early assumptions did not survive contact with student behaviour. The paper reports that iterative process honestly, including the cases where the design did not perform as intended. The study makes three contributions to blended learning research and computing education. First, it develops a theoretically informed and empirically grounded account of the syntax barrier as a recurring and instructionally consequential pattern in programming classrooms. Second, it proposes a design-oriented Blended Learning Design Framework (BLDF) that articulates four functionally distinct types of digital affordances — simulation, anonymity, synchronous co-construction, and asynchronous preparation — and specifies the conditions under which each becomes pedagogically meaningful. Third, it introduces a ladder of autonomy as a structured scaffold-fading protocol that addresses challenges associated with sustained reliance on cognitive supports in blended environments.

The study addresses three research questions:

RQ1: What digital affordance types are operative in a blended learning design for secondary programming instruction, and what cognitive or affective functions does each perform?

RQ2: How are the identified affordance types associated with observable patterns in students' conceptual understanding of programming constructs, particularly in relation to the syntax barrier?

RQ3: What are the implications for scaffold fading and assessment validity when digital tools function as cognitive externalisation devices in blended programming instruction?

2. Theoretical Framework

2.1 Instructional Challenges in Programming: A Cognitive Load Perspective

Cognitive Load Theory (CLT) *(Sweller, 1988; van Merriënboer and Sweller, 2005)* identifies three load types: intrinsic (inherent task complexity), extraneous (poor instructional design), and germane (schema formation). Programming places high intrinsic load on novice learners, who must simultaneously coordinate syntactic form, semantic meaning, algorithmic logic, and problem context. In the multilingual classrooms of this study, where instruction is delivered in Russian as a second language for Kazakh-medium students, a further dimension of load is present: learners process the programming construct, its formal notation, and the instructional language concurrently. In this study, the syntax barrier is conceptualised as a recurring and theoretically interpretable instructional pattern, rather than a formally validated construct. It is interpreted as a design-relevant manifestation of cognitive overload: one that arises when formal notation is introduced before learners have developed a sufficiently robust

semantic model of the underlying process. The prescriptive implication is instructional — semantic understanding should precede, or at minimum accompany, the introduction of formal syntax — and it is this implication that motivates the design framework proposed in subsequent sections.

The syntax barrier is distinguished here from two related constructs. The split-attention effect (Sweller and Chandler, 1994) describes interference between spatially separated information sources, addressed by physical integration. The pattern observed in this study is instructional rather than perceptual: it arises when instruction proceeds from syntactic form to semantic meaning rather than the reverse. Novice programmer misconceptions research (e.g., Hermans and Aivaloglou, 2017; Sorva, 2013) catalogues specific student errors — variable assignment confusion, loop termination errors, scope misunderstanding — but does not foreground the instructional design condition that may systematically produce them. The syntax barrier, as used in this study, names that condition as an observed instructional pattern: semantic-last instruction. Its design implication is semantic-first instruction, where code is the terminal formalisation of a process already understood, not the entry point to its understanding. We present this not as a formally validated construct but as a generative design target grounded in cross-grade classroom evidence.

Evidence for this pattern in the study is worth noting because of its cross-grade recurrence: Grade 7 students reproduce logical operator syntax without demonstrating understanding of condition evaluation; Grade 8 students copy loop templates without grasping the three-part header's functional logic; Grade 10 students use database sorting methods procedurally without engaging the data organisation logic; Grade 12 students construct truth tables from memory but cannot apply XOR correctly in novel automation scenarios. The teachers observed this pattern across four grade levels and three programming paradigms (C++, C#, Boolean logic). We are cautious about over-interpreting this: all four teachers work in the same school with similar instructional traditions, and the pattern may partly reflect shared institutional practice rather than a universal property of programming instruction. Nonetheless, its recurrence across such different content domains was what motivated the PLC to treat it as a design target rather than a Grade-specific difficulty.

2.2 Blended Learning Design and Digital Affordances

Blended learning *(Graham, 2006; Garrison and Kanuka, 2004; Means et al., 2013)* has increasingly been understood not as a delivery modality, but as a design question concerning the distribution of cognitive and social functions across digital and face-to-face environments (Graham, 2006; Garrison and Kanuka, 2004; Means et al., 2013). From this perspective, the key question is not whether a tool is digital, but what it enables learners and teachers to do at a specific point in the instructional sequence. This is precisely the question that affordance theory is positioned to answer. The four affordance types proposed in this study are not intended as an exhaustive taxonomy of digital possibilities in programming education. Rather, they were derived from iterative classroom analysis on the basis of three criteria: recurrence across multiple lesson cycles and grade levels; functional distinctiveness in addressing specific cognitive or affective demands; and applicability across different programming content areas

within the studied setting. These criteria provide the basis for treating the BLDF as an analytically grounded design framework rather than a descriptive list of tools.

Building on Gibson's (1979) ecological concept of affordances and its educational extension by Bower (2008) and Kirsh (2013), we define a **digital affordance** as a specific cognitive or affective action-possibility enabled by a digital environment that is not efficiently achievable through face-to-face alternatives at instructional scale. Crucially, affordance is relational: it is not a property of the tool alone, but of the tool in relation to the learner's needs and the instructional goal. The same platform (e.g., Nearpod) has different affordances for different pedagogical purposes.

Puentedura's (2006) SAMR model *(Substitution–Augmentation–Modification–Redefinition)* provides a complementary frame for evaluating the level of transformation a digital tool introduces. The BLDF developed in this study operates primarily at Modification and Redefinition levels: digital tools do not substitute for face-to-face activities but change their fundamental structure (Modification) or create new activities not previously conceivable (Redefinition). Logic.ly's real-time simulation of logical circuits is not a digital substitution for drawing circuits on paper; it creates a new form of immediate feedback that changes what is epistemically possible in the lesson.

2.3 Scaffolding, Fading, and the Habituation Effect

Vygotsky's Zone of Proximal Development *(Vygotsky, 1978)* grounds the scaffolding strategies in this study. In blended learning contexts, digital tools frequently function as scaffolds: they externalise cognitive processes, reduce working memory demands, and enable performance that would not be possible without support. This is their value. But it is also their risk.

Wood et al. (1976) identified fading as a definitional feature of scaffolding; Koedinger and Aleven (2007) articulate the related 'assistance dilemma' — too little support impedes learning, too much prevents transfer. In this study, classroom observations raise a related design hypothesis, which we term the 'habituation effect': students who perform well within scaffolded digital environments may struggle when those supports are removed, because the scaffold has externalised a cognitive process that has not yet been internalised. We treat this as an analytically generative hypothesis, not as an established finding. The evidence is limited to a single cycle of observation in one class, and the mechanism is inferred rather than measured. Its value lies in the design question it surfaces: if formative assessment in blended environments is routinely conducted within scaffolded conditions — as it typically is — then the assessment may measure supported performance rather than autonomous competence. Planning scaffold withdrawal systematically, rather than leaving it to emerge from lesson-by-lesson contingency, is the design response this hypothesis motivates. Despite its exploratory status, this pattern raises significant questions for blended learning design more broadly — particularly regarding the relationship between supported performance and the development of independent competence.

We propose a five-step **ladder of autonomy** as a domain-specific scaffold-fading protocol for programming instruction: (1) complete externalisation (tracing table provided and completed collaboratively); (2) partial externalisation (structure provided, student completes

values); (3) prompt-only scaffold ('Where is the start / condition / step?'); (4) self-generated externalisation (student constructs their own table before coding); (5) independent production (no external scaffold). This protocol complements Margulieux et al.'s (2020) subgoal labelling framework: where subgoal labelling addresses worked example design, the ladder of autonomy addresses lesson sequence design — the temporal dimension of fading across a teaching unit.

2.4 TPACK and the Professional Learning Mechanism

Technological Pedagogical Content Knowledge (TPACK) *(Mishra and Koehler, 2006)* provides a useful integrative lens for understanding the knowledge teachers draw on when making blended learning design decisions: effective technology-mediated instruction requires simultaneous integration of technological, pedagogical, and content knowledge. In this study, TPACK functions as a descriptive frame rather than a structural component of the BLDF: it contextualises why a collaborative PLC mechanism is needed to develop principled tool-selection competence, and why individual teacher intuition is insufficient. Teachers in this study evaluated digital tools not in isolation but in relation to the specific pedagogical challenge (reducing cognitive overload from the syntax barrier) and the specific content (programming constructs in C++, C#, and Boolean logic) — the practical exercise of TPACK integration.

Lesson Study *(Lewis, 2002; Dudley, 2014)* and Action Research *(Elliott, 1991)* are used here as the professional learning mechanism through which TPACK development occurs. LS provides rapid, lesson-level design-test-revise cycles; AR provides longitudinal tracking of design decisions across a multi-year programme. Together within a mentoring-structured PLC, they enable the collaborative TPACK development that individual teacher reflection cannot generate.

3. Methodology

3.1 Research Design

This study is primarily a design-based practitioner inquiry: its aim is to identify, describe, and theorise instructional design mechanisms operative in a specific blended learning context, not to establish causal effects. Lesson Study (LS) and Action Research (AR) function as complementary iterative design mechanisms within this primary orientation — LS providing rapid, lesson-level design–test–revise cycles, and AR providing longitudinal tracking across a multi-year programme. Thematic analysis and outcome data serve as analytical tools within, not alongside, this design. Claims throughout are presented as evidence-consistent patterns supporting analytical generalisation (Yin, 2018) — the transferability of theorised mechanisms to contexts sharing the relevant design conditions — rather than statistical generalisation from a sample to a population.

3.2 Research Context

The study was conducted at Nazarbayev Intellectual School of Science and Mathematics, Nura District, Astana, Kazakhstan. NIS schools operate a curriculum aligned with IGCSE standards and a formal teacher certification system with graded levels (Teacher, Teacher-Moderator, Expert Teacher). ICT instruction is delivered in Russian — a second language (L2) for Kazakh-medium students — adding a linguistic dimension to the cognitive

load of programming instruction. The school's ICT infrastructure includes access to online simulation tools, collaborative platforms, and digital assessment environments, enabling the blended learning designs described in this study.

A significant policy context motivates the study: analysis of external summative assessment data (accessed by teacher-researchers through institutional records) consistently reveals a gap of 25–30 percentage points between students' school-based formative performance and external examination results in Informatics. This gap is consistent with the syntax barrier as theorised here: students who perform well on familiar classroom tasks struggle when encountering unfamiliar problem contexts under examination conditions. This pattern provided the empirical motivation for both the LS cycles and the AR programme.

3.3 Participants

Author	Certification level	LS/AR role	Primary focus	Data contribution
Akhmetova B.	Expert Teacher	LS researcher Cy.1–2	Compound conditions; game project (C++, Gr.7)	2 reflective reports; exit-ticket data; student artefacts
Yesmagambetova D.	Expert Teacher	LS researcher Cy.3c; AR lead (2yr)	Network topology (Gr.7); logical structures AR (Gr.11–12)	2 reflective reports; 2-year AR dataset; conference outputs
Kazhykenova B.	Teacher (developing)	LS researcher Cy.3a	for-loop scaffolding; tracing table design (C++, Gr.8)	1 reflective report; exit-ticket data (primary habituation evidence)
Yermukhambetova M.	Teacher-Moderator	LS researcher Cy.3b	Database/OOP scaffolding (C#, Gr.10); institutional assessment co-author	1 reflective report; student artefacts; peer assessment data
Saltanova G.[1] · Kultan J.[3]	PhD, Professor (Saltanova); PhD, Associate Prof. (Kultan)	Theoretical framing; methodology; academic supervision (Saltanova); methodology; formal analysis (Kultan)	TPACK; BL design; practitioner research	Theoretical framework; independent coding; manuscript review and editing (Saltanova); methodological review; formal analysis; manuscript editing (Kultan)

Table 1. PLC composition, certification levels, and data contribution.

3.4 Data Sources and Analysis

Six primary data sources were used: (1) teacher reflective reports (six total, written within two weeks of each research lesson using a structured framework); (2) structured observation notes compiled by PLC colleagues; (3) student artefacts (code, block-diagrams, tracing tables, Logic.ly simulation screenshots, mini-project slides); (4) exit-ticket assessments (individual written production tasks mapped to lesson learning objectives, scored against binary criteria by the lesson teacher and independently reviewed by a PLC colleague); (5) real-

time formative feedback data (signal cards, Nearpod analytics, online quiz item results); (6) school assessment records accessed in the authors' institutional roles, providing longitudinal performance data.

Thematic analysis (Braun and Clarke, 2006) was applied to reflective reports and observation notes. Initial coding was conducted independently by two team members (Kazhykenova B. and Saltanova G.); discrepancies were resolved through structured discussion. Table 2 illustrates the coding chain with one confirming and one disconfirming case. A full coding log is available from the corresponding author.

Representative excerpt	Initial code	Theme	RQ	Type
Learner C — previously passive — independently explained the logic of variable change using the completed tracing table (Kazhykenova, Cy.3a)	Passive→active progression following digital visual scaffold	Simulation affordance enabling cognitive externalisation	RQ1/2	Confirming
I observed a significant shift: students who held yellow tokens at lesson start held blue by the end (Yesmagambetova, Cy.3c)	Observable metacognitive shift via formative digital signal	Anonymity/signal affordance enabling real-time self-monitoring	RQ1/2	Confirming
The four-modality differentiation did not fully achieve the intended bridge to the new lesson topic — students already knew the component (Yermukhambetova, Cy.3b)	Tool function mismatch: prior knowledge exceeded scaffold design	Digital tool misfit as analytically informative BL design finding	RQ1	Disconfirming
The Learning Target activity was proposed by a colleague during planning; I found it irreplaceable for motivating students at this age (Akhmetova, Cy.2)	Cross-teacher strategy transfer via collaborative planning	PLC as TPACK development mechanism	RQ3	Confirming

Table 2. Coding chain illustration (Braun and Clarke, 2006). Row 3 shows the disconfirming case included in analysis.

Table 2a makes explicit the analytical logic through which findings are inferred from data, distinguishing descriptive findings (what was observed), interpretive claims (what the pattern may mean), and design propositions (what the evidence implies for instructional design). This separation is important for a practitioner inquiry study: without it, observations, interpretations, and recommendations risk being conflated, weakening the evidential basis of each type of claim.

Data source	Inference type	Representative claim	Claim strength	Limitation
Exit-ticket scores (Gr. 8)	Descriptive finding	83–85% of students correctly identified for-loop components without scaffold present	Evidence-consistent pattern (no control condition; N unreported)	Single class; teacher-scored; no pre-test baseline

Data source	Inference type	Representative claim	Claim strength	Limitation
Teacher reflective reports (all cycles)	Interpretive claim	Simulation affordance decouples symbolic expression from operational consequence	Theoretically grounded interpretation; consistent across cycles	Researcher-as-teacher; positional bias; no independent classroom observer
AR longitudinal data (Gr. 12, 2024–2025)	Contextual pattern only	Trend from 40.95% to 47.75% is contextually consistent with AR design intentions	No causal attribution; no control group; multiple confounds	Reported as contextual trend only; not used to support intervention efficacy claims
Misfit case (Gr. 10 four-modality differentiation)	Design proposition (disconfirming)	Prior knowledge assessment is a design requirement; affordance is relational, not intrinsic to tool	Single instance; analytically generalisable principle	Cannot rule out other explanations for misfit; prior knowledge not formally assessed
Post-scaffold performance drop (Gr. 8 habituation observation)	Design hypothesis only	Scaffolded performance may not predict autonomous competence; planned fading is required	Hypothesis only; one cycle; requires longitudinal confirmation	Presented as theoretically grounded hypothesis, not empirical finding

Table 2a. Analytical logic of inference: data sources, inference types, claim strength, and limitations. This table separates descriptive findings, interpretive claims, and design propositions to clarify the evidential status of each contribution.

4. Findings Part I: The Blended Learning Design Framework (BLDF)

Analysis of the six research lessons and their associated artefacts identifies four digital affordance types that constitute the BLDF. Table 3 presents the framework; the following subsections develop each type with evidence. An affordance type is classified within the BLDF when it satisfies three conditions: (1) it enables a cognitive or affective function that is not efficiently achievable through face-to-face alternatives at instructional scale; (2) its function can be specified independently of the particular tool implementing it (i.e., the same function can, in principle, be delivered by an analogue alternative); and (3) its presence or absence demonstrably changes the cognitive entry point of the lesson. This relational definition is operationally important: it prevents tool-feature descriptions from being misclassified as affordances and grounds classification in pedagogical function rather than platform capability. It is important to note at the outset that the four affordance types are not equally well-evidenced. Simulation and anonymity are supported by the strongest within-study evidence and were the most consistently reliable across instructional contexts. Synchronous co-construction showed clear potential but also depended heavily on group composition and prior task familiarity. Asynchronous preparation had the weakest direct evidence in this study: its benefits were reported qualitatively by the teacher and consistent with theory, but were not independently measured. This differentiation matters: the BLDF is not a flat taxonomy of four equivalent tools, but a set of design options with different empirical footings.

Affordance type	Tool(s)	Cognitive/affective function	Syntax barrier mechanism addressed	SAMR level	Evidence
Simulation	Logic.ly (Gr.12); online quiz with item feedback (Gr.7–8)	Real-time consequence visibility: student sees output of their design immediately	Decouples symbolic expression from operational consequence — makes the semantic process visible without requiring L2 verbal mediation	Redefinition	All Gr.12 pairs completed logic circuit designs; XOR error identified in simulation before teacher intervention
Anonymity	Padlet (anonymous mode, Gr.7); signal cards (Gr.7, low-tech analogue)	Reduces error-anxiety by decoupling contribution from individual identity	Removes affective component of cognitive overload — fear of error suppresses participation at the moment of first encounter with new syntax	Modification	Students with error-anxiety who were silent in verbal discussion contributed written ideas; signal card shifts (yellow→blue) observed across lessons
Synchronous co-construction	Nearpod Collaborate Board (Gr.12); Padlet shared (Gr.7)	All groups contribute simultaneously; all contributions visible to all learners in real time	Creates distributed cognition structure that reduces individual working memory demand while maintaining semantic richness of peer perspectives	Redefinition	Grade 12 Collaborate Board enabled comparison of 4 simultaneous case solutions; discussions moved directly to critical comparison rather than sequential presentation
Asynchronous preparation	Case pre-distribution (Gr.12 AR); bzfar.org reference (Gr.12)	Flipped design: students encounter problem context before lesson, arrive with initial observations formed	Shifts cognitive activation work to individual pre-lesson processing, freeing in-lesson time for higher-order collaborative analysis — directly supports case-method instruction at Bloom's analysis/synthesis level	Modification	Grade 12 in-class discussions began at analysis level rather than orientation level; teacher observed qualitative improvement in discussion depth
[Misfit case]	4-modality differentiation (Gr.10): audio/visual/kinaesthetic/digital	Intended: activate prior knowledge differentiated by processing style	Did not achieve intended bridging function — students' prior knowledge exceeded the scaffold design (already knew	Substitution only	Analytically informative negative case: demonstrates affordance is relational, not intrinsic to tool

Affordance type	Tool(s)	Cognitive/affective function	Syntax barrier mechanism addressed	SAMR level	Evidence
			BindingNavigator from Gr.9)		

Table 3. The Blended Learning Design Framework (BLDF): four digital affordance types with evidence. SAMR levels follow Puentedura (2006).

4.1 Simulation Affordance: Making the Invisible Visible

The most cognitively powerful affordance type in this study was simulation — the capacity of a digital environment to show students the real-time consequences of their logical or programmatic decisions. In Grade 12, Logic.ly enabled students to design Boolean logic circuits and observe their truth table behaviour instantly. The pedagogical value was not the tool's novelty but its epistemic function: it made visible the relationship between symbolic expression and operational consequence that is precisely what the syntax barrier prevents students from constructing.

A critical case vignette illustrates this: when the Grade 12 students encountered difficulty with the XOR (exclusive OR) operator, the simulation environment allowed them to test their hypothesis about XOR's truth conditions immediately and observe the discrepancy between their expectation and the circuit's output. The teacher reflected that this created a 'testable prediction' learning environment — students could form a hypothesis, encode it in a circuit, observe the result, and revise. This sequence is not possible at instructional scale through face-to-face means: teacher-led demonstration removes the student's agency in hypothesis formation, and paper-and-pencil construction is too slow to support iterative testing. In SAMR terms, this constitutes Redefinition rather than Modification: the activity of iterative student-led hypothesis testing about circuit logic — at the pace and scale observed — is not an enhanced version of a prior paper-based activity; it is a qualitatively new task type whose existence depends on the simulation environment.

Simulation affordance also appeared in lower-technology form in Kazhykenova's tracing table design for Grade 8 C++ loops. The tracing table is an analogue simulation: it externalises the machine's execution of a program step by step, making memory states visible that are invisible in the code text. When Learner C — previously consistently passive — completed a tracing table for a for-loop and independently identified the logical role of the increment variable, the teacher observed a qualitative shift: 'the student's relationship to the code had changed'. The simulation (analogue or digital) had provided the semantic scaffold that syntactic instruction could not.

4.2 Anonymity Affordance: Removing the Affective Barrier

The anonymity affordance addresses a dimension of the syntax barrier that cognitive overload theory alone does not capture: the affective amplification of cognitive load through error-anxiety. When students fear making visible errors in front of peers, they disengage from productive cognitive risk-taking. Akhmetova's use of Padlet's anonymous contribution mode in Grade 7, at the moment of first encounter with compound Boolean conditions, provided a

specific digital solution: students who would not speak in discussion posted ideas freely in writing, without identity exposure.

The low-technology analogue — the signal card system (blue/yellow/red tokens) used by Yesmagambetova in the network topology lesson — demonstrates that the anonymity affordance can be achieved without digital tools in appropriate designs. Students held colour tokens to signal their comprehension state; the anonymity came not from digital identity removal but from the non-verbal, non-judgmental nature of the signal. The shift from yellow to blue tokens observed across the lesson provided real-time formative data to the teacher without exposing any individual's confusion publicly. This comparison between digital (Padlet) and analogue (signal cards) instantiations of the same affordance type is methodologically significant: it demonstrates that affordances are properties of instructional designs, not of tools per se. There is, however, a complication worth reporting honestly. In the Grade 7 Padlet session, the anonymity affordance did not operate cleanly for all students: two students, recognising each other's writing style from previous group work, began privately identifying contributions despite the anonymous interface. This did not collapse the activity, but the teacher noted post-lesson that digital anonymity in small, closely-knit classes is partial rather than absolute — a limitation that signal cards in fact handle more robustly, since handwriting is not visible to peers in the same way. This tension between the two instantiations was not resolved within the study; it surfaces a boundary condition for the anonymity affordance that future designs should address explicitly.

4.3 Synchronous Co-Construction Affordance

Nearpod's Collaborate Board enabled simultaneous multi-group contribution in Grade 12's logical structures lesson: all four student pairs posted their case solutions at the same moment, making all solutions visible to all students simultaneously. The instructional consequence was a qualitative change in discussion structure — students began the class discussion by comparing solutions, not by presenting them sequentially. This shift is difficult to achieve in face-to-face settings at instructional scale without significant time investment in physical display organisation.

The synchronous co-construction affordance also supported distributed cognition (Kirsh, 2013): the visible presence of multiple simultaneous solutions reduced the cognitive burden on any individual student, who could perceive the problem's solution space rather than constructing it internally. For students encountering complex logical structures for the first time, this reduction in working memory demand is not trivial.

4.4 Asynchronous Preparation Affordance

The asynchronous preparation affordance — the capacity of digital distribution to enable meaningful pre-lesson engagement with problem contexts — was operationalised in Yesmagambetova's Grade 12 AR programme through case pre-distribution. Students received case problems digitally before the lesson; they were not expected to solve them, but to form initial observations. The effect was a qualitative shift in the lesson's cognitive entry point: where unprimed students would spend the first phase of a case lesson orienting to the problem context, pre-primed students began at analysis level.

This is the defining blended learning design move — the flipped approach — and it directly addresses the syntax barrier by separating problem familiarisation (asynchronous, low-stakes, individual) from solution construction and justification (synchronous, collaborative, high-cognitive). The cognitive load management is explicit: syntax-level details of the case (technical vocabulary, structural requirements) are encountered before the lesson; semantic reasoning about the case is the work of the lesson itself. The evidence for this affordance is, however, the most interpretive of the four types. The teacher's observation that discussion 'began at analysis level' is a qualitative judgement without a baseline comparison: there was no equivalent lesson run without pre-distribution to establish what 'orientation level' entry would actually look like with this particular group. It is possible — and the team discussed this — that the Grade 12 students' stronger performance reflected cohort maturity or the case topic's familiarity rather than the pre-distribution itself. The asynchronous preparation affordance is included in the BLDF because the theoretical logic is sound and the teacher's observations are consistent with it, but its empirical standing is weaker than simulation or anonymity, and it requires more controlled evaluation before strong claims can be made.

4.5 The Analytically Significant Misfit Case

The four-modality differentiation in Yermukhambetova's Grade 10 lesson is reported here as an analytically significant disconfirming finding, not merely as a limitation. The strategy was designed to activate prior knowledge through learners' dominant processing modalities (auditory, visual, kinaesthetic, digital). It did not achieve its intended function: students already knew the BindingNavigator component from Grade 9, and the differentiated materials served as review rather than discovery.

Three design lessons follow from this case. First, affordance is relational — the same tool design has different functions for different learners with different prior knowledge profiles. Second, prior knowledge assessment before blended learning design is a design requirement, not optional. Third, the PLC's live observation and post-lesson reflection identified this misfit in real time, enabling an immediate design revision (the teacher bridged to the new topic through whole-class comparison of sorted and unsorted data). This illustrates the value of the LS process as a quality assurance mechanism for blended learning design: collaborative observation catches misfit that individual lesson reflection often does not.

5. Findings Part II: Computational Thinking Outcomes and the Habituation Effect

5.1 Student Outcome Evidence

Evidence of student computational thinking development is reported across four data sources, triangulated across the six research lessons. Claims are framed as evidence-consistent patterns, not causal demonstrations.

Grade 8 exit-ticket data (Kazhykenova, Cy.3a): Following the tracing table and role-based group intervention for C++ for-loops, 83–85% of students correctly identified all three functional components of the for-loop header (initialisation, condition, increment) in an individual written task. This is notable because the task was administered without the tracing table scaffold — students who had used the scaffold were required to demonstrate

understanding without it. The result suggests, but does not prove, that the scaffolded instruction was associated with schema formation rather than merely supported performance.

Grade 12 mini-project data (Yesmagambetova, AR): All student pairs in the research lesson successfully completed and defended case-method mini-projects on Boolean logical structures, including constructing logic circuits in Logic.ly, simplifying Boolean expressions using algebra laws, and constructing truth tables. The teacher observed that students could articulate the relationship between the symbolic expression and the physical circuit behaviour — the precise semantic connection that the syntax barrier prevents. One specific difficulty was identified (XOR operator application in novel contexts), providing a target for subsequent instruction.

Grade 7 signal card data (Yesmagambetova, Cy.3c): Students who indicated partial understanding (yellow tokens) at lesson start indicated full understanding (blue tokens) by lesson end after the embodied role-play topology activity. This shift is formative evidence of learning progression, not a validated learning measure, but it was consistent across students and was supported by peer assessment data showing active critical engagement.

Longitudinal AR trend (Yesmagambetova, 2022–2025): Institutional assessment records show a modest improvement in Grade 12 Component 3 (programming) performance between 2024 (40.95%) and 2025 (47.75%), following two years of case-method AR instruction. No causal claim is made; the AR programme was one among many factors that changed across this period. The trend is reported as contextually consistent with the AR design's intentions.

5.2 The Habituation Effect: A Critical Finding for BL Assessment Design

The most analytically generative hypothesis to emerge from this study concerns the habituation effect. Following the tracing table intervention in Grade 8 (Cy.3a), the teacher observed that students who performed at 83–85% accuracy on individual exit tickets — administered while the lesson's collaborative and scaffolded structure was still in effect — showed substantially reduced performance when the same constructs were encountered without scaffolds in subsequent independent settings. The teacher described this as 'stress at the blank page of code'.

The mechanism is dependency formation: digital and physical scaffolds that externalise cognitive processes (tracing tables, role-based groups, puzzle-coded fragments) enable performance without necessarily producing the internalised schemas that performance requires to be autonomous. This is not a failure of scaffolding per se — the scaffolds achieved their immediate goal. It is a failure of scaffold design: an entry without a planned exit.

For blended learning assessment, this finding has a direct implication that the field has not yet systematically addressed. When formative assessment is conducted within scaffolded digital environments — as it routinely is in blended learning designs — the assessment measures supported performance rather than autonomous competence. The gap between scaffolded exit-ticket performance (83–85%) and unscaffolded examination performance (the 25–30 percentage point gap observed in institutional data) is precisely this distinction made visible.

The habituation effect is currently based on limited observational evidence from a single lesson cycle and requires systematic longitudinal investigation before strong prevalence claims can be made. We present it as a theoretically grounded design problem that BL researchers and designers should investigate, not as an established empirical result.

5.3 The Ladder of Autonomy as Design Response

The ladder of autonomy fading protocol is the study's direct design response to the habituation effect. Its five steps — complete externalisation, partial externalisation, prompt-only scaffold, self-generated externalisation, independent production — provide a temporal design specification for scaffold withdrawal in programming instruction. The protocol was not fully implemented within the reported cycles; its value in this study is as a theoretically grounded design prescription generated from the PLC's reflective analysis.

The ladder extends Margulieux et al.'s (2020) subgoal labelling framework. Subgoal labelling addresses scaffold design at the level of the worked example: it structures the content representation. The ladder addresses scaffold withdrawal at the level of the lesson sequence across time: it structures the progression from supported to autonomous performance. These are complementary design decisions that must both be made explicitly for blended programming instruction to achieve transfer.

6. Discussion

6.1 From Tool Use to Design Reasoning: The Core Contribution

This study responds to a persistent gap in blended learning research: while existing frameworks provide valuable high-level perspectives on technology integration (e.g., SAMR, TPACK), they offer limited guidance for function-level instructional decision-making in subject-specific contexts such as programming education. A central contribution of this study lies in reframing digital tool use in programming education as a problem of design reasoning rather than tool selection. The findings suggest that effective integration of digital technologies depends less on the tools themselves and more on the clarity with which their intended cognitive or affective functions are specified at the point of lesson design. The BLDF proposed here offers one way of structuring this reasoning, identifying four affordance types associated with functionally distinct instructional roles. The misfit case — in which the four-modality differentiation failed because students' prior knowledge had already extended beyond the scaffold's intended reach — underscores that affordances are relational outcomes, not tool properties. This reinforces the need for diagnostic prior knowledge assessment before blended learning design decisions are made, rather than the routine adoption of fixed design solutions. Unlike transformation-oriented frameworks such as SAMR, which evaluate the extent to which technology modifies or redefines a task, the BLDF operates at the level of instructional function: it addresses what specific cognitive or affective process a tool enables within a learning sequence, and whether that function is required at this point in instruction. Similarly, where TPACK describes the knowledge domains a teacher must integrate, the BLDF provides a more fine-grained account of how that integration is enacted in concrete design decisions about tool selection and sequencing. Interpreting the syntax barrier as an instructional design problem — rather than a learner deficit — follows directly from this orientation: it locates the

source of the difficulty not in student ability, but in the sequencing and structuring of conceptual and formal elements. Blended learning, within this framework, is positioned not as a supplementary enhancement but as a means of restructuring how complex computational concepts are made accessible to learners at different points in the learning trajectory.

This framework offers a level of practical specificity that complements more general BL frameworks such as SAMR and TPACK. Where SAMR helps a teacher evaluate the level of transformation a digital tool introduces, the BLDF specifies which cognitive or affective transformation occurs and why. Where TPACK describes the knowledge integration required for effective technology use, the BLDF operationalises one dimension of that integration — identifying which pedagogical functions genuinely require digital mediation and which do not. The frameworks are complementary rather than competing; the BLDF is proposed as a domain-specific design tool that functions within the broader orientations SAMR and TPACK provide.

The misfit case (Grade 10, four-modality differentiation) is as theoretically important as the successful cases. An affordance is only an affordance in relation to the learner's current state. A tool designed to activate prior knowledge cannot function as a bridge when prior knowledge already extends beyond the bridge's destination. The BLDF's practical implication is not 'always use these four affordance types' but 'assess which affordance function is needed, select the tool accordingly, and evaluate whether the function was achieved'.

6.2 The Habituation Effect and BL Assessment Validity

The habituation effect hypothesis points to a practical tension in blended learning design: the same scaffolds that enable productive participation may also obscure how much learning has been internalised. While the evidence in this study is exploratory and limited to a single classroom cycle, it raises a question that is not unique to this school: when formative assessment in blended environments is conducted within scaffolded digital conditions — as it routinely is, because the scaffold is the learning environment — then the assessment measures supported performance rather than autonomous competence. The gap between scaffolded exit-ticket results (83–85%) and institutional examination performance (consistently 25–30 percentage points lower) may be precisely this distinction made visible. This is not an argument against scaffolding; it is an argument for planning scaffold withdrawal as an integral component of lesson sequence design, rather than as an afterthought when dependency becomes apparent. While the evidence for this pattern remains limited to a single classroom cycle, it highlights a potentially underexamined tension in blended learning environments between the benefits of sustained scaffolding and the risks of delayed internalisation.

This is not an argument against digital scaffolding; it is an argument for planned scaffold fading as an integral component of BL design, and for assessment design that distinguishes scaffolded from unscaffolded performance. The ladder of autonomy fading protocol addresses the design side; assessment designers should develop parallel instruments that measure the same constructs at different points on the ladder, not only at the fully scaffolded end.

6.3 The L2 Dimension: Language Load as a Design Variable

A dimension of the syntax barrier that is rarely theorised in CS education research is the interaction between linguistic and cognitive load in L2 instructional contexts. In the classrooms of this study, students who receive programming instruction in Russian (L2) face simultaneous demands: understanding the programming construct, processing the formal notation, and comprehending the instructional language. The BLDF addresses this in two ways.

First, visual and simulation affordances (tracing tables, Logic.ly circuits, block-diagrams) reduce dependence on L2 verbal processing by encoding the semantic content visually. A student who does not know the L2 term for 'condition' can understand the Boolean structure of 'if temperature > 30 AND humidity > 80' from an irrigation scenario that maps to their physics or biology knowledge. The interdisciplinary task contexts employed across all cycles serve a linguistic as well as a cognitive scaffolding function. Second, the anonymity affordance specifically addresses the heightened error-anxiety of L2 learners, for whom the risk of verbal exposure is amplified by language uncertainty. These design moves do not require explicit language instruction; they require awareness that language load and cognitive load are not independent variables in multilingual classroom blended learning.

6.4 Implications for the Professional Development of BL Design Competence

The BLDF did not emerge from individual teacher reflection; it was produced through collaborative inquiry. Several of the study's most effective digital tool deployments originated with a colleague during PLC planning discussion: the Padlet anonymous brainstorm, the Learning Target digital activity, the pre-distribution of case materials. None of these appeared in individually planned lessons. This finding has a direct implication for teacher professional development: BL design competence is a collective, not individual, achievement. It should be noted, however, that the PLC process was not uniformly harmonious. During the planning of Cycle 3b (Yermukhambetova, Grade 10), there was genuine disagreement within the team about whether the four-modality differentiation addressed a real cognitive need or was primarily a structural exercise in form-filling — one team member argued before the lesson that the prior knowledge gap had already been closed in Grade 9. The decision to proceed was the lesson teacher's, and the post-lesson analysis confirmed the dissenting view. This is reported not to assign blame but because it illustrates something important: the collaborative process surfaces disagreement that might otherwise remain implicit, and the ability to act on disconfirming post-lesson analysis — rather than defend the original design — is a professional capacity that the PLC structure made possible.

The LS and AR structures provided the mechanism for this collective achievement by creating systematic cycles of design, observation, and evidence-based revision. Individual teacher TPACK development occurs through unstructured professional experience; collaborative TPACK development through LS occurs faster, is more directly tied to student learning evidence, and produces knowledge that is shared across the team rather than siloed in individual practice. The three-year trajectory from the AR programme's 40.95% baseline (2024) to 47.75% (2025) is consistent with — though cannot be attributed solely to — this sustained collaborative inquiry.

7. Conclusions and Implications

This study contributes four interconnected findings to the blended learning design and CS education literature.

1. The syntax barrier — the observed pattern of dissociation between syntactic reproduction and semantic understanding in programming education — appears to respond to affordance-driven design intervention rather than remedial instruction, though the scope of this claim is bounded by the single-school, practitioner-inquiry design of this study.
2. The BLDF — four digital affordance types (simulation, anonymity, synchronous co-construction, asynchronous preparation) — provides a theoretically grounded and practically operationalisable framework for tool selection in programming-focused blended learning environments.
3. The habituation effect — a hypothesised dependency formation through digital scaffolding — is proposed as a critical challenge for BL assessment validity warranting systematic longitudinal investigation, with assessment instruments that distinguish scaffolded from autonomous performance.
4. The ladder of autonomy — a five-step fading protocol — provides a domain-specific design response to the habituation effect that complements existing approaches (subgoal labelling) at a different level of instructional design.

7.1 Implications for BL Design Practice

For blended learning designers and ICT teachers, three practical implications follow. First, tool selection should be driven by affordance analysis: identify the cognitive or affective function the tool performs, assess whether that function is required at this point in the lesson, and evaluate whether the tool achieves its function for this specific learner population. The BLDF provides a vocabulary and a four-type taxonomy for this analysis. Second, every scaffold requires a designed exit: the ladder of autonomy protocol should be built into lesson sequence design at the point of scaffold introduction, not retrofitted when dependency becomes visible. Third, formative assessment in blended environments should explicitly distinguish scaffolded and unscaffolded measurement conditions; results from fully scaffolded environments should be interpreted as measures of supported performance rather than autonomous competence.

7.2 Implications for Teacher Education

Five principles for pre-service ICT teacher education emerge from this study's practitioner knowledge base. First: teach the 'why' before the 'how' — the syntax barrier is produced by instructional inversion, and pre-service teachers should understand this mechanism before they learn to teach code. Second: replace 'evaluate' with 'help' in peer assessment framing — this single reframing consistently improved the quality and specificity of peer interaction across three lesson cycles and five grade levels. Third: design your scaffolding exit, not just your entry — pre-service teachers should plan fading from the moment they introduce any scaffold. Fourth: your colleague's pedagogical perspective is a cognitive resource — several of this study's most effective digital tool deployments were generated

through collaborative planning. Fifth: in multilingual contexts, language load and cognitive load are not independent variables — blended learning designs must address both simultaneously.

7.3 Limitations and Future Research

The study was conducted in a single specialised school with above-average digital infrastructure and a formal certification-based mentoring structure. The BLDF is proposed as analytically generalisable — the affordance types and their cognitive functions are argued to apply where the conditions that produce the syntax barrier exist — but the specific tool implementations require adaptation to different resource contexts. Notably, the network topology role-play (rope, physical movement, structured questioning) demonstrates that simulation and co-construction affordances can be achieved without digital tools, constraining any claim that the BLDF requires specific technologies.

The habituation effect is the most important target for future research. Longitudinal studies tracking student performance across the ladder of autonomy, with systematic assessment at each rung, would provide the empirical foundation currently absent. Experimental or quasi-experimental designs comparing scaffold-fading conditions would allow causal claims that this study's design cannot make. Extension of the BLDF to non-specialised schools, different programming paradigms, and different L2 contexts would test the framework's transferability boundaries.

Declaration of Contributions (CRediT)

Author	CRediT contribution
Akhmetova B.	Conceptualisation; Data collection; Investigation; Writing – original draft (Sections 4.1–4.2, compound conditions & game project cycles); Visualisation
Yesmagambetova D.	Conceptualisation; Data collection; Investigation; Writing – original draft (Sections 4.3–4.4, 5.1 AR data); Project administration; Dissemination (ECER-2024; network journal)
Kazhykenova B.	Conceptualisation; Data collection; Investigation; Writing – original draft (Sections 4.1, 5.1–5.3, for-loop cycle; habituation effect identification)
Yermukhambetova M.	Conceptualisation; Data collection; Investigation; Writing – original draft (Section 4.5, database/OOP cycle); Resources (institutional assessment instrument co-authorship)
Saltanova G.	Conceptualisation; Formal analysis; Methodology; Supervision; Theoretical framework; Writing – review and editing; Validation
Kultan J.	Methodology; Formal analysis; Writing – review and editing; Validation

Statements and Declarations

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Data availability: Anonymised reflective reports and assessment instruments are available from the corresponding author on reasonable request.

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Figures

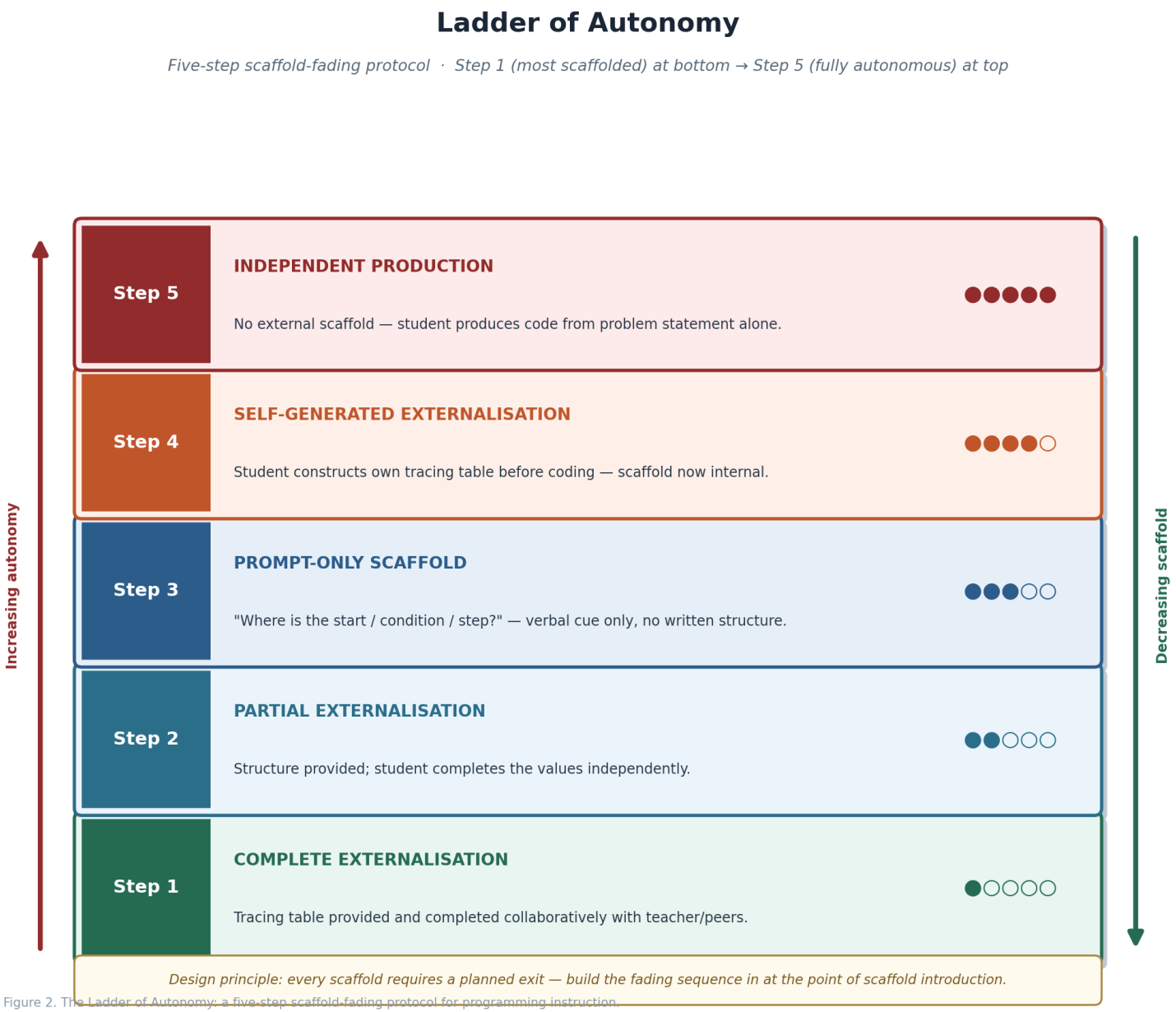


Figure 2. The Ladder of Autonomy: a five-step scaffold-fading protocol for programming instruction.

Figure 2

The Ladder of Autonomy: a five-step scaffold-fading protocol for programming instruction.