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Akbar Handoko*, Denny Philip, and HuongVu

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Research Article

Tracing Digital Learning Trajectories in Biology Education Across the Life Course: A Qualitative Study of Learners' Transitions and Meaning Making

Akbar Handoko*, Denny Philip, and HuongVu

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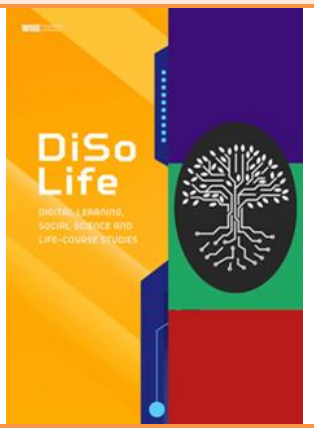
Abstract

The increasing integration of digital technologies in science education has reshaped how biology is learned across formal and informal contexts; however, existing research has predominantly focused on short-term outcomes, offering limited insight into how digital biology learning evolves across individuals' life courses. This study aims to explore digital biology learning experiences through a life-course perspective, examining learning trajectories, critical transitions, and meaning-making processes across different stages of life. Employing a qualitative narrative inquiry design, data were collected from 15 participants through in-depth semi-structured interviews, written reflections, and digital learning artifacts, and analyzed using thematic narrative analysis informed by life-course theory. The findings reveal three interconnected themes: evolving digital learning trajectories characterized by a shift from teacher-directed to self directed learning, critical transitions that reshape engagement with digital biology learning, and dynamic processes of meaning-making that increasingly connect biological knowledge to everyday life contexts such as health and environmental awareness. These results demonstrate that digital biology learning is a cumulative and adaptive process shaped by temporal, contextual, and biographical factors rather than isolated instructional events. The study contributes to the literature by integrating life-course theory with digital biology education research, highlighting the importance of designing flexible and learner-centered digital learning environments that support continuity, agency, and lifelong engagement with biological knowledge, with implications for educators, curriculum developers, and education policymakers seeking to promote sustainable lifelong science learning.

Keywords: Digital biology learning; Life course perspective; Lifelong learning; Narrative inquiry; Science education



INTRODUCTION

In the 21st century, the integration of digital technologies has transformed the landscape of science education, enabling new modes of teaching and learning that extend beyond traditional classroom boundaries [1], [2], [3]. Digital learning has increasingly been recognized as a critical component for facilitating access to scientific knowledge, enhancing learner engagement, and enabling personalized instruction across diverse learning contexts [4], [5], [6]. Within biology education specifically, the adoption of digital tools such as interactive simulations, concept mapping environments, and mobile learning platforms has shown promise for supporting complex conceptual understanding and improving learning outcomes [7], [8], [9]. Despite these advances, the majority of existing studies focus predominantly on cross-sectional measures of learning outcomes or technology efficacy, often overlooking how learners' engagements with digital learning evolve over time across their life paths.

Concurrently, the field of educational research has witnessed a growing interest in *life course perspectives* as a theoretical lens for understanding how individual learning trajectories are shaped by temporal, contextual, and socio-institutional factors [10], [11], [12]. Life course theory emphasizes the importance of sequences, transitions, and trajectories that unfold over time, offering a framework that can capture how educational experiences accrue and interact with personal and social contexts throughout a learner's lifespan [12], [13], [14]. In the context of digital literacy and learning, research suggests that significant life events and transitions, such as shifts in career, access to technologies, or participation in online learning environments, can influence how individuals accumulate and apply digital competencies over [15], [16], [17]. However, empirical investigations that integrate life course theory with digital learning experiences especially within biology education remain scarce.

In biology education research, qualitative approaches such as narrative inquiry have been leveraged to understand individual learning experiences. For instance, narrative studies of e-learning development in biology have illuminated factors that influence effective implementation of technology for promoting health literacy and instructional design [18], [19]. Similarly, research on beginning science teachers' online practices has highlighted how narratives can reveal challenges and adaptive processes associated with transitioning to digital environments [19], [20], [21]. While these studies provide valuable insights into specific aspects of digital learning, they typically contextualize experiences within limited rather than exploring *longitudinal trajectories* of digital learning across a broader life continuum.

Moreover, systematic reviews of digital learning in scientific education reveal a burgeoning literature base but also underscore a lack of deep, theory-informed investigations that connect technological engagement with developmental and contextual dynamics over time [4]. This limitation is similarly evident in biology education literature, where much research on mobile learning, digital storytelling, and interactive platforms describes immediate pedagogical effects but does not account for *how learners' experiences evolve and relate to broader educational pathways and life transitions* [7], [22], [23].

Taken together, the extant literature suggests that while digital learning in biology and science education has been extensively studied in terms of tool effectiveness and immediate learning outcomes, there is a clear gap in understanding how *individual experiences with digital learning unfold across different phases of life and educational contexts*. Specifically, there is a lack

of research that situates digital biology learning within a life course framework to capture the temporal and biographical dimensions of learning, transitions, and meaning-making processes. Therefore, this study aims to address this gap by exploring how digital biology learning experiences shape and are shaped by learners' educational trajectories over time, with a specific focus on transitions, accumulated experiences, and narrative meanings of learning across different life stages. By adopting a narrative inquiry approach grounded in life course theory, this research seeks to contribute to both theory and practice by illuminating the dynamic interplay between digital learning engagements and individuals' evolving educational journeys.

METHODS

Research Design

This study employed a qualitative research approach using narrative inquiry within a life history framework to explore individuals' digital biology learning experiences across different stages of life. Narrative inquiry was selected because it enables an in-depth examination of how learners construct, interpret, and assign meaning to their educational experiences over time, particularly in relation to critical transitions and accumulated learning trajectories [24], [25], [26]. Grounded in life-course theory, this design allowed the study to capture the temporal, contextual, and biographical dimensions of digital learning, which are often overlooked in cross-sectional or outcome-oriented research. By focusing on personal narratives, the study sought to illuminate how digital biology learning evolves as part of broader educational and life pathways.

Participant and Sample

The participants consisted of 15 individuals representing diverse stages of the life course, ranging from late adolescence to adulthood. Participants were selected using purposive sampling to ensure that they had substantive experience with digital biology learning in either formal (school or higher education) or informal (online platforms, self-directed learning) contexts. To broaden the range of experiences and capture varied learning trajectories, snowball sampling was subsequently employed, allowing initial participants to recommend others with relevant backgrounds. This sampling strategy facilitated the inclusion of participants with heterogeneous educational pathways, professional backgrounds, and levels of digital engagement, which is essential for life course analysis.

Data Collection

Data were collected through multiple qualitative sources to support depth and rigor. The primary data source was in depth, semi structured interviews, each lasting approximately 60–90 minutes. The interviews focused on participants' educational histories, experiences with digital biology learning, significant transitions (e.g., shifts between educational levels or learning modalities), and the meanings they attributed to these experiences. To complement interview data, participants were invited to provide written reflections describing memorable digital learning experiences and perceived changes in their understanding of biology over time. In addition, digital learning artifacts such as screenshots of learning platforms, notes from online courses, or records of digital learning activities were collected when available. The combination of interviews, reflections, and artifacts

enabled a richer understanding of participants' learning trajectories and supported data triangulation.

Data Analytics

Data analysis followed a thematic narrative analysis approach aligned with life-course concepts. All interview transcripts, written reflections, and digital artifacts were analyzed iteratively. The analysis began with open coding to identify meaningful segments related to digital learning experiences, transitions, and contextual influences. These initial codes were then grouped into broader categories through axial coding, guided by key life-course constructs such as trajectories, transitions, and turning points. In the final stage, selective coding was conducted to refine overarching themes that captured patterns of meaning-making across participants' narratives. Throughout the analysis, constant comparison was employed to examine similarities and differences across life stages and generational contexts, ensuring that themes reflected both individual experiences and shared patterns.

Trustworthiness and Research Rigor

To ensure the trustworthiness of the findings, several strategies were employed. Data triangulation was achieved by integrating interviews, written reflections, and digital artifacts. Member checking was conducted by sharing preliminary interpretations and thematic summaries with selected participants to confirm the accuracy and resonance of the findings. An audit trail documenting analytic decisions, coding processes, and theme development was maintained to enhance transparency. In addition, researcher reflexivity was addressed through reflective memos that acknowledged the researchers' assumptions and positionality in relation to digital learning and biology education. These strategies collectively enhanced the credibility, dependability, and confirmability of the study.

Ethical Considerations

Ethical approval for the study was obtained prior to data collection. All participants provided informed consent and were informed of their right to withdraw from the study at any time without consequence. To protect confidentiality, pseudonyms were used, and any identifying information was removed from transcripts and reports. Digital artifacts were collected and stored securely, and access was limited to the research team. The study adhered to ethical principles for qualitative research involving human participants, ensuring respect, confidentiality, and responsible data management throughout the research process.

RESULTS AND DISCUSSION

Results

The analysis of narrative interviews, written reflections, and digital learning artifacts from 15 participants revealed three interrelated overarching themes that characterize digital biology learning across the life course: (1) evolving digital learning trajectories, (2) critical transitions shaping engagement with biology learning, and (3) processes of meaning-making across life stages. These themes illuminate how digital learning experiences are not static but dynamically constructed through temporal, contextual, and biographical influences.

The first theme, *evolving digital learning trajectories*, describes how participants' engagement with digital biology learning developed progressively over time. During earlier educational stages, digital learning was primarily experienced as a supplementary tool, often limited to multimedia presentations or online assignments provided by teachers. As participants progressed into higher education or adulthood, digital learning became more self-directed and intentional, involving online courses, educational videos, simulations, and informal learning communities. This shift reflects a transition from externally structured learning toward autonomous learning trajectories, in which participants actively selected digital resources aligned with personal interests, academic needs, or professional demands.

The second theme, *critical transitions shaping engagement with biology learning*, highlights key moments that altered participants' learning pathways. Transitions such as moving from secondary school to university, entering the workforce, or returning to learning after educational interruption were identified as turning points that reshaped how participants interacted with digital biology content. These transitions often required learners to adapt to new learning environments, expectations, and technological demands. For many participants, digital platforms functioned as bridges that supported continuity of biology learning during periods of change, enabling flexible access to learning resources despite institutional or temporal constraints

The third theme, *meaning-making across life stages*, captures how participants interpreted and reinterpreted their digital biology learning experiences over time. In early stages, learning biology was frequently described as content-oriented and assessment-driven. However, in later life stages, participants increasingly framed biology learning as personally meaningful, particularly in relation to health, environmental awareness, and everyday decision-making. Digital learning environments facilitated this shift by allowing learners to connect biological concepts with real-life contexts, thereby fostering reflective and applied understanding rather than rote knowledge acquisition.

Discussion

The findings of this study extend existing research on digital learning by situating biology education within a life course perspective, demonstrating that digital learning experiences are shaped by cumulative trajectories and critical transitions rather than isolated instructional events. Consistent with prior studies emphasizing the role of digital learning in enhancing engagement and conceptual understanding in science education [4], [27], [28], the present findings further reveal how these benefits evolve longitudinally as learners navigate different educational and life stages. The identified progression from teacher-directed to self-directed digital learning aligns with research on lifelong learning and digital literacy development, which suggests that learners gradually assume greater agency as they gain experience and confidence with digital technologies [1], [13], [29]. However, unlike previous studies that primarily focus on competency outcomes, this study highlights the *narrative continuity* of learning trajectories, illustrating how earlier experiences with digital biology learning shape later learning behaviors and preferences.

The role of critical transitions observed in this study resonates with research on educational transitions and digital adaptation, which emphasizes the importance of flexibility and accessibility in sustaining learning across changing contexts [19], [30], [31]. While prior studies acknowledge transitions as challenging periods, the present findings demonstrate that digital learning can function as a stabilizing mechanism, enabling learners to maintain engagement with biology

learning during periods of disruption. This insight contributes to the literature by reframing transitions not merely as obstacles but as opportunities for reconfiguring learning trajectories through digital means. In terms of meaning-making, the findings support and extend previous qualitative research indicating that digital learning environments can facilitate reflective and contextualized understanding of scientific concepts [18], [22], [32], [33]. Importantly, this study shows that meaning-making is not confined to instructional design alone but emerges through learners' evolving life experiences, social roles, and personal priorities. This life course oriented interpretation represents a novel contribution, as existing digital biology education research rarely examines how learners' interpretations of scientific knowledge transform over extended periods.

The primary novelty of this study lies in its integration of life-course theory with narrative inquiry to examine digital biology learning longitudinally. Unlike previous research that focuses on short-term outcomes or single educational phases, this study reveals how digital learning experiences accumulate, intersect with life transitions, and shape meaning-making processes across time. By foregrounding learners' narratives, the study offers a holistic understanding of digital biology learning as a lifelong and contextually embedded process. The findings have several important implications. For biology educators, the results underscore the need to design digital learning experiences that support continuity across educational stages and encourage learner agency. For curriculum developers, incorporating flexible and modular digital resources may better accommodate diverse learning trajectories and transitions. At the policy level, the study highlights the importance of supporting digital learning infrastructures that facilitate lifelong access to biology education, particularly during periods of educational or professional transition.

Despite its contributions, this study has several limitations. First, the qualitative narrative design and limited number of participants restrict the generalizability of the findings. Second, participants' narratives relied on retrospective accounts, which may be influenced by memory bias. Third, the study focused primarily on learners' perspectives and did not include systematic observation of instructional practices or platform analytics. Future research could address these limitations by employing mixed-method or longitudinal designs that integrate narrative data with quantitative measures and learning analytics.

CONCLUSION

This study provides a nuanced understanding of digital biology learning by situating learners' experiences within a life-course perspective, revealing that engagement with digital learning is a dynamic and cumulative process shaped by evolving trajectories, critical transitions, and ongoing meaning-making across different stages of life. The findings demonstrate that digital learning in biology extends beyond short-term instructional outcomes, functioning instead as a longitudinal learning pathway that supports continuity, adaptability, and personal relevance in response to changing educational and social contexts. By integrating narrative inquiry with life-course theory, this study contributes a theoretically grounded framework for examining how digital learning experiences in biology are constructed and reconstructed over time, addressing a critical gap in existing research that has largely overlooked the temporal and biographical dimensions of learning. The study further underscores the importance of designing digital biology learning environments that promote learner agency, contextual relevance, and flexibility to accommodate diverse life transitions, thereby supporting lifelong science learning. Although the findings are

context-specific and based on qualitative narratives, they offer valuable insights for educators, curriculum designers, and policymakers seeking to enhance the sustainability and inclusivity of digital biology education across the lifespan.

AUTHOR INFORMATION

Corresponding Author

Akbar Handoko – Biology Education, Faculty of Tarbiyah and Teacher Training, Raden Intan Lampung State Islamic University (Indonesia)
orcid.org/0009-0008-7849-684X
Email: akbarhandoko@radenintan.ac.id

Authors

Akbar Handoko – Departement of Biology Education, Faculty of Tarbiyah and Teacher Training, Raden Intan Lampung State Islamic University (Indonesia)
orcid.org/0009-0008-7849-684X
Email: akbarhandoko@radenintan.ac.id
Denny Philip – Principal, St. Joseph's College Pilathara Kannur University Kerala (India)
orcid.org/0009-0003-4238-9683
Email: philipdenny1967@gmail.com
HuongVu – Senior Lecturer in English, Mahasarankham University (Thailand)
orcid.org/0000-0002-1596-2507
Email: thuyvutea@gmail.com

AUTHOR CONTRIBUTION

AH was responsible for the conceptualization, methodology, data collection and formal analysis, drafting of the original manuscript, review, and editing. DP contributed to the refinement of methodology, provided critical inputs during analysis, supervised the overall research process, and contributed to reviewing and editing the manuscript. GTI, HV, BF, and UG contributed equally to the analysis and interpretation of data, providing valuable insights into the overall research design and contributing to the final manuscript revisions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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