Smart Learning Environments

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What is the Science of Learning? a comprehensive review and analysis of the existing definitions

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Abstract

With the increased interest in Science of Learning (SoL) to enhance learning experiences and outcomes, several SoL definitions have been proposed from different fields and research backgrounds. This has created some ambiguity about what SoL is and how it can contribute to the educational field. To address this research issue, this study conducts a literature review of the different SoL definitions presented in the literature between 2000 and 2024. It then analyzes how these definitions evolved over time in terms of the mentioned fields, involved stakeholders, and cognitive practices. The obtained results revealed that most of the SoL definitions are rooted in the neuroscience field with an increased interest in the use of technology and Artificial Intelligence (AI) in the last few years. Particularly, it is found that some areas, such as the role of genes in learning, need more attention and were surprisingly not found in the definitions. Additionally, it is found that most of the stakeholders mentioned are generic (e.g., human, adult, etc.), depicting that learning can happen outside of schools and at any age. The findings of this study call for more cross-disciplinary collaboration on SoL implementation and impact, particularly in classroom and digital learning settings.

Keywords: Science of Learning, Education, Definitions, Review, Concepts

Introduction

Science of Learning

The Science of Learning (SoL) is gaining increasing attention from researchers and practitioners across various domains, reflecting the importance of understanding how people learn (Bransford et al., 2000; Darling-Hammond et al., 2024; Zosh et al., 2024). However, despite the growing research and practice interest, there is no widely accepted definition of SoL in the literature. Several definitions from different fields (e.g., neuroscience, education, psychology, etc.) exist (Pasquinelli, 2011). For instance, Meltzoff et al. (2009) defined SoL as "the convergence of discoveries in psychology, neuroscience, and machine learning that results in principles of human learning that are leading to changes in educational theory and the design of learning environments" (p. 288). This is different

from the definition by Swain (2025), who describes SoL as "a multidisciplinary body of knowledge about learning encompassing insights from neuroscience, psychology, sociology, and cognitive science". Although the term "science of learning" is commonly used, some researchers also use the term "learning science" (Sawyer, 2005; Suherman, 2023), or "learning sciences" (Nathan et al., 2010), and the three terms are often used interchangeably (e.g., Van Hoof et al., 2022), depending on the researchers' academic background (Sawyer, 2005). As a result, researchers often encounter confusion regarding the scope and boundaries of this field (Privitera et al., 2023), and there is also confusion among practitioners and policy-makers about what SoL actually means, with several myths surrounding it (Kucirkova & Guerriero, 2025). This lack of clarity calls for a systematic investigation into how SoL has been conceptualized and understood. This paper aims to review the literature and key aspects of SoL—including its main stakeholders, practical and policy foci, cognitive mechanisms in research, their integration with practice, and educational factors—for a comprehensive understanding of the field. It also examines which disciplinary fields SoL connects to, and how learning and education are defined within its evolving scope.

Over the past century, educational psychologists and researchers have proposed numerous theories to explain how individuals learn—that is, how they acquire, organize, and apply knowledge and skills (Seel, 2012). In the late twentieth century, the Science of Learning (SoL) emerged as an interdisciplinary field that integrates insights from cognitive psychology, neuroscience, and educational research. Initially, SoL was deeply rooted in behaviorist theories, which emphasized observable outcomes and reinforcement (Privitera et al., 2023). With the advent of the cognitive revolution, its focus shifted toward internal mental processes such as memory and problem-solving (ibid). Advances in neuroscience further expanded the scope of SoL by enabling deeper understanding of brain plasticity and helping to dispel widespread neuromyths (Jha, 2024). In recent years, rapid technological developments have begun to influence SoL, bringing the role of technology into its broader framework (Horvath & Lodge, 2016; Schmied & Jamaludin, 2023). For instance, SoL increasingly emphasizes design-based research and interdisciplinary collaboration, aiming to optimize learning environments through evidence-based strategies such as explicit instruction and cognitive load management (Jha, 2024).

Research gap and study objectives

Over the past few years, as technological advancements have rapidly reshaped education, the concept of technology has started to be incorporated into the broader umbrella of SoL (Horvath & Lodge, 2016; Schmied & Jamaludin, 2023). Technology plays a vital role in students' lives, and as it continues to evolve, education settings are increasingly integrating it into learning (Carstens et al., 2021). Despite the increasing number of studies exploring various facets of SoL, a comprehensive review of the field's multiple definitions remains scarce. Much of the existing literature focuses on isolated aspects of SoL, such as cognitive and neural mechanisms (Privitera et al., 2024) or applications of SoL (e.g. Nugent et al., 2023 to higher education; Kucirkova et al., 2023 to Educational Technology), rarely offering a holistic view of the ways SoL is conceptualized, its focus, and the involved stakeholders. A scoping review about SoL definitions offered the first

integrative perspective on SoL (Privitera et al., 2023), but this review relied on searches from Web of Science and ProQuest databases, which resulted in including and analyzing only 43 articles and definitions of SoL published between 2002 and 2022. In addition, Privitera et al's (2023) review mainly focused on the fields and institutions that contributed to the definition of SoL, the research objectives of SoL, and how the definition of SoL has changed over time, without delving into other crucial aspects such as the main stakeholders involved in shaping SoL, the key foci of SoL in practice and policy, cognitive mechanisms involved in SoL research and their combination with and educational factors.

To address this research gap, the present study expands the search for SoL definitions to cover more databases, including Web of Science, ProQuest, and Scopus databases, between the years 2000 and 2024, allowing for a more comprehensive analysis and understanding of the SoL field. Additionally, the analysis goes beyond the fields that contributed to the definition of SoL to also investigate and identify the stakeholders included in SoL definitions. The focus on key stakeholders builds on Sulthani and Thoifah's (2022) recommendation that the execution of learning requires the participation of various stakeholders, whose involvement is intended to gather relevant references and identify the right information to enhance the quality of education. Apart from students (Murphy & Knight, 2016), the definitions of SoL therefore also include other stakeholders, such as children (Hammond, 2020), teachers (Hindman et al., 2020), and parents, who play crucial roles in how SoL is approached and applied.

Furthermore, the definitions of SoL also include various applied foci that are worth further analysis to inform the practice and implementation of SoL. For instance, some researchers and policy makers focused on the translation of SoL research into practice (Conyers, 2017; Njeri, 2002), informing teaching skills (James & Bryant 2007), and improving learning experience (Horvath & Lodge, 2016). Therefore, identifying these practical foci would provide better understanding of the SoL's value to the field. Moreover, there are think tanks and educational organizations, such as for example *Deans for Impact*, an organization representing educational leaders, which propose focusing on cognitive science when discussing SoL to enhance learning and advance the professional development of teaching (Riley, 2016). The scoping review from Privitera et al. (2023) also showed that cognitive-related fields have made significant contributions to the definitions of SoL. Therefore, the present study also explores the unique role of cognitive science and practice when discussing SoL. Besides, the definitions of SoL encompass various educational factors that shape learning contexts and are essential for its practical implementation. For instance, researchers and definitions explicitly reference fact such as learning environments (Pasquinelli, 2011), real-world educational settings like schools and informal learning spaces (Conyers, 2017), curriculum frameworks (Zosh et al., 2024), and assessment practices (Privitera et al., 2023). Therefore, identifying and analyzing these educational factors is crucial for understanding how SoL principles are operationalized within tangible educational structures and systems. To sum up, while the scoping review by Privitera et al. (2023) provided an important initial synthesis of how SoL has been defined across academic literature, the present study extends this work in several key ways. First, it draws from a broader dataset, including 91 definitions sourced not only from peer-reviewed academic journals but also from reports and

policy documents by educational organizations, offering a more comprehensive and practice-informed perspective. Second, whereas Privitera et al. (2023) focused mainly on the disciplinary origins and historical shifts in SoL, this study introduces novel dimensions such as stakeholder analysis, cognitive practices, and educational factors, offering a richer, multi-layered understanding of how SoL is conceptualized and applied. Additionally, the current analysis highlights underexplored but increasingly relevant themes, SoL and technology-empowered education, which were not addressed in previous reviews. Specifically, this study aims to address the following research questions (RQs):

RQ1. What are the research foci of SoL?

RQ2. Which fields are mentioned across the SoL definitions and how have they evolved over years?

RQ3. Who are the key stakeholders involved in adopting and applying the SoL?

RQ4. Which cognitive practices are covered in SoL?

RQ5. Which educational factors are mentioned when defining SoL?

Methodology

This study followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for conducting systematic literature reviews and a mixed-method data analysis. PRISMA provides a standard peer-accepted methodology that uses a guideline checklist (Tlili et al., 2024).

Data selection

To compile a comprehensive set of definitions for the SoL, a systematic search process was employed. This process collected a diverse range of definitions from both academic and other relevant sources (e.g. reports from educational organizations) to ensure a comprehensive understanding of the term. Covering definitions from international organizations is crucial as these organizations provide global perspective and understanding of a given domain. Therefore, analyzing their SoL definitions will enrich the results beyond what was found and reported from researchers and research studies. In the beginning, the search was conducted across several academic databases, including Web of Science, ProQuest, and Scopus. These databases were chosen due to their extensive coverage of journal articles, conference proceedings, and book chapters.

To maintain a manageable number of studies and to include only relevant studies (recall) within the present review, thereby achieving a high precision rate, we used only the exact same search keyword, i.e., "science of learning". In the Web of Science database, by limiting the search to the topic, title, and abstract, a total of 481 relevant articles were identified. In ProQuest, by using the search string "noft("science of learning")" and only choosing "full-text" and "peer-reviewed" articles, 456 articles were found. In Scopus, by using the search string "TITLE-ABS-KEY ("science of learning")", 465 articles were retrieved. As a result, 1401 articles were obtained, where 233 duplicates were deleted.

The remaining studies (n = 1168) were filtered through the inclusion/exclusion criteria. A study was excluded if: (1) it was not in English; (2) it did not discuss SoL; (3) it did not provide any definition of SoL; and (4) the full-text was not available or accessible online. As a result, sixty-one studies were included containing definitions of SoL.

In addition to scientific studies (journal and conference papers, book chapters, etc.), definitions were also gathered from organizations that contribute to the field of learning and education (e.g., National Science Foundations). A total of thirty definitions were sourced from such organizations, and these definitions were sourced through general Google searches. Appendix A presents the list of organizations where the SoL definitions were collected. These definitions were particularly valuable in capturing how SoL is understood and applied outside of traditional academic settings, providing insight into how the term is used in policy and practice. Consequently, a corpus of ninety-one non-redundant SoL definitions (from research papers and organizations) were captured and analyzed in the present study. Figure 1 presents the data selection process.

Data analysis

Textual analysis

After collecting the 91 definitions of SoL, the texts of these definitions were compiled and organized into a Word document for analysis. Before conducting the analysis, the

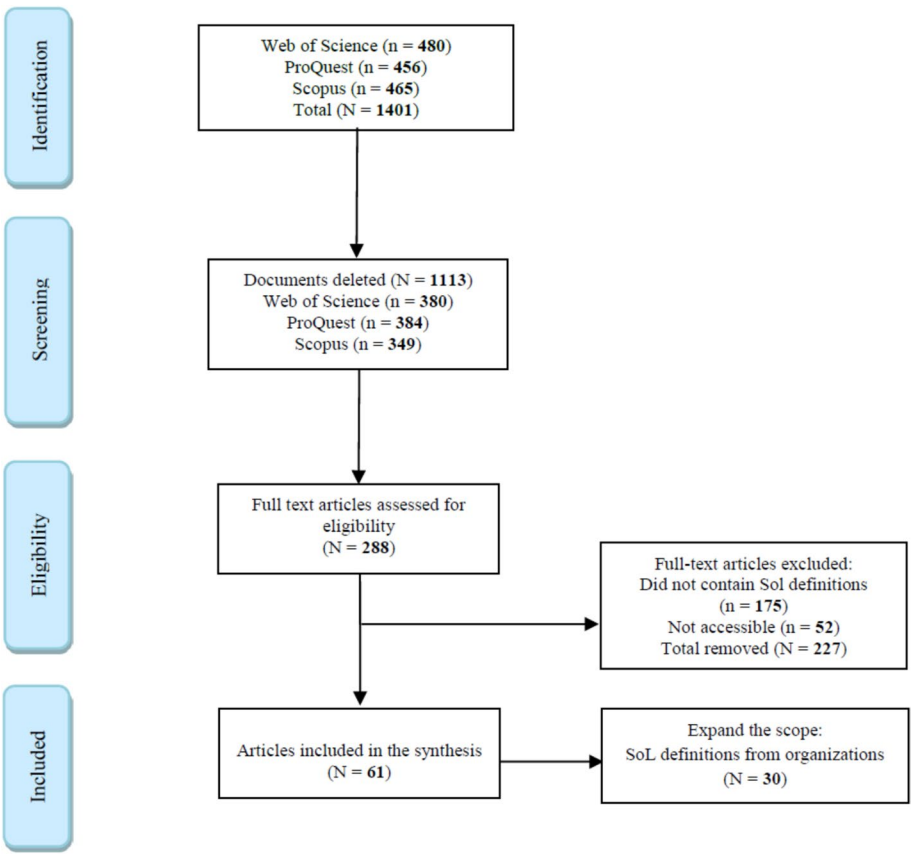

Fig. 1 SoL related definitions searching and collecting process

text corpus was pre-processed to enhance the validity of results. This process involved the removal of stop words and generic terms (e.g., "hav", "new", "such", "term") that do not convey substantive meaning, as well as the elimination of duplicates and the standardization of spelling and terminology. The document was then uploaded to the *WeiCiYun* software, a specialized tool for text analysis and visualization. WeiCiYun is designed to assist researchers in processing and analyzing large volumes of textual data efficiently, offering features such as word frequency analysis, keyword extraction, and advanced visualization capabilities (Guo et al., 2023).

To identify the research foci of SoL (RQ1), textual analysis was conducted. It helped in identifying the most common words used across these definitions, thereby identifying key themes and ideas. It also created a word cloud, showing which terms were the most frequent terms, making it easy to know what words were most important. The co-occurrence network was conducted to reveal how different keywords in the definitions are connected to each other. This helped in understanding how the concepts in the definitions relate to one another.

Qualitative analysis

In addition to the textual analysis, a content analysis was conducted to dive deeper into the meanings and characteristics of the definitions. Analyses of the definitions included various aspects, i.e. the fields, stakeholders, SoL focus, cognitive practices, and educational factors.

The coding process was conducted by two coders. During the coding period, each definition was read carefully, and relevant parts of the text were marked with specific codes, where each code corresponds to one of the aforementioned research questions. For example, when a definition mentioned different disciplines or fields, such as "education" or "psychology", the related text was coded under the "fields" category (RQ2). A table was then created, and the total number of times each field got mentioned across all definitions was calculated. Similarly, when a definition mentioned different stakeholders, such as teachers or students, the related text was coded under the "stakeholders" category (RQ3). A counting table was then created to show how many times each stakeholder was mentioned. If the definition referred to different thinking or learning practices, such as "how the brain learns" or "attention and memory" it was coded under "cognitive practices" (RQ4). Finally, if any of the definitions mention some educational factors or elements that could influence SoL (RQ5), these factors/elements are captured and organized in a table to count their frequency of occurring within the SoL definitions.

After coding the text and creating the counting tables, a general pattern emerged for how often certain ideas appeared in the definitions and how they might have changed over time based on when the definitions were published. By synthesizing all information, the analysis yielded comprehensive insights into SoL's meanings.

Results

The results are structured and presented according to each of the aforementioned research questions.

What are the research foci of SoL?

Figure 2 presents the word cloud of related terms after text analysis. Larger word size indicates a higher frequency of occurrence. It shows that the most frequent terms in the analyzed definitions are science (n = 149), learning (n = 115), cognitive (n = 54), neuroscience (n = 50), psychology (n = 49), research (n = 42), and education (n = 37).

Figure 3 presents the co-occurrence network. It is generated by calculating the co-occurrence values between keywords through measuring the degree of association between them. It indicates the frequency and closeness of their appearance in the text. Each keyword is represented by a node, and the connection lines between them indicate the frequency of their co-occurrence. The higher the keyword frequency, the larger the node; the higher the co-occurrence value between keywords, the thicker the connection line.

As shown in Fig. 3, the connection lines between "learning" and "neuroscience", "education" and "neuroscience", as well as "learning" and "science" are relatively thick, suggesting that these words often co-occur and have a strong correlation. A thick line was also seen between "research" and "learning".

Figure 4 shows the varying SoL focus based on the analysis of definitions. Among these, "practical applications" (13%), "informing teaching/instruction/pedagogy" (11%), and "improving learning/learning experience" (9%) are the most prominent focuses. On the other hand, "improving educational/learning outcomes" (3%) and "becoming active learners" (2%) were the least mentioned. It should be noted that 61% of the SoL definitions did not mention any particular focus. This broad or unspecified focus could be because the SoL field aims to be interdisciplinary, generalizable, and inclusive of many types of learners, contents, and goals. That breadth makes the

Fig. 2 Word cloud of SoL definitions

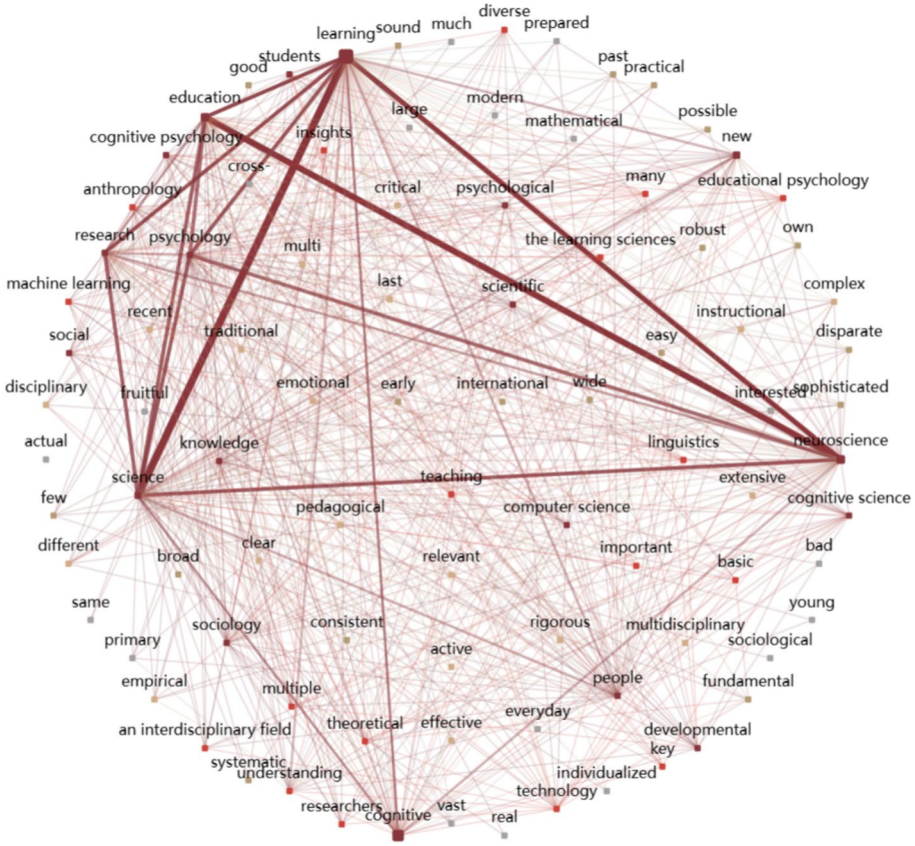

Fig. 3 Co-occurrence network

Educational Practices/Year	2000 N=1	2002 N=2	2005 N=2	2006 N=1	2007 N=1	2008 N=1	2009 N=1	2011 N=2	2013 N=1	2015 N=3	2016 N=3	2017 N=3	2018 N=5	2019 N=5	2020 N=9	2021 N=7	2022 N=5	2023 N=9	2024 N=9	n.d. N=21	Total N=91	Total
Become active learners	1																	1			2	2%
Rethink educational theory								1													1	1%
Improve educational/learning outcomes															1					2	3	3%
Improve learning/learning experience			1								1	1			1		1	1		3	9	9%
Practical applications			1	2	1	1				1	1		1	2	1	4				2	5	22	23%
Not mentioned				1			1	1	1		2	2	1	3	4	3	7	4	7	7	14	58	61%
																						95	

Fig. 4 The distribution of SoL focuses over years

definition useful and applicable across various fields (e.g., psychology, neuroscience, education, etc.).

"Practical applications", which constitutes 23% of the total entries, was first mentioned in 2002 and has appeared intermittently through 2024. This category highlights the importance of evidence-based research and applying theoretical insights to real-world educational contexts, emphasizing the practical benefits of learning science. The ways in which "practical applications" have been mentioned include "link the findings of research to actual practice", "lay the groundwork for the schools of the future", "practical implications", "educational practices", "leverage findings into effective teaching techniques", "implications for the teaching", and "helping teachers … on decision-making".

Another critical area is "Improving learning/learning experience", representing 9% of the definitions. Although it was first mentioned in 2002, it did not reappear until

2016, when it began to be mentioned more frequently. This focus area emphasizes enhancing the quality and effectiveness of learning processes. "Improving learning/learning experience" was referenced in various ways, including "improve the learning experience", "how learning experiences can be most effective", "improve learning", "design and implement experiences", "improve reading and mathematical skills", and "learn more effectively". Additionally, "Improve educational/learning outcomes," "Become active learners", and "Change educational theory" were mentioned less frequently, accounting for 3%, 2%, and 1% of the definitions, respectively.

Which fields are mentioned across the SoL definitions and how they have evolved over years?

Figure 5 presents an analysis of the fields mentioned in definitions related to the SoL across different years. Each year's analyzed definitions are denoted by N, and the total number of definitions analyzed is 91. Each number in the cells represents the number of times the field was mentioned in that year. The darker the cell color, the higher the number of references. According to Fig. 5, the SoL definitions cover 28 fields, where 27 definitions did mention any specific field. It is seen that in the early years, the fields mentioned were limited, primarily including psychology, cognitive science, and education. However, there is a growing diversity of the mentioned fields in recent years. Starting from 2017, definitions began to incorporate a broader range of disciplines, with many fields such as anthropology, behavior development/economics, linguistics, and machine learning seeing more appearances.

It is evident that neuroscience, cognitive neuroscience, and cognitive psychology stand out as four prominent fields with the highest frequency of occurrence. They first appeared in 2002 and later consistently mentioned, totaling 57 times (26.64%), making it the most frequently cited field in the dataset. Education and educational psychology were the second most mentioned field (15.89%). It started being mentioned in 2002 and over the last year most of the SoL definitions focused on mentioned education and educational psychology as important fields to consider. Sociology first appeared in 2005, and although not continuously, its frequency of occurrence has significantly increased since 2016, with a total of 11 mentions (4.44%).

Fields/Year	2000 N=1	2002 N=2	2005 N=2	2006 N=1	2007 N=1	2008 N=1	2009 N=1	2011 N=2	2013 N=1	2015 N=3	2016 N=3	2017 N=3	2018 N=5	2019 N=5	2020 N=9	2021 N=7	2022 N=5	2023 N=9	2024 N=9	n.d. N=21	Total N=91	Total
Technology/AI/Machine Learning							1	1					2			1		2	2	3	12	5.61%
Athropology				1									1		1		1				5	2.34%
Behavior Development / Behavior Economics															2		1			2	5	2.34%
Neuroscience/ Cognitive Neuroscience / Cognitive Psychology		1	1		2		1	2		2	3	2	6	3	8	4	4	3	5	10	57	26.64%
Computer Science				1							1	1		1	1					2	7	3.27%
Critical Theory																				1	1	0.47%
Data Science															1					1	2	0.93%
Design																		1		1	2	0.93%
Developmental Psychology / Development Science			1							1				2		2			1	2	9	4.21%
Education / Educational Psychology		1		1			1						3	2	3	2	3	3	4	11	34	15.89%
Human Computer Interaction															1						1	0.47%
Linguistics													1	1		1			2		5	2.34%
Natural Science															1						1	0.47%
Pedagogy														1							1	0.47%
Philosophy													1	1							2	0.93%
Psychology				1	1		1	1		1		2	2	2	2	1	1	3	4	5	27	12.62%
Sociology / Social Psychology			1								1	1		3	4	2	1		1	2	16	7.48%
Not Mentioned	1	1	1			1			1		1	1			2	3	2	6	2	5	27	12.62%
																					214	

Fig. 5 Fields mentioned in the SoL definitions across years

Who are the key stakeholders involved in the SoL?

Figure 6 presents the distributions of stakeholders in the SoL definitions over the years. Among the 91 definitions, a total of 43 definitions do not mention stakeholders, accounting for the largest proportion (43%). This shows that the SoL field aims to be inclusive without narrowing the involved stakeholders, thereby risk excluding specific groups and create practical and theoretical complications.

"Adult/People/Human/Author", as a broad and inclusive stakeholder category, represents the most frequently mentioned group, accounting for 21%. This category is consistently represented across multiple years, since the year 2000, particularly in recent periods such as 2020, 2022, 2023 and 2024. Its broadness reflects its applicability to diverse contexts. Their associated differences cover phrases like "how people/human learn" and in contexts such as "helping people take control of their own learning", "how to improve active learning wherein people seek to understand complex content…" "people naturally reason and learn" and "advance human potential". These highlight the central role of individuals in the SoL. These definitions further show that learning can happen outside of schools and at any age.

"Learners/Students", with 16% of the total, emerge as a critical stakeholder group. Since it was first mentioned in 2015, it has continued to appear consistently in the following years, reflecting a growing recognition of the central role of learners in the Science of Learning. Compared to "People/Human", the ways in which "Learners/Students" are mentioned are more diverse, including "how students/learners learn/develop", "the nature and processes of student learning", "students can use to improve the learning experience", and "students are 'pulled out' from their everyday classroom context to participate in a study". Other references "advocate for more student-centered pedagogy", explore the "potentials of the students/learners", highlight approaches that "cater to the diverse needs of learner", and emphasize the importance of promoting 'students' well-being, healthy development, and transferable learning".

Other stakeholder groups, such as "Researcher" (7%), and "Teacher/Instructors" (5%), are less prominently featured but still hold significance. The term "Researcher" first appeared in 2006 and has consistently appeared since 2022, highlights the academic and investigative foundations of the field, underscoring the importance of evidence-based approaches. The term "researcher" is referenced in various ways, including "how researchers are using that science to lay the groundwork for the schools of the future", "researchers in growing numbers are conducting cognitive research on learning". "Collaboration among researchers in education and neuroscience" is highlighted, as well as "the interdisciplinary approaches employed by researchers from diverse fields". "Teacher/Instructors" often appear alongside stakeholders such as students, researchers, and

Stakeholders/Year	2000 N=1	2002 N=2	2005 N=2	2006 N=1	2007 N=1	2008 N=1	2009 N=1	2011 N=2	2013 N=1	2015 N=3	2016 N=3	2017 N=3	2018 N=5	2019 N=5	2020 N=9	2021 N=7	2 N=5	2023 N=9	2024 N=9	n.d. N=21	Total N=91	Total
Children															2			1			3	3%
Learner/Student										1	2		1	1	1	1		1	2	6	16	16%
Parent																		1			1	1%
Adult/People/Human/Author	1		1		1	1		1	1	1					2	1	3	2	2	4	21	21%
Teacher/Instructors/Expert/ Practitioner		1									1				2			1	2	1	8	8%
Researcher/Theorist		1		1									1				1	1	2	1	8	8%
Not Mentioned		1	1				1	1		1	1	3	3	4	3	5	2	5	2	10	43	43%
																					100	

Fig. 6 Distribution of stakeholders

parents. However, despite their direct involvement in learning environments, the limited representation may suggest that definitions focus more on learners than educators.

"Children" account for only 3% of mentions, despite their intrinsic connection to learning contexts. Similarly, categories like "Expert", "Parent", and "Adult" appear sporadically, with minimal representation, indicating that these groups are less frequently positioned as central to the definitions.

Which cognitive practices are covered in SoL?

Figure 7 presents the cognitive practices covered in the SoL definitions. It is seen that 56% of the definitions did not cover any cognitive practice, showing that these definitions considered learning as a broad concept without being limited to a particular practice. However, the remaining categories highlight significant emphasis on specific aspects related to learning processes, including "Processes of learning/knowing/thinking/cognition" (11%), "How the brain learn" (10%), "Acquire, retain, and apply knowledge" (9%), and "Principles/theories/mechanisms of learning" (9%), among others. These categories reflect the evolving research priorities and the interdisciplinary SoL nature.

The largest proportion, outside "Not Mentioned", is attributed to "Processes of Learning/Knowing/Thinking/Cognition", which accounts for 11% of the mentions. Although the references are spread across different years, they cover a wide time span, appearing as early as 2000 and as recently as 2024. Examples of its usage in the text include contexts such as "nature and processes of learning", "the way people naturally reason and learn", "processes of knowing", "thinking processes", and "cognitive processes".

"How the brain learns" contributes 10% to the overall mentions. It was first mentioned in 2002, but it began to appear more frequently from 2018 onwards. In the text, the context in which "brain" is mentioned includes phrases such as "how the brain learns", "brain development", "brain processes", "how the brain processes, stores, and retrieves information", and "how learning occurs in the brain".

Another key part is "Acquire, retain, and apply knowledge", which constitutes 9% of the mentions. This category first appeared in 2017 and has been intermittently mentioned in the following years, with phrases such as "acquire knowledge, skills, and competencies", "acquire and retain knowledge", "acquire, retain, and apply knowledge" appearing in the text.

"Principles/theories/mechanisms of learning", also at 9%, emphasizes the theoretical underpinnings of Science of Learning. It first appeared in 2011 and was mentioned continuously from 2019 to 2022. This category includes phrases like "principles of human learning", "cognitive development theories", "sociocognitive principles", and "nature,

Cognitive practices/Year	2000 N=1	2002 N=2	2005 N=2	2006 N=1	2007 N=1	2008 N=1	2009 N=1	2011 N=2	2013 N=1	2015 N=3	2016 N=3	2017 N=3	2018 N=5	2019 N=5	2020 N=9	2021 N=7	2022 N=5	2023 N=9	2024 N=9	n.d. N=2 1	Total N=9 1	Total	
Acquire, retain, and apply knowledge												1			1		1	3	1	2	9	9%
Attention and memory																				2	2	2	2%
How the brain learns		2											1	1		2			1	3	10	10%	
Principles/theories/mechanisms of learning								1						2	2	1	1			2	9	9%	
Processes of learning/knowing/thinking/cognition	1								1	1	1				2				1	4	11	11%	
Take control of learning	1																				1	1%	
Transfer knowledge to new problems and settings	1																	1			2	2%	
Not mentioned			2	1	1	1	1	1		2	2	2	4	3	5	4	4	5	6	13	57	56%	
																					101		

Fig. 7 Distribution of cognitive practices covered in SoL

mechanisms, and potentials of the human learner", underscoring efforts to build a systematic and theoretical foundation for understanding learning.

In addition, "Attention and memory", "Transfer knowledge to new problems and settings", and "Take control of learning" account for smaller proportions, at 2%, 2%, and 1% respectively.

Which educational factors should be considered when adopting SoL?

Figure 8 shows that 15% of the definitions related to the SoL mention educational factors, while 85% do not. However, since 2017, definitions referring to learning environments have increased compared to earlier years. Notably, in 2024, "Technology related learning environments" (4%) emerged as a distinct category, highlighting a growing focus on the integration of technology into learning contexts. As shown in Fig. 8, educational factors have been mentioned in various ways, including "contextual/environmental factors" (5%), and "design of learning environments" (2%).

Discussion

This paper aimed to clarify how the SoL is defined and conceptualized across disciplines. By identifying key research foci, the fields connected to SoL, the primary stakeholders involved, as well as the cognitive and educational factors emphasized in its definitions, the study aims to provide a more comprehensive and structured understanding of this increasingly prominent—yet often ambiguously defined—field.

SoL foci

The study results revealed that in addition to "science" and "learning", which were expectedly prominent given their foundational role in the definition of SoL, the most frequently mentioned terms in the analyzed definitions included "cognitive", "neuroscience", and "psychology". This indicates that despite the multidisciplinary nature of SoL, its deep roots in cognitive science are part of most of its definitions (Fischer et al., 2007). These frequent terms also suggest that understanding learning processes draws heavily

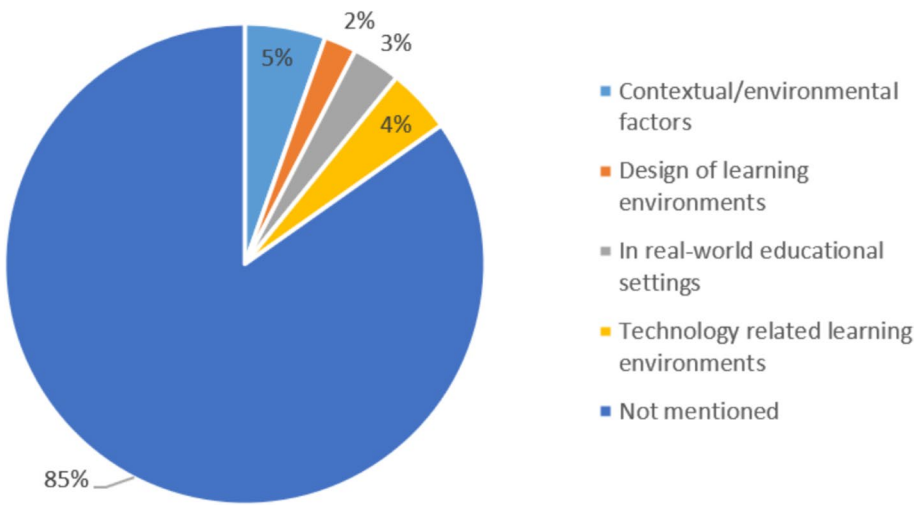

Fig. 8 Distribution of educational factors in SoL

from both psychological theories and neuroscience evidence (Dubinsky & Hamid, 2024). Moreover, "research" and "education" also appeared with high frequency across the analyzed definitions. This indicates that SoL is not only concerned with insights from science but also from pedagogy, educational practice and multi-disciplinary research that provides the contextual understanding necessary for SoL to support educational practice (Kucirkova & Guerriero, 2025).

It was interesting to note that all the frequently mentioned words had the strongest correlation with "neuroscience". This suggests that neuroscience is a critical nexus linking diverse perspectives in SoL and might be considered the key discipline associated with SoL. Furthermore, the term most highly correlated with "neuroscience" was "model", highlighting the field's emphasis on constructing explanatory frameworks for learning mechanisms (Howard-Jones et al., 2020). This indicates that compared to Learning Sciences, which typically emphasizes the design of learning environments and often integrates insights from education, computer science, and design-based research (Sawyer, 2005), SoL appears to focus more on uncovering the underlying mechanisms of learning (UNESCO, 2024b). While both fields are interdisciplinary, SoL leans more toward empirical and biological foundations, whereas Learning Sciences tends to prioritize contextual, technological, and pedagogical applications (Kucrikova and Guerriero, 2025).

Perhaps surprisingly, the commonly emphasized words in contemporary multi-disciplinary studies of learning, such as "technology", "machine", etc., appeared relatively infrequently in the analyzed definitions. This finding suggests that despite the rapid technological advancements and increasing integration of artificial intelligence and machine learning into education, the conceptual foundations of SoL have not yet fully incorporated these emerging trends. Consequently, future directions for SoL should place greater emphasis on examining how new technologies impact learning processes, environments and outcomes (Luckin & Cukurova, 2019), and as such, shape researchers' understandings. The findings also suggest that SoL is still very much science based and not much yet happening in the translation bit which would mean a more focus on context, outcomes, processes.

Although often described as a new field, SoL has developed a growing body of evidence and shared understandings that point to its increasing maturity and consolidation. Over the years, the SoL has maintained a strong emphasis on practical impact, highlighting the aim of SoL is to bridge the gap between what we know about how humans learn and the solutions to real-world educational needs (Anudin et al., 2024). The growing attention to "improving learning/learning experience" after 2016 indicates rising concerns about how to design learning processes that better support individual student needs. Although less frequently mentioned, themes like "improving educational outcomes" and "becoming active learners" suggest that SoL researchers are increasingly aware of the broader educational changes required to empower learners. Overall, the results show that SoL continues to build on evidence-based research while moving toward practical, learner-centered innovations to better connect theory with educational practice.

SoL related fields

The results of this research revealed that the early definitions of SoL were mostly grounded in neuroscience, cognitive neuroscience and cognitive psychology fields. This

shows that SoL was first framed around individual mental processes, including memory, attention and information processing. This may be attributed to what has been termed the "neuro-turn" in educational research which refers to a movement aimed at identifying the neural underpinnings of learning and linking brain-based measurements with observable behavioral outcomes (Ansari et al., 2012). After 2016, the variety of disciplines invoked in SoL definitions grew markedly. Fields such as anthropology, linguistics, data science, and sociology began to appear alongside the established pillars of psychology and neuroscience. This reflects that scholars have integrated sociocultural and contextual factors that shape learning, thereby addressing longstanding critiques that SoL research is overly decontextualized (Privitera et al., 2023). The evolution of SoL's affiliated disciplines further reflects the complexity of education which requires analyzing several intertwined variables (e.g., personality, brain, culture, motivation, pedagogical approaches, contextual factors etc.) from different perspectives to better understand how learning occurs (Saqr et al., 2024).

In addition, AI/machine learning, and technology related fields were also included in SoL definitions from 2018 onward. This trend mirrors the digital-era shift toward data-driven, adaptive learning systems and the rise of learning analytics (Huang et al., 2024), although more of such terminology would have been expected in the current highly digitally-framed education system. Indeed, as education becomes increasingly mediated by digital platforms, computational approaches have become essential for modeling, personalizing and scaling learning interventions (UNESCO, 2024a). The gradual inclusion of sociocultural and computational disciplines, on the other hand, suggests a maturing field that seeks to integrate multiple levels of analysis, from neural circuits to social systems. Another area that would merit more attention, and was surprisingly not found in the definitions, was the role of genes in learning. Latest research indicates that genetics are a more important factor than environment in explaining educational inequality (van Bergen et al., 2025) and that genetic influences play a far more significant role in explaining learning outcomes than previously assumed (Hart et al., 2021).

Stakeholders involved in the SoL

The findings revealed that early conceptualizations of SoL were rooted in disciplines like cognitive psychology and neuroscience, which tend to use generalized terms such as "humans" or "adults" in experimental and theoretical work. This recognizes that learning goes beyond classrooms and can happen in any context. Starting from 2015, there was a gradual refinement of stakeholders, including more specific mentions of students and teachers. This could be due to the rise of student-centered pedagogies; Educational paradigms have shifted toward learner-centered approaches, which necessitate more explicit focus on students as individual learners (McPherson, 2020). Additionally, the development of targeted interventions and adaptive learning systems required a more fine-grained understanding of the learner population (Benkhalfallah et al., 2024). This might also be related to the drive to practice and policy about learning in schools so now students and teachers are explicitly mentioned in definitions.

Additionally, starting from 2020, there was a specific interest in age-specific groups, such as adults and children. This might be due to the growing insights from developmental neuroscience have highlighted significant differences in brain plasticity and

learning processes between children and adults (Bryck & Fisher, 2012). Interestingly, while early childhood education emphasizes parental involvement, SoL definitions have yet to fully incorporate this domain into their core conceptual frameworks. This reflects a gap in explicitly framing the SoL in terms of child development, which could be an area for further exploration.

Cognitive practices covered in SoL

The results indicate a consistent focus on the learning process within the SoL. This emphasis stems from SoL's foundational aim to understand the cognitive mechanisms underlying learning and to explore how individuals acquire, retain, and apply knowledge (Sawyer, 2022). Rooted in cognitive psychology, neuroscience, and educational research, SoL has long prioritized processes such as memory, attention, and reasoning as the basis for enhancing educational outcomes (Bransford et al., 2000). In addition, its reliance on empirical methods—including experimental designs and neuroimaging—makes it particularly well-suited for examining dynamic cognitive and neural processes (Ansari et al., 2012). As a result, topics such as "how the brain learns" and "processes of learning, knowing, thinking, and cognition" have become the most frequently addressed stages of the learning process within SoL.

Compared to its strong emphasis on core cognitive processes involved in acquiring knowledge, the SoL field has relatively limited attention to higher-order learning outcomes, such as the ability to take control of learning and transfer knowledge to new problems and contexts. However, these capacities are essential for developing self-regulated learners and for promoting the flexible application of knowledge in diverse contexts. The implementation of SoL findings to enhance learning efficiency and effectiveness is equally important as understanding the mechanisms behind learning itself. Therefore, future research in SoL should place greater emphasis on these areas to advance its relevance and impact in real educational settings.

Educational factors in SoL

Most definitions of SoL did not explicitly incorporate educational factors, such as design of environment, technology enhanced learning environment and real-world educational settings, likely because the field has historically emerged from cognitive psychology and neuroscience, with a primary focus on uncovering universal mechanisms of learning rather than addressing context-specific instructional practices (Sawyer, 2022). However, in recent years, the emergence of the "new science of learning" reflects a paradigm shift. This perspective views SoL not merely as a cognitive or psychological science focused on human intelligence but as a multidisciplinary field that includes insights from education, sociology and developmental sciences (Pasquinelli, 2011). This expanded approach emphasizes the reciprocal interactions between individuals and their learning environments, exploring how children's development and learning are shaped by environmental factors, social relationships and the learning opportunities they encounter both within and beyond formal schooling (Hammond, 2020). As such, there is a growing recognition of the importance of integrating contextual and educational dimensions into the conceptualization of SoL to better inform practice and policy.

Based on the obtained results and the aforementioned discussion, SoL can be defined in the present research, as follows:

The science of learning (SoL) is an interdisciplinary, evidence-driven effort to understand how people of all ages, abilities, and cultures acquire, retain, transfer, and apply knowledge, skills, and dispositions across contexts by investigating biological, cognitive, emotional, social, cultural, technological, and environmental mechanisms—and to translate that knowledge into valid, equitable, and actionable guidance for learners, educators, caregivers/parents, clinicians, policymakers, curriculum and assessment designers, and technology developers, including clear statements of for whom, when, and under what conditions findings hold.

Conclusions, implications, and limitations

Study limitations

While this study systematically reviewed and analyzed the SoL definitions, it still has some limitations that should be acknowledged and further researched. First, the included definitions and the obtained results are limited by the search keywords and electronic databases. Therefore, future research studies are encouraged to complement this study by including more keywords and databases. In this context, it is possible to go beyond the typical term "science of learning" to also various terms more commonly in other fields such as "educational neuroscience". Additionally, the present study did not investigate how SoL definitions differ from learning sciences. Therefore, our future research direction will aim to address this latter point to further provide a more comprehensive understanding of SoL and its related terms.

Study implications

The findings of this study highlight several implications for advancing the Science of Learning (SoL). While SoL remains strongly grounded in neuroscience and cognitive psychology, there is a pressing need to broaden its conceptual scope to include sociocultural, technological, and contextual dimensions. Such expansion would allow SoL to better capture the complexity of learning across diverse environments and populations. In addition, the limited visibility of teachers, parents, and policymakers as stakeholders indicates the importance of more inclusive framings that support the effective translation of SoL into practice and systemic reform. Although evidence-based applications are increasingly emphasized, further attention is required to higher-order outcomes, such as knowledge transfer, self-regulation, and lifelong learning. Finally, the marginal presence of technology-related learning environments underscores the urgency of integrating digital and AI-driven contexts into SoL frameworks. Collectively, these implications call for SoL to consolidate its interdisciplinary and practice-oriented orientation, ensuring that research evidence is systematically mobilized to inform equitable and effective educational policy and practice.

Appendix A. List of organizations that defined SoL

The list is ordered alphabetically

1. American Educational Research Association (AERA)
2. American Psychological Association (APA)
3. Association for Talent Development
4. Australian Christian College
5. Brookings Institution
6. Center for Applied Neuroscience
7. Centre for Independent Studies
8. Chan Zuckerberg Initiative (CZI)
9. Cognitive Science Society
10. Dana Foundation
11. Deans for Impact
12. Education hub
13. FutureMakers
14. International Mind, Brain, and Education Society (IMBES)
15. Iowa State University
16. Learning Agency
17. Learning Policy Institute
18. Learning Scientists
19. Learning.com
20. Ministry of Education, New Zealand
21. National Academy of Sciences
22. National Institute of Child Health and Human Development (NICHD)
23. Organisation for Economic Co-operation and Development (OECD)
24. Science of Learning Research Centre
25. Spencer Foundation
26. STEM Learning
27. Teaching Council of Aotearoa New Zealand
28. Thomas Jefferson University
29. U.S. National Science Foundation
30. United Nations Educational, Scientific and Cultural Organization (UNESCO)

Abbreviations

AI Artificial Intelligence
SoL Science of Learning (SoL)

Author contributions

Each author contributed evenly to this manuscript. All authors read and approved the final manuscript.

Data availability

The data that support the findings of this study are available based on a reasonable request from the corresponding author.

Declarations

Competing interests

The authors Ronghuai Huang and Ahmed Tlili are part of the Editorial Board Member.

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