Science of Learning: Its promise for education transformation and the need to bridge science and practice

Working Paper

Prepared by the Working Groups of the

Global Alliance on the Science of Learning for Education

Draft for consultation only (20.10.2024)

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UNESCO, as the United Nations' specialized agency for education, is entrusted to lead and coordinate the Education 2030 Agenda, which is part of a global movement to eradicate poverty through 17 Sustainable Development Goals by 2030. Education, essential to achieve all of these goals, has its own dedicated Goal 4, which aims to ***"ensure inclusive and equitable quality education and promote lifelong learning opportunities for all."*** The Education 2030 Framework for Action provides guidance for the implementation of this ambitious goal and commitments.

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The global commitment to achieving Sustainable Development Goal 4 (SDG 4) emphasizes the importance of ensuring inclusive and equitable quality education for all. Central to this goal is the improvement of foundational learning, particularly in literacy and numeracy, which remains a significant challenge worldwide.

But there is a global learning crisis. The recent Global Education Monitoring Report (UNESCO, 2024) revealed that many of those in school are not learning even the basic literacy and numeracy skills. Globally, it is estimated that only 58% of students achieve the minimum proficiency level in reading and 44% achieve the minimum proficiency level in mathematics at the end of primary school. Poor learning outcomes at the end of primary school means that students have not learned the basic skills needed to succeed in secondary school. Indeed, most recent estimates indicate that only 64% of students achieve the minimum proficiency level in reading and 51% achieve the minimum proficiency level in mathematics at the end of lower secondary school. It is no surprise then that about one out of seven young people and adults (754 million) still lack basic literacy skills.

Despite global political commitments for universal access to education, 251 million children and youth still remain out of school, with the global out-of-school population having been reduced by only 1% over the last ten years. Economic and regional disparities show the extent of global inequalities: whereas 33% of school-aged children and youth are out of school in low-income countries, the out-of-school population in high-income countries is only 3%. Over half of all out-of-school children and youth in the world reside in the sub-Saharan African region (UNESCO, 2024).

- The UN calls to transform education to meet the needs of current and future societies. Meeting the Education 2030 goals is off-track.
- Student achievement is declining, and students are becoming disengaged from education.
- Education is no longer fit for purpose – there are issues of equity and relevance. We live in a time of increasing social disparities, climate-related disasters, political and economic instability.
- Digital technologies have become an important part of education, the economy and society. However, these can both reduce and increase educational access and learning outcomes.
- We have improved on education access globally, but education quality remains an elusive challenge.
- There is the also call for more data and evidence in education decision-making.

Despite political commitments, recent data reveal stark disparities in foundational skills attainment, with low-income regions and marginalized communities disproportionately affected. Poor literacy and numeracy skills, not only hinder students' academic progress but also limit their access to higher education, reduce their employability, and restrict their ability to fully participate in society. This is a problem that the Science of Learning has been actively addressing.

What is the Science of Learning?

Human learning involves complex sets of processes applied to consistent patterns in an individual's environment that cause behavioural changes (Houwer et al., 2013; Jarvis, 2005). Given the importance of learning in all human endeavours, it is not surprising that learning has been a central topic of research in many disciplines. Unfortunately, much of the knowledge tended to reside in disciplinary silos; not shared or integrated across disciplinary boundaries and not effectively brought to bear on addressing the many complexities that constitute human learning.

The Science of Learning builds on a long history of research on learning in diverse disciplines including biology, neuroscience, cognitive and behavioural sciences, social science, mathematics, computer and information sciences and education. Scientists across many disciplines have engaged in research that has relevance to educational learning, including from psychology, developmental science, cognitive science and cognitive neuroscience. In recent years, interdisciplinary work has been proceeding to interrelate and integrate their findings with each other and with education and to develop a conceptual scientific understanding that has value and meaning for educators. The different names under which this interdisciplinary work proceeds include "Mind, Brain and Education," "Neuroeducation," "Learning Sciences," "Educational Neuroscience," "Learning Engineering," and "Science of Learning." The different names may represent different emphasises in the approach taken, but they share a common belief that educational practice can be transformed by science, just as medical practice was transformed by science about a century ago (Royal Society, 2011).

The Science of Learning has been described variously 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" (Meltzoff, et al. 2009, p. 288) and "an accumulated body of knowledge about the nature and processes of student learning that has been derived through scientifically sound, empirical research" (Murphy and Knight, 2016, p. xxx). A review of 43 such definitions concluded that the Science of Learning might be defined as "the scientific study of the underlying bases of learning with the goal of describing, understanding, engineering and improving learning across developmental stages and diverse contexts" (Privitera, Ng, and Chen, 2023).

Researchers working in the various fields of the Science of Learning draw on multiple types of data at different levels of analysis, from neuro-imaging and cognitive experiments to classroom and field studies, to construct an understanding of how learning is achieved at all ages, levels and contexts (including pre-primary, higher education, adult and corporate learning). It seeks to leverage all sources of science-based knowledge towards a more holistic and comprehensive understanding of learning, recognizing that the complexities of human learning and education are not addressed by simply providing a "magic bullet" or a "one-size-fits-all" prescription.

For the purposes of this report, we adopt the term "Science of Learning" to indicate this interdisciplinary venture. We expand on the above proposals to include the domains of biology, physiology, neuroscience, cognitive science, behavioural science, cognitive neuroscience, developmental psychology, but also linguistics, mathematics, pedagogy, economics, sociology, political science, and machine learning and artificial intelligence for improving understanding of human learning across the lifespan. This conceptualization of the Science of Learning brings together experimental and laboratory research with classroom-based research.

In doing so, Science of Learning seeks to (1) improve cross-disciplinary investigations and knowledge-sharing of research into learning; (2) facilitate the understanding of how the scientific findings have implications for teaching and learning practices; (3) foster two-way collaborations between research and practitioners for a mutual research-practice production and uptake of scientific knowledge about learning for use in education policies and practice; and (4) meet the challenges and opportunities in bringing education policy and the Science of Learning into alignment to synergistically transform capabilities for improved production and uptake of scientific knowledge for education policies and practices. Through these efforts, scientific understanding of learning is naturally complementary to (rather than substituting) educators' own expertise, helping them to interpret their experiences and inform their decisions.

The contribution of the Science of Learning to education

What can the Science of Learning contribute to education policy and practice? Can scientific knowledge really be applied to reducing inequalities and informing pedagogies? What are some examples of scientifically informed understanding of learning that are of particular relevance in considerations of learning opportunities and challenges? How can they be better designed or implemented in ways that can advance our understanding of why they support or fail to support learning?

These are key questions we aim to highlight in this report as we delve into the research presented. There is no universal consensus of what scientific ideas about learning are most relevant for education. However, by examining how learning occurs across diverse contexts and populations, the Science of Learning offers valuable insights that can help bridge educational gaps and foster more inclusive and effective teaching strategies.

The key gap, as argued in this report, is that there hasn't been enough attention to Science of Learning. This is the value-added contribution of this work and initiative. Using a Science of Learning approach means we take a developmental perspective for the design of curricula, pedagogy and assessment practices. This report marks UNESCO's first systematic and explicit focus on the Science of Learning and its role in education.

Scope and structure of this report

This report summarizes latest research in the domains of Science of Learning concerned with foundational literacy and mathematics, digital learning, as well as social and emotional learning. The report takes a novel approach by leveraging the latest insights from the Science of Learning to inform the design of curricula, pedagogical methods, and assessment practices. It aims to bridge the gap between research and practice, offering evidence-based insights to improve teacher training and, ultimately, student outcomes. By integrating these scientific principles, the report aims to provide a roadmap for more effective and equitable education systems globally.

The report is based on expert consultation and the latest evidence to reflect the views of leading scientists on what the Science of Learning can offer education policy and practice. As such, the report is not a systematic literature review typical of peer-reviewed journals. Rather, it provides insights from the collective expertise of an international community of Science of Learning researchers, practitioners and former policymakers aimed at providing key insights for decision-makers.

This report summarizes research conducted by carefully selected global experts in key areas of learning—literacy, mathematics, digital learning and socio-emotional development—highlighting how the Science of Learning can address the global learning crisis and support UNESCO's broader educational goals.

This report serves as an accessible go-to guide for practitioners and policymakers interested in content across critical areas like literacy, numeracy, digital and social-emotional learning, and to provide a cohesive resource for addressing the global learning crisis, without jargon that could be difficult to understand.

Crucially for policymakers, in particular, the report provides a tool to answer questions they might have on the critical challenge of how to design and implement effective educational strategies that address fundamental learning gaps and ensure that all students acquire the foundational skills necessary for lifelong learning and success.

Research has made a persuasive case that relationship exists between children's early foundational skills and succeeding at school and beyond. Students who are not reading at grade level by grade 3 are especially at risk of failure in a variety of subject areas whereas those who possess a set of strong reading skills do learn effectively (e.g., Sparks et al., 2014; Stanley et al., 2018). Hence, early development of reading proficiency is a critical priority not only for closing the achievement gap and reducing dropout rates but eventually cultivating the educated and skilled workforce needed for an effective economy. Research evidence has also shown that on par with reading, numeracy skills are also an important predictor of subsequent academic achievement and school success, because such skills provide the foundation for more advanced and complex skills of universal applicability such as logical thinking and analysis, critical thinking, among others (e.g., Claessens & Engel, 2013; Duncan et al., 2007). Furthermore, early development of mathematical skills leads to a higher likelihood of entering math-intensive fields of tertiary study and math-based careers (Orpwood, Schmidt, & Jun, 2012). Consequently, instructional approaches need to focus on early prevention and continuous support rather than later remediation. Later remediation, no matter how extensive and costly, because it is initiated after years of student frustration and failure, cannot succeed as well as early intervention.

The report is structured in four major sections following the Introduction, which briefly covers how the developing brain learns (key concepts). Each of the following sections cover development of literacy (reading), mathematics, socio-emotional learning and digital learning, or learning with digital technologies (education technology). All four sections review the most recent findings from the science of learning literature, followed by insights derived from what we know for improving curriculum, pedagogy, assessment and teacher education. Knowledge and evidence gaps in each learning area are also identified.

Finally, report aims to raise awareness of the critical work being done by the Global Alliance of Science of Learning for Education, an international community of practice established to advance the integration of the Science of Learning with education practice and policy. The shared goal of the community of practice is to illuminate how the Science of Learning can be leveraged to create fairer, more responsive educational systems worldwide.

Key concepts from the Science of Learning that are relevant to education

The purpose of this section is to outline, in an accessible way, key concepts and terms related to the science of learning. This can act as a reference point for anyone reading the full report. In addition, it serves to provide consistency in the terminology used for these concepts. In the research literature, many terms are used interchangeably with, occasionally, the same term being used to describe multiple concepts, or a single concept being described using different terminology. This is born out of several decades of empirical and theoretical work across multiple disciplines. As there is no consensus, this document can act as a disambiguation reference to avoid confusion. Another benefit of this section is to avoid duplication of content throughout the sections.

Long-term memory. When information is required for future use, we create long-term memories, which are retained through auditory and/or visual rehearsal. These can be further broken down into categories and sub-categories: (1) **Explicit long-term memory**. These are memories we actively and consciously recall; that is, we are aware we are recalling the information. It is sometimes referred to as declarative long-term memory and includes recall of events we have personally experienced (autobiographical) or episodic memories (specific events) that refer to an experience occurring in a particular place at a particular time, and more objective information such as facts and dates (memories that accrue after active encoding or repeated exposure). (2) **Implicit long-term memory**. Sometimes referred to as procedural or non-declarative long-term memory, this is information that we recall without being aware we are retrieving it (automated reactions developed after practice, sometimes casually referred to as "muscle memory"). It includes skills such as riding a bicycle, playing a musical instrument and other behaviours that have become automatic.

Attention. Literature related to attention can be complex, but here we attempt to give enough information for the reader to understand any terms that might be specific to the numeracy, literacy and social-emotional learning sections of the report. Although we provide some simple examples of how these types of attention are used in learning, each section will go into more detail regarding how and why they are important, where necessary. Also, here we focus on active attention (referred to as endogenous or top-down), which is voluntary and consciously controlled, as opposed to involuntary attention which is evoked by an external event such as a movement, sound or other sensation. We do this because voluntary, active or sustained attention is most pertinent to the learning process. Within this, you will see references to sub-types of attentional control. These include: (1) **Sustained attention**: concentrating on an activity or event for long periods of time, without losing focus or drifting. The links to learning might include listening to the teacher or staying focussed on a classroom task. (2) **Divided attention**: focusing on more than one task or event at the same time, such as listening to the teacher, looking at information on the board and taking notes. This is not to be confused with multi-tasking, which is commonly referred to, but a concept with limited empirical evidence to support it. (3) **Selective attention**: directing attention to salient, or prominent, information and ignoring information deemed irrelevant at the time, such as focusing on an individual task while ignoring the instruction a teacher is giving to another student. This is sometimes referred to as cognitive flexibility or inhibitory control (i.e. of goal directed attention). Closely related to these types of voluntary attention are two interwoven constructs, working memory and executive function.

Working memory. Working memory, not to be confused with short-term memory, is commonly described as the ability to flexibly process and store information for short periods of time, in pursuit of a known goal. It is studied extensively in the fields of developmental and educational research and is a good predictor of academic achievement in children. Deficits in working memory capacity are also found in learning-related disabilities and neurodevelopmental conditions including attention-deficit/hyperactivity (ADHD), autism, dyslexia, and developmental language conditions. Working memory, a crucial executive function, is responsible for holding and using information during cognitive tasks (Cowan, 2014). Working memory is limited and can become a bottleneck in learning and distractions can consume working memory capacity, inhibiting efficient learning. Working memory is closer to sustained attention with the addition of using the new information to direct the next behaviour or set the next step. **Short-term memory** has no cognitive processing, for example, if you hear anything, without paying attention, your brain remembers it for about 30 seconds and within those 30 seconds you can regurgitate it without even knowing what you said. However, if you process the information (i.e. have active sustained attention and relate to long-term memory storage such as past events or past knowledge), working memory is involved.

Executive function. A set of abilities that enable goal-directed behaviour. These are inhibitory control (the ability to suppress irrelevant information, inhibit inappropriate behaviour), set-shifting or task-switching (the ability to switch attention between one task, rule or dimension and another), and updating (monitoring and revising relevant information for a specific task). Executive function is required when automated or routine behaviour is insufficient to achieve a known goal or goals. As with working memory, developmental and educational psychologists have adopted executive function as a means to explain differences in specific cognitive abilities such as literacy, numeracy and educational outcomes more generally.

Learner engagement. Engagement in learning is closely tied to emotions such as interest and enthusiasm, and involves effortful thinking processes, as learners focus and persist in tasks (Hidi, Renninger, & Krapp, 2004; Schiefele, 2001). It specifically refers to being "caught and held" by a learning opportunity (Skinner, Kindermann, & Furrer, 2009). Multitasking, which involves switching attention between tasks, often impairs focused attention and learning due to the cognitive costs of frequent switching (Monsell, 2003; Rosen, Carrier, & Cheever, 2013; Spink, Cole, & Waller, 2008).

Rewards. Research shows that brain structures like the striatum and amygdala are crucial in learner engagement and motivation, with social rewards activating similar areas as monetary or food rewards (Izuma, Saito, & Sadato, 2008; Knutson et al., 2001; Farooqi et al., 2007). The anticipation and receipt of rewards trigger the release of dopamine in the brain which enhances attention and memory for learning tasks (Miendlarzewska, Bavelier, & Schwartz, 2016; Howard-Jones & Jay, 2016). Learners' responses to rewards are influenced by predictability; rewards are most effective when they align with the learner's sense of challenge, balancing between too easy and too difficult—a concept known as the "Goldilocks effect" (Wilson et al., 2019; Kidd, Piantadosi, & Aslin, 2012).

Multisensory and multimodal learning. The brain processes information from our senses and responds with movement, making enactment crucial for understanding and retaining new content. This principle underscores the value of multimedia resources that provide experiential learning opportunities. However, the effectiveness of multimodal approaches depends on context; combining auditory and visual modalities can boost memory if learners focus on the relationship between them (Mayer & Anderson, 1991 Conversely, overlapping modalities, such as reading text while listening to speech, can hinder understanding due to cognitive overload (Buchweitz et al., 2009; Horvath, 2014). Successful use of multisensory approaches requires a scientific understanding of the learning processes involved to avoid interference from excessive cognitive demands.

Congruent learning and congruency effects. Learning is enhanced when new information connects with existing knowledge that is congruent with it (Brod & Shing, 2022). Teachers can facilitate this by prompting learners to reactivate relevant prior knowledge, such as through engaging revision quizzes with immediate feedback. Personal experiences also play a crucial role; connecting new content to personal memories, like understanding "clowning" through a holiday memory, helps make learning more meaningful (Rousell & Cutter-Mackenzie-Knowles, 2022). While children, having less prior knowledge, may struggle to make these connections (Brod & Shing, 2022), teachers can aid this process. Scaffolding and classroom discussions can support students in explicitly linking personal experiences to new learning, enhancing congruency that fosters deeper understanding.

Consolidation of learning. New learning is initially fragile and can overwhelm our limited working memory, which must be freed up for further learning. Consolidation makes knowledge more permanent and easier to access with less conscious effort (Tham, Lindsay, & Gaskell, 2015). To aid consolidation, practicing recall in varied, low-risk contexts helps integrate knowledge with different meanings, enhancing retrieval (Wirebring et al., 2015). Studies show that interleaved and post-learning tests significantly improve retention compared to no tests (Roediger & Karpicke, 2006). Sleep is crucial for consolidating learning, with good sleep enhancing both immediate and long-term memory (Ashworth et al., 2014; Siegel, 2001).

Spacing effects and repetition. Rehearsing knowledge is more effective when sessions are spaced over time rather than crammed together, a principle discovered by Ebbinghaus in 1885. This "spacing effect" occurs because content recently processed is easier to recall without extensive searching (Li & Yang, 2020). Regular practice of recall enhances memory retrieval even after longer intervals. Optimal learning involves increasing intervals of repetition.

Individual differences and neurodiversity

Variations in brain circuitry, influenced by genetic endowments and the environment, especially during the sensitive time-windows in the first few years of life, play a crucial role in how individuals learn and process information. (Cohen, 2001; Eichenbaum 2000; Geake, 2009). For example, variability in the prefrontal cortex, involved in decision-making and attentional control, correlates with differences in executive function skills, affecting academic and problem-solving abilities (Diamond, 2013). Similarly, differences in hippocampal connectivity influence memory performance and learning, with enhanced connectivity often leading to better memory consolidation (Eichenbaum, 2017) and differences in striatal connectivity predict differences in our long-term perseverance towards our goals (grit) and our belief we can improve our own talents (growth mind-set) (Myers et al., 2016).

This variability can reflect typical changes during a child's development but are sometimes also associated with neurodevelopmental disorders such as dyslexia, ADHD, and autism spectrum disorder (ASD). For instance, dyslexia is associated with differences in phonological processing regions of the brain, helping to explain the challenges children can experience in reading and language acquisition (Nicolson & Fawcett, 2011). Individuals with ADHD often exhibit altered activity in attentional networks involving the striatum, impacting their ability to focus and regulate impulsivity (Barkley, 2015). Meanwhile, ASD is characterized by atypical connectivity patterns across various brain regions, influencing social communication and sensory processing (Haigh et al., 2016).

Understanding neurodiversity is crucial for creating more equitable, inclusive and effective learning environments. This knowledge can also aid in identifying and supporting individuals with learning difficulties, ensuring they receive appropriate interventions and resources (Goswami, 2006; McEwen & Gianaros, 2011). For example, some of the problems certain children might experience during learning might be due to an underlying attentional or executive mechanism. For example, we often see with Attention Deficit/Hyperactivity Disorder (ADHD) a limitation in one's ability to inhibit distractors, whether internal mental thoughts (drifting) or externally in the environment. However, this limitation is not only specific to ADHD, and we see this effect in children with anxiety, where they are unable to control their anxious thoughts and consequently unable to attend to and perform on lessons in the classroom. Educators understanding this better will allow them to more effectively teach and monitor their students.

This report offers descriptions of learning development at specific stages of childhood based on established empirical evidence. Nevertheless, it is important to note that child development should be interpreted with an understanding that development is a continuous process and is not naturally delimited by age groups or education levels. It should also be kept in mind that, while the underlying brain mechanisms are the same among all individuals, each learner learns differently and individual differences are the norm, rather than the exception (Duraiappah, et al, 2021). This approach recognizes that learning and development are not a "one size fits all" process; there is considerable variability both among children and within contexts. Each learner brings unique cognitive, emotional, and social attributes that interact dynamically with their environment, resulting in diverse learning pathways. In essence, the term 'neurodiversity' applies to all learners, not just those identified with learning challenges. By offering a description of the 'typical' stages of learning and development, this report aims to support in the early identification of children at risk of learning difficulties, acknowledging that effective learning approaches must be adaptable to individual needs and situational factors.

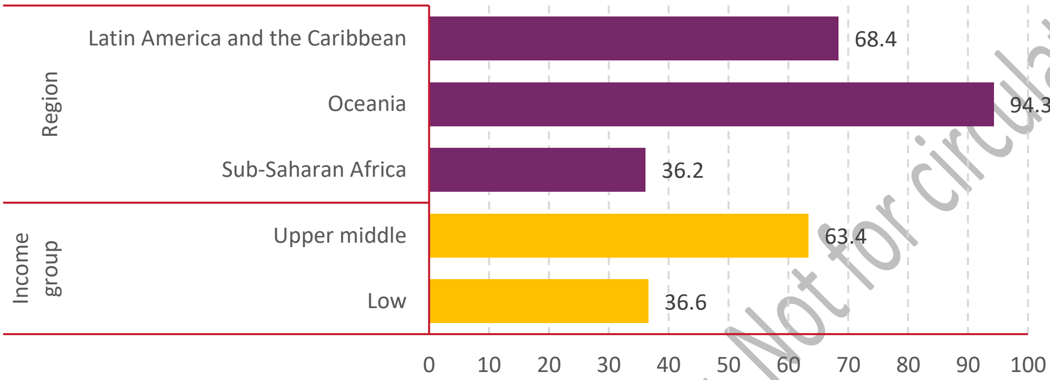
The science of learning to read

What is the challenge for policy-makers?

[Under development]

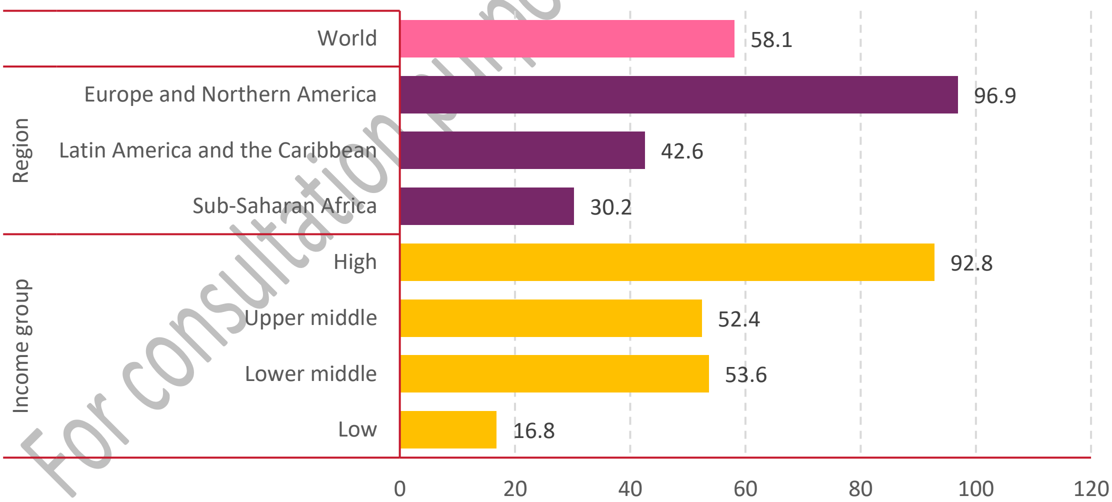
Despite a great deal of effort and financing at country and at international levels, many typically developing students are not learning basic skills. The figures below illustrate the most recent data on global reading rates for 10-year-olds (Grades 2 or 3), at the end of primary school and at the end of lower-secondary school.

Figure 1. Proportion of students in Grade 2 or 3 achieving at least a minimum proficiency level in reading, both sexes (2019)



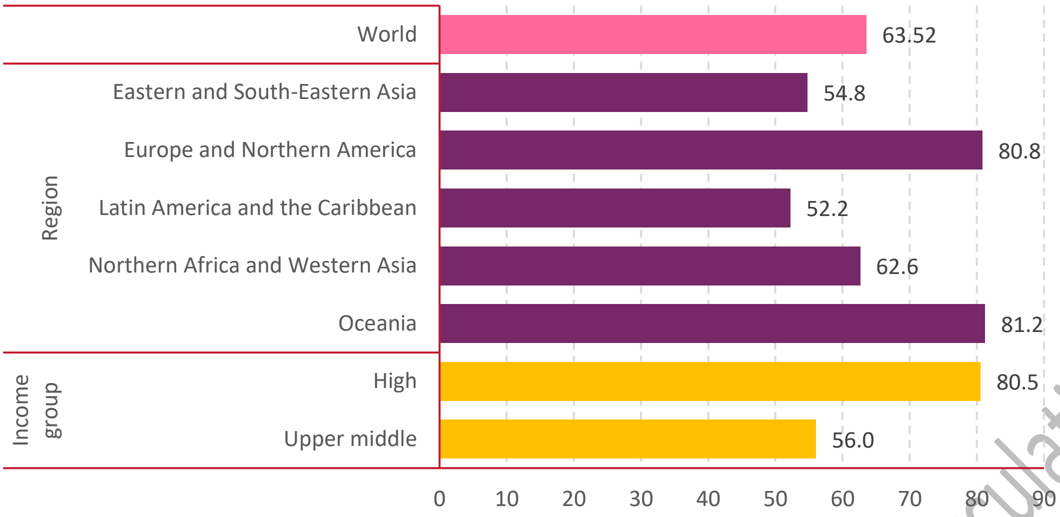
Note: It is not possible to report a global average due to poor coverage.
Data Source: UNESCO Institute of Statistics, SDG 4 Indicator Dashboard, data release March 2024. Available at http://sdg4-data.uis.unesco.org/

Figure 2. Proportion of students at the end of primary education achieving at least a minimum proficiency level in reading, both sexes (2019)



Data Source: UNESCO Institute of Statistics, SDG 4 Indicator Dashboard, data release March 2024. Available at http://sdg4-data.uis.unesco.org/

Figure 3. Proportion of students at the end of lower secondary education achieving at least a minimum proficiency level in reading, both sexes (2019)



Data Source: UNESCO Institute of Statistics, SDG 4 Indicator Dashboard, data release March 2024. Available at http://sdg4-data.uis.unesco.org/

Theoretical models of reading

Learning to read involves the conversion of written (orthographic) codes onto speech sounds (phonology) and meaning (semantics) and is a process that is supported by multiple perceptual, cognitive and linguistic abilities. To attain literacy, students must learn to identify each letter or character with a corresponding sound instantly and correctly. Considerable practice is needed with sound-letter combinations to increase speed and accuracy.

Several models describe the complex process of learning to read, with those grounded in the science of reading being particularly relevant. The science of reading is part of the science of learning with a focus on reading. Like the science of learning more broadly, the science of reading is not a singular approach or entity but a comprehensive, diverse body of evidence that informs curriculum and pedagogy and encompasses research across multiple disciplines, including education, psychology, linguistics, neuroscience, sociology, speech and language pathology, and implementation science (Goodwin & Jiménez, 2020; Moje et al., 2020).

The theoretical models underpinning the science of reading are largely grounded in the **Simple View of Reading** (SVR), a foundational theory that defines the skills contributing to early reading comprehension. Originally proposed by Gough and Tunmer (1986), the Simple View of Reading posits that **reading comprehension (RC)** is the product of two essential components: **word recognition (WR)** and **oral language comprehension (LC)**. This relationship is often represented mathematically as: $RC = WR \times LC$.

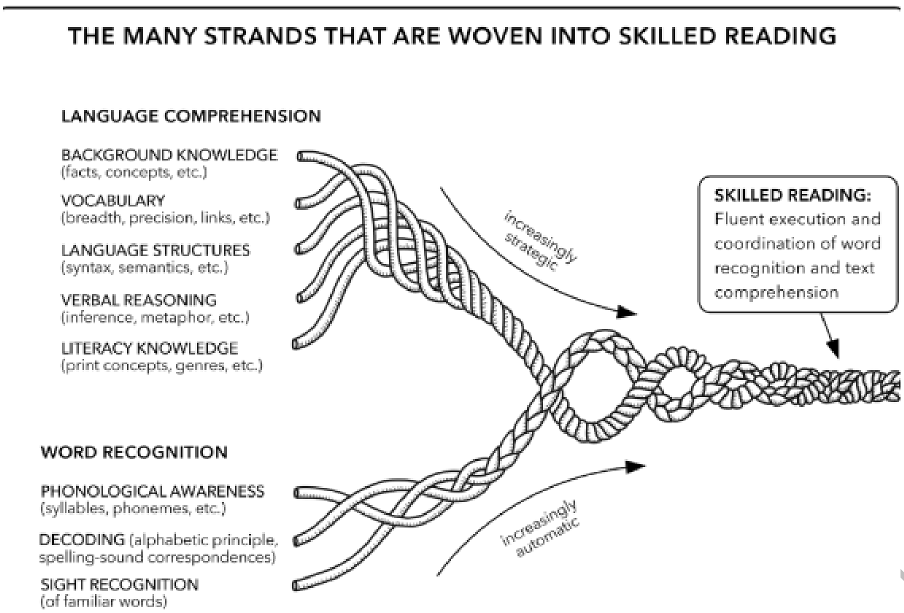
The central idea is that both components are necessary for successful reading comprehension. Decoding (or word recognition) involves the ability to translate written text into spoken language, while language comprehension refers to the understanding of spoken language.

Recent advances in reading research have refined the decoding aspect of the equation, emphasizing fluent word reading, which includes both automaticity and fluency in word recognition. This enhancement highlights that efficient, automatic word reading is critical to freeing up cognitive resources for comprehension.

The Simple View of Reading provides a clear and concise framework for understanding the interplay between these two components and their collective impact on reading comprehension, serving as a cornerstone for evidence-based approaches to reading instruction.

The Simple View of Reading is often illustrated by Scarborough's Reading Rope Model illustrated in Figure 4. This model reveals the many strands that are woven into skilled reading and is based on two key strands that need to be interwoven: (1) language comprehension that is increasingly strategic and involves the components of background knowledge, vocabulary, language structures, verbal reasoning and literacy knowledge and (2) word recognition that includes phonological awareness, decoding and sight recognition, that are increasingly automatic.

Figure 4. Scarborough's Reading Rope Model.

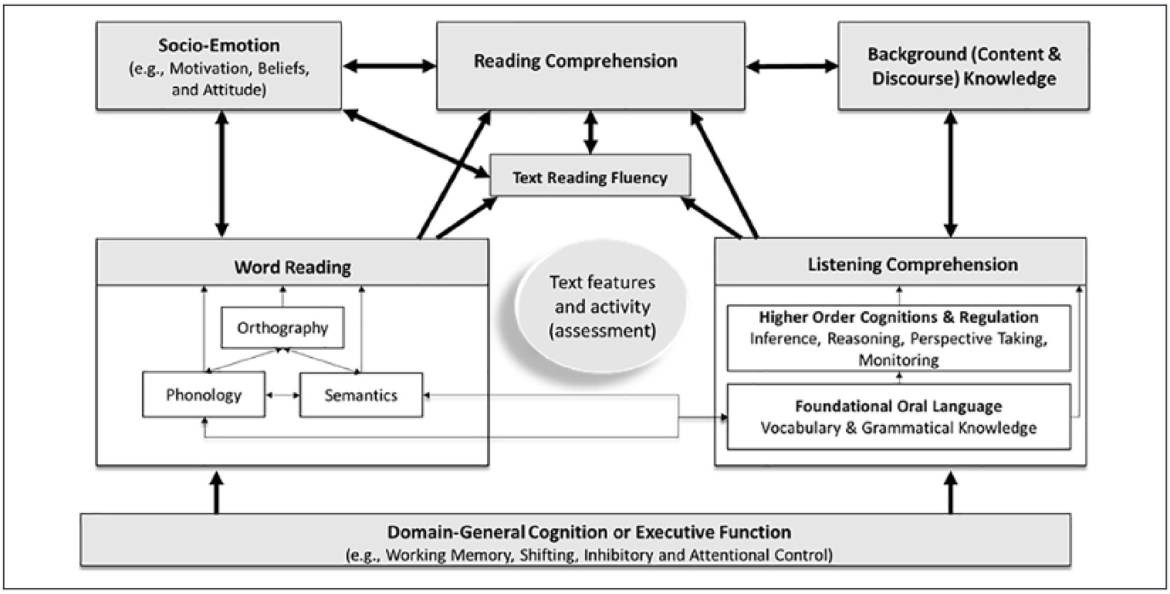


Source: Scarborough, H. S. (2001) in Merkeley (in press). [Temporary figure for consultation purposes only]

The **Complex Model of Reading** builds on and expands several existing theories, including the Simple View of Reading. While the Simple View suggests that reading comprehension depends on two main factors—word reading and listening comprehension (Hoover & Gough, 1990)—the more recent multicomponent view (Cain, 2009; Kim, 2021) argues that reading comprehension is influenced by a wider range of factors. These include cognitive skills such as working memory, attention, vocabulary, syntactic knowledge, the ability to make inferences, and comprehension monitoring. These factors are relevant to reading across all languages, not just English, even though much of the research on the science of reading has focused on English.

The complex model of reading recognizes that comprehension is not just about decoding and listening comprehension. It also takes into account other processes and skills, such as text reading fluency, higher-order thinking skills, background knowledge, motivation to read, and general cognitive abilities. Furthermore, this model broadens the scope by considering not only the individual cognitive skills of the reader but also external factors, such as the text itself and the activity of reading. The complex, or integrated, model of reading (see Kim, 2017) moves beyond earlier models that mostly focused on individual characteristics like word recognition and language comprehension (Cervetti et al., 2020). The complex model highlights the interrelationships among these various factors, recognizing that they are not isolated but interact with each other in dynamic and hierarchical ways (Duke & Cartwright, 2021). These relationships are essential for understanding how reading comprehension develops and how it can be supported through instruction and intervention.

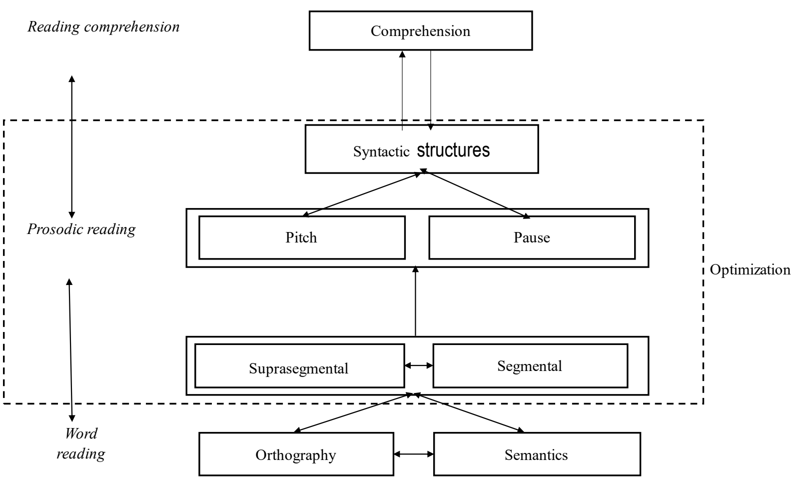
Figure 5. An example of a complex model of reading.



Source: Kim, Y. S. G. (2020). Toward integrative reading science: The direct and indirect effects model of reading. *Journal of Learning Disabilities*, *53*(6), 469-491. [Temporary figure for consultation purposes only.]

Another complex model of reading is the Prosodic Catalyzing Hypothesis, which recognizes that reading comprehension functions as a coordinated effort between a low-level word reading system and a high-level language comprehension system (see Figure 6). The word reading system relies on interconnected phonology, orthography and semantics. The language comprehension systems involve syntax-prosody mapping. These two systems are synchronized through prosodic reading and manifested as pitch and pause patterns, which are essential elements of phonology for words that contribute to word reading. Simultaneously, pitch and pause patterns map onto syntactic structure, which is connected to the language comprehension system. Through prosodic reading, word reading and language comprehension are constantly coupled and reinforce each other, leading to an optimal processing system for comprehension. In particular, as a child's word reading becomes automatic and effortless, they can reallocate attention to higher level comprehension (LaBerge & Samuels, 1974).

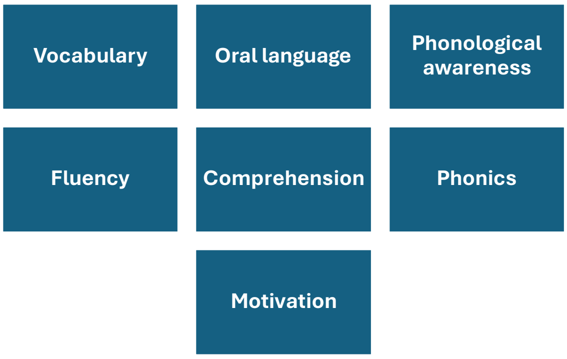
Figure 6. The Prosodic Catalyzing Hypothesis



Source: Tong et al. (2024).

This evidence underscores effective strategies for teaching reading from early childhood through adolescence and for all student populations, including those at risk for or identified with special needs, as well as multilingual and second language learners. The science of reading makes it clear that with appropriate structures, supports, and individualized interventions, all students can become proficient readers (Shanahan, 2020). In particular, structured literacy instruction is a framework for effective literacy teaching based on the science of reading. It aims to maximize student learning opportunities and improve literacy outcomes by focusing on some core components that need to be taught explicitly and in a specific sequence. Experts differ slightly in how many core components of structured literacy they define—whether five, six, or seven—but they converge around the following seven key skills or core components of learning to read, as illustrated in Figure 7.

Figure 7. Key skills in learning to read



Source: Authors.

These skills are taught through approaches that break the reading process into components introduced systematically and logically. In other words, the key characteristics of structured literacy instruction are that it is explicit, direct, and responsive, combining systematic teaching with authentic, meaningful learning experiences.

The components are mutually reinforcing and strongly interrelated, often represented in models with two-way arrows indicating their dynamic relationships. By leveraging these insights, educators can provide comprehensive and effective reading instruction tailored to diverse learner needs.

In the sections that follow, we explore in depth the scientific findings behind the components involved in skilled reading.

The stages of learning to read

In all writing systems, or orthographies, the main reading functions are the same and reflect the abilities of the human brain. As children learn to read, brain regions associated with visual, speech and language processing form specialized cortical circuits—the brain's 'reading network'. Instant and accurate decoding activates a brain area that decodes multiple letters or characters at the same time. Connections to the language areas then enable students to understand the meaning of words and texts. With consistent and repeated exposure to reading and practice, speed rises and reading gradually becomes effortless. Accurate and effortless reading of multiple words, or fluency, enables people to read ahead, and is a basic element of prosodic reading, or reading with expressive tones (various pitches and duration), and thus an essential component of comprehension.

Fluent reading is a product of skilled decoding and a complex process involving multiple underlying linguistic and cognitive components. To read expressively and comprehend a sentence or paragraph, a minimum speed is necessary (often stated as 45-60 words per minute). Speed is needed because for comprehension, a message must be retained into the brain's working memory. This holding bin is very small and fleeting. People who read slowly, letter by letter or character by character, may forget the beginning what they have read by the end of a sentence. Fluent but slow readers may miss the middle of a paragraph. For comprehension, students must also learn vocabulary and grammar, particularly if the language of instruction differs from their home language. Corrective feedback and practice are necessary to attain proficient reading and comprehension of extensive texts.

As reading involves deriving meaning from visual symbols, beginning readers need good spoken language skills like knowing speech sounds (e.g., phonological awareness), word formation rules (morphological awareness), and vocabulary to understand words when reading (e.g., Rastle, 2018; Tong & McBride-Chang, 2010). The conversion of printed words into sound-based codes requires phonological awareness, or the ability to segment speech sounds into individual phonemes (e.g., cat → /k/-/æ/-/t/). The print-to-sound is one necessary route to access to word meaning at the initial stage of reading across languages. Another route is a direct route, i.e., spelling to meaning (Coltheart et al., 2001; Frost, 1998; Taylor et al., 2013). The dual-pathway of skilled reading is supported by neuroscience evidence revealing the dorsal (phonological encoding) and ventral (spelling-to-meaning) pathways involved during reading (Taylor et al., 2013).

There is evidence that all emergent readers access phonological information associated with print in all languages (Ziegler et al., 2010). Although there is variety in consistency of print-to-sound mappings, phonological awareness is an important component in learning to read for all languages. Languages such as Spanish, Italian and Russian have nearly one-to-one print-to-sound correspondences, indicating that they are **transparent orthographies** (Katz & Feldman, 1983). Many alphabetic languages have a transparent orthography. On the other hand, the English language is considered an **opaque orthography** due to its many inconsistencies in spelling-to-sound mappings (e.g., the letter 'c' can correspond to both the sound /s/ and /k/ as in 'circus'). Evidence indicates phonological awareness continues to be a key component of learning to read in both transparent and opaque orthographies (Caravolas, Lervag, Defior, Seidlova Malkova, & Hulme, 2013; Cossu, Shankweiler, Liberman, Katz, & Tola, 1988; Katz & Frost, 1992; Ziegler et al., 2010). Further, this general principle applies to different writing systems, both alphabetic languages (e.g., English) and logographic languages (e.g., Chinese) (Lo, Hue, & Tsai, 2007; Wang, Yang, & Cheng, 2009). However, the impact of phonological awareness on reading is modulated by the transparency of the orthography and phonological awareness is a stronger predictor in less transparent orthographies, like English.

Phonological decoding skills are essential at the beginning of reading, and it needs explicit teaching of sound-spelling relationship, and the extensive exposure of language and literacy experiences (Rastle, 2019; Rayner et al., 2001). To develop skilled spelling-to-meaning mapping, children need to learn how words are formed to understand new ones. Morphemes are the smallest units of meaning and understanding the internal organizing principle of word formation (e.g., happy-happiness-happily-unhappy) - morphological awareness - is closely related to vocabulary (Nagy et al., 2003). Knowing how words are formed helps children learn new words, and knowing more words helps children understand more morphemes (McBride-Chang et al., 2008). Research has shown that early morphological awareness can predict later vocabulary breadth (number of words) (Sparks & Deacon, 2013) and vocabulary depth (knowledge of each word) (Spencer et al., 2015). Vocabulary (e.g., Berends & Reitsma, 2006) and morphological awareness (Deacon et al., 2013; Levesque & Deacon, 2022; Levesque et al., 2021) are robust predictors of word reading and reading comprehension (Tong & Tong, 2022).

Word recognition is the ability to accurately decode and recognize individual written words. Once children's understanding of the speech-sound mappings is secure, they apply these skills to decoding increasingly larger parts of words – children use morphemes to decode words (termed morphological decoding). Evidence from English suggests that morphemes may be more efficient chunks than orthographic patterns because they carry meaning and can support directly print-meaning mapping—as posited in the Morphological Pathways Framework (Levesque et al., 2021). Morphological awareness is linked to English word reading (Kirby et al., 2012), spelling (e.g., Deacon et al., 2009), and reading comprehension (e.g., Levesque et al., 2017). Successful comprehension requires children to automatically and accurately retrieve meaning from their vocabulary knowledge (Perfetti, 2007). Vocabulary is a strong predictor of reading comprehension across languages (e.g., Ouellette, 2006 Tong & Tong, 2022) and becomes more important as children become fluent readers (Garcia & Cain, 2014; Hjetland et al., 2019).

Reading comprehension is a complex process that requires various cognitive and linguistic skills working in tandem (Deng & Tong, 2021, Tong & Deacon, 2017, Tong et al., 2023). To develop strong comprehension skills, children must possess the ability to decipher words (word reading), understand language (linguistic comprehension), and connect the text with their prior knowledge (background knowledge and text structure) by constructing a situation model (Simple View of Reading: Gough & Tunmer, 1986; Construction–Integration model: Kintsch & Rawson, 2005; Wharton & Kintsch, 1991).

The importance of language development for reading comprehension

Early language experiences are crucial for young children's speech and later literacy development. As outlined by Merkeley (in press), language learning begins in the womb, with babies even showing traces of the language they are exposed to prenatally (Werker & Hensch, 2015). In infancy, babies can learn any language, but as they grow, they become attuned to the sounds of the languages they hear, a process called perceptual narrowing (Kuhl, 2004). As they gain experience, connections in the brain are strengthened or pruned based on use (Bishop, 2000). By using statistical learning, infants begin to segment language into words and understand sound patterns (Saffran & Kirkham, 2018).

Language development varies, but strong early language skills predict better language and literacy outcomes later (Vehkavuori et al., 2021). Milestones, such as babbling around six months and speaking first words at one year, help identify children at risk for language difficulties (Visser-Bochane et al., 2020). Vocabulary typically accelerates around 16-20 months (Frank et al., 2021). By age two, children have over 200 words, and by secondary school, they learn more than 60,000 words (Frank et al., 2021). Along with vocabulary, children also learn grammar and how to communicate effectively with others from a young age (Tomasello et al., 2005).

Language comprehension involves the capacity to derive meaning from spoken language. Word recognition and oral language comprehension skills require complex cognitive and linguistic processes including phonological and morphological awareness, as well as orthographic knowledge for word recognition. Language comprehension also requires several language and cognitive component skills such as vocabulary, executive functioning, and working memory. For example, a child's vocabulary development, which is related to their background knowledge, supports language comprehension. Numerous research studies have demonstrated that this theoretical model accounts for a significant portion of the variation in reading comprehension in primary- and middle-school children in various orthographies.

Language comprehension plays a crucial role in reading comprehension, as it involves understanding the meaning of words and sentences, which is essential for making sense of written text. A strong language comprehension ability supports reading comprehension by enabling children to connect words and ideas, make inferences, and derive meaning from text.

Prosodic reading

Most children develop oral language skills before learning to read. Teachers and parents play a crucial role in helping children connect their spoken language skills with written text comprehension. One effective method for achieving this is through the practice of prosodic reading (Tong et al., 2024). In fact, when adults read to children, they often use expressive pitch and extended pause to act out scenes and characters in the story. Though the goal is to entertain the children and direct their attention to various meanings in the text, a more important dynamic is also at play. Known as prosodic reading, this form of expressive reading is a powerful tool that can help children seamlessly synchronize their spoken language skills with reading, enabling them to become more proficient readers. This kind of prosodic or expressive reading, involving changes in pitch patterns and pause duration, is recognized as a hallmark of children's fluent reading (National Reading Panel, 2000; for a review, see Kuhn et al., 2010; Tong et al., 2024). As prosodic reading requires the use of appropriate pitch and pause for correct semantic and syntactic emphasis, children must learn to chunk connected texts into smaller syntactic units. This process directs their attention to morphological and syntactic cues, enabling them to apply what they have learned from speech comprehension to reading comprehension. Thus, prosodic reading acts as a "catalyst" for expediting the connection between spoken language and print reading, facilitating children's transition from word-by-word reading to reading in meaningful phrases. This critical role of prosodic reading has been verified in English (e.g., Miller & Schwanenflugel, 2006), French (e.g., Arcand et al., 2014), Spanish (Álvarez-Cañizo et al., 2015), Hebrew (Ravid & Mashraki, 2007), and Chinese-English bilingual children (Tong et al., 2024).

Background knowledge and text structure

To understand what they read, children need to connect the information in the text to their background knowledge. This requires generating inferences using vocabulary and topic knowledge (Lucas & Norbury, 2015; Kintsch, 1988). However, this task can be difficult since children have limited cognitive resources to access their background knowledge while in the act of reading or, afterwards, remembering what they read (Rapp et al., 2007). Text structure refers to how the information is organized and presented in written text, i.e., the relationship between ideas in the passage (Pyle et al., 2017). Several common types of text structures include chronological order, cause and effect, problem and solution, compare and contrast, and description. Exposing children to different types of text structure helps them anticipate what to expect and understand which information is essential (Bogaerds-Hazenberg et al., 2020). As a result, this liberates cognitive resources that would otherwise be expended on the task of organizing information and enhances their ability to focus on understanding the content (Hebert et al., 2016). Thus, improving children's ability to access background knowledge and understand the text structure can enhance their reading comprehension skills (Willingham, 2006). Overall, background knowledge and text structure facilitates meaning integration.

Early identification of potential risk for reading comprehension difficulties is crucial, as these problems can arise from multiple factors. Children who have difficulty in this area have developed age-appropriate word reading skills, but struggle to comprehend text. This typically manifests in grades 4 or 5 (by the end of lower primary school) when children transition from "learning to read" to "reading for learning" (Leach et al., 2003, Tong et al., 2011). Recent research has shown that these difficulties can be traced back to earlier grades (Tong & Deacon, 2013) and include weaker suprasegmental phonological awareness (i.e., the ability to distinguish pitch patterns, duration, and intensity; Deng & Tong, 2018), delay of oral language comprehension skills (Tong & Deng, 2021), and poor morphological (Tong et al., 2011) and syntactic awareness (Tong et al., 2023). These metalinguistic and language skills can be objectively assessed even before children acquire text reading comprehension, thus enabling early identification of poor comprehension by measuring critical linguistic factors necessary for reading comprehension development.

Cognitive requirements for decoding and fluency acquisition

As emphasised by the complex model of reading, a long-term, relatively permanent memory system is important for learning to read, both in terms of an explicit conscious recollections of events and facts and an implicit memory, which allows us to store instructions on how to do things. In addition, to a well-functioning memory, reading also requires spatial attention to focus on specific stimuli in a visual environment. It requires the ability to focus on relevant information, maintain selective attention, and persist despite difficulties. This ability to self-regulate is part of **executive functions** (Anderson et al., 2001). This ability develops primarily in ages 3 to 6. **Inhibitory control** supports an emerging reader's ability to suppress irrelevant and distracting information both in their environment and in their prepotent responses to the visual stimulus of written language (Altemeier et al., 2008; Dehaene et al., 2015) (Booth et al., 2010; Monette et al., 2011). **Cognitive flexibility**, or the ability to switch between tasks, allows an emerging reader to develop the meta-linguistic knowledge to understand the segmental nature of language, which in turn allows the reader to map sounds to individual graphemes (e.g. phonological awareness; Colé et al., 2014).

Executive function is another key skill to nurture for skilled reading. The development of executive functions is particularly protracted, making executive functions more susceptible to negative environmental influences including poverty. Poverty negatively impacts reading indirectly through executive functions (e.g. Jasińska et al., 2022a). Children with delays in executive function may have trouble focusing on specific letters (Franceschini et al., 2012). Young students who have difficulty with executive functioning may not stay long on this rather challenging task and may be distracted.

Perceptual learning and attainment of automaticity

Reading is not innate, but it relies on the brain's ability to identify visual objects (including letters and words) (Dehaene & Cohen, 2010, 2011). Over the course of reading acquisition, existing neural circuits for visual object recognition are repurposed to detect the shapes of a writing system instantly and to link these to language areas. The visual process of detecting letters and their features is an example of perceptual learning (Yu et al., 2009), which has been emphasised in some models of reading development.

Perceptual learning involves all senses and memory, and these are implicated in some key reading processes and mechanisms, such as the size and spacing of print and letter features and visual complexity. More complex shapes have more features, so they take longer to recognize (Changizi & Shimojo, 2005; Perfetti & Cao, 2013; Chang, Plaut & Perfetti, 2016). They also must be distinguished from other letters of multiple features. Scripts that consist of multiple parts that are connected in some places and disconnected in others require more practice. Alphabets and characters with more complex forms or shapes (like Asian scripts) take longer to learn. By contrast, simpler shapes and separated letters may be learned more easily. Several variables influence the probability of letter and word recognition. These include shape complexity, critical size and spacing, distance from a page or blackboard, and others. Long words without spaces slow down the reading rate (Marinelli et al., 2012; Martelli et al., 2009). Other studies also suggest benefits of using large and spaced letters (Project Tomorrow, 2019; Stagg & Kiss, 2021; Masarwa et al., 2022).

Typically, writing systems with larger character sets, more complex shapes, or greater spelling inconsistency require longer instruction and longer practice periods for students to attain automaticity. However, research-based guidance in languages other than English has been scarce. With practice people get habituated to dense masses of small symbols (Hussain et al. 2011), so an experienced reader easily reads tiny and dense script. However, habituation depends on the amount of practice. Texts easily read by the middle-class children may be too dense for the poor, who get few books. Colours and complex graphics may further slowdown reading for beginners, since they must detect letters among distractors. Since letter detection depends on repeated neuronal circuit connections, it is likely that a lengthier focus on letters of words would facilitate consolidation. Reading proficiency requires multiple exposures and practice (Palmeri & Flannery, 1999). The more students practice reading, the more they can gradually progress from reading effortfully and consciously into fluency and unconscious processing (Speelman and Kirsner 2005).

It should be noted that whether and how decreased font and spacing affect learning to read is not sufficiently researched and known. The literature on font and spacing effects is very mixed, with some recent work casting doubt on whether font and spacing effects are related to reading performance, especially in beginning readers (Luniewska et al., 2022). Even in cases of dyslexia, fonts that are supposedly dyslexia friendly by adding more spacing are not found to be effective (Kuster et al., 2018). Overall, a better understanding is needed about optimal size and spacing for lower-income or lower-performing students. The studies by perceptual researchers have been carried out on adult expert readers using the Roman script. For beginner children or for Asian scripts, specific research is needed. Until that takes place, it is not possible to approximate size and spacing for new readers empirically.

The importance of writing for script consolidation and spelling mastery in learning to read

All writing systems have spelling rules, and even the most transparent ones have some writing conventions that students must learn. The writing brain network emerges after the reading network, but it supports it. Multiple studies have shown the advantages of writing for reading consolidation. (Perfetti & Cao, 2012). Writing by hand enables a stronger representation in one's mind that helps students scaffold toward other types of tasks that do not involve handwriting (Wiley et al., 2024). Handwriting has instructional, practice, fluency, automaticity processes of its own, as are pertinent to implicit memory.

In sum, reading instruction must be consistent and early and learners need frequent and systematic exposure to literacy instruction to learn to read. Yet, absenteeism (both teacher and student) and school closures (due to poor weather, [e.g., rainy season], political instability, disease, teacher strikes, among others) are unfortunately far more common in countries with the largest burden of the learning crisis. Cumulatively, these prevent learners from getting frequent and systematic exposure to literacy instruction that they require.

The design of children's picture books

Illustrations in books for beginning readers may facilitate reading comprehension by helping define story setting and characters, and increase children's motivation (Carney & Levin, 2002). However, reading materials for beginning readers often contain elaborate illustrations that may include visual details irrelevant to the story. This design of reading practice materials may reduce attention to text, promote guessing from the picture rather than decode text, and reduce reading accuracy and comprehension (Eng, Godwin & Fisher, 2020; Rose, 1986; Rice, Doan & Brown, 1981; Torcasio & Sweller, 2010; Willows, 1978). Therefore, it is important to choose reading practice materials that are optimized for children's developing attention and reading skills (Eng, Godwin & Fisher, 2020).

Books for emergent readers should be decodable. Decodable reading books are instructional texts that provide opportunities for emergent readers to apply phonological skills progressively. Decodable texts are based on a specific phonic teaching sequence (Cheatham & Allor, 2012; Buckingham, 2018) and emphasize phonics to build orthographic knowledge and fluency. Decodable books are contrasted with leveled books, which do not emphasize phonics, but rather focus on multiple language and reading skills including visual (graphophonic), meaning (semantic context), and structure (grammatical context, i.e., Clay, 1991). Rather than decode, emergent readers can guess words by inferring from other cues in leveled books, which is not optimal.

Pre-primary school readiness

The developmental timing of reading instruction matters. Over the course of their development, children pass through sensitive periods characterized by greater neural plasticity for specific forms of learning. The reduction of these sensitive periods has been linked to the onset of puberty, potentially as changing hormones affect neural plasticity (Laube et al., 2020; Fandakova & Hartley, 2020). There are well-established sensitive periods for learning language (Lenneberg, 1967; Johnson & Newport, 1989; Birdsong, 1999). Learning a language at an older age (i.e. beyond puberty) is more challenging. This is particularly the case for learning phonology and syntax; it is easier to acquire these aspects of language knowledge–foundational to literacy–earlier in life (e.g., Oyama, 1976). In many developed contexts, learners first encounter the language of literacy at school. For many, they become literate only in their second language. When children enrol in school late (i.e. well beyond the typical government-mandated age of six years for first grade), their exposure to the language of literacy is delayed, leading to a greater challenge to acquire the language system that underpins decoding.

Several studies report that children who start learning to read at an older age struggle to read (e.g. Whitehead et al., 2024; Jasińska et al., 2024). From a developmental perspective, learning to read requires a level of preparedness to master its complexities, as well as sufficient neural plasticity to accommodate the new neural circuitry that develops for reading. While it is possible to learn to read later in life, often it is more challenging. For example, illiterate adults who learn to read in adulthood show improved phonological awareness skills and reading outcomes, but these still lag behind compared to literate adults (Landgraf et al., 2012; Greenberg et al., 2002).

Adults acquire phonological and syntactic patterns of a new language using largely explicit (and less efficient) learning, while children do so using largely implicit learning (Fabbro & Paradis, 1995; Grenfell & Harris, 2015; Arthur et al., 2021). Studies in developing country contexts show that learning to read is largely predicted by sensitivity to implicitly-learned regularities between print and speech (Brice et al., 2021, Siegelman et al. 2020). However, emerging research in developing contexts with older (late childhood and adolescent) emergent readers finds that learning to read is predicted by sensitivity to more explicitly-learned lexical-semantic information (Brice et al., 2024), and that explicit learning is linked with lower reading ability (Hannon et al., under review).

The confluence of late school enrolment, higher grade repetition, inconsistent attendance, and low-quality education means that many children persist as emergent readers into adolescence (and even adulthood) critically at a time in development when learning to read seems to be more challenging.

Reading assessment

This section provides a brief overview of the challenge of effectively identifying typically-developing children who struggle with reading. These children have reading difficulties but are not dyslexic. For consistent writing systems, oral reading of a brief text is a rough fluency indicator. Teachers or parents readily detect if a person reads fluently, haltingly, or not at all.

Research suggests that bilingual children know fewer words in each of their languages individually (Bialystok et al., 2010; Westerveld, 2014), but when considering both of their languages together, score equal to or better than their monolingual peers on language measures (De Houwer et al., 2014; Genesee & Nicoladis, 1995; Westerveld, 2014). Bilingual children may also score better on assessments in their mother tongue compared to the language of instruction (Jasinska et al., 2022). Assessing bilingual or multilingual children in more than just the language of instruction can provide a better understanding of their language and literacy skills (Altinkamis & Simon, 2020; Hovens, 2002). Comprehensive assessments can help us understand children's learning compared to national and international standards and provide a clearer picture of which children in a classroom may be experiencing learning differences over and above being a second language learner (Knauer et al., 2019; Snilsveit et al., 2016). One important caveat to assessing children in their own language is knowledge of how the local-language phonemes are written.

Also, care must be taken to ensure that administration procedures are appropriate, and assessment items are culturally relevant; that is, vocabulary and stories refer to objects, concepts, or customs that are familiar to the target audience (Jasińska et al., 2022).

Contextual factors that influence literacy

Bilingual and multilingual contexts

It is estimated that more than half of the world's population speaks two or more languages (Grosjean, 2021). Within a country, there may be hundreds of languages spoken by its population, for example, 840 languages in Papua New Guinea, 711 in Indonesia, and 517 in Nigeria (World Economic Forum, 2023). Some languages may not be written, and may only be spoken. This multilingual complexity makes it difficult to decide which languages to use for school instruction. Thus, one contributing factor to poor literacy outcomes is that many children throughout the world are attending school learning in a new language. Learning to read is a challenging task. Not only do these children have to learn to speak the language of instruction, but they have to learn to read it simultaneously, making learning to read especially challenging.

However, as bilingual and multilingual children learn to read, there may be opportunities related to their exposure to different languages that facilitate their learning. Children who are bilingual, particularly those who are exposed to both of their languages from a young age (i.e., at home from birth) perform better on language tasks representative of important skills for reading (particularly phonological awareness, vocabulary), and better on literacy tasks compared to their peers (Ball et al., 2022; Eviatar & Ibrahim, 2000; Jasińska & Petitto, 2018; Petitto et al., 2012; Petitto & Holowka, 2002). However, children who are exposed to their second language at a later age (i.e., when starting school) perform at least as well as, if not better than, their monolingual peers in language and reading skills (Berens et al., 2013; Jasińska & Petitto, 2018; Kovelman et al., 2008; Rubin & Turner, 1989). Bilingual children's first language and literacy skills may also facilitate their second language and literacy skills (Bruck et al., 1997; Cisero & Royer, 1995; Comeau et al., 1999; D'Angiulli et al., 2001; Durgunoğlu, 1998; Durgunoğlu et al., 1993; Relyea & Addendum, 2020; Wang et al., 2005; 2009), this is especially the case when languages have similar sound systems (Jasińska et al., 2019). However, this transfer of skills is not limited to transfer from first to second language. Language and literacy skills may also transfer from the second language to the first language in some circumstances (Chen et al., 2010; Chung et al., 2018; 2019; Manis et al., 2004; Pasquarella et al., 2011; Wang et al., 2006). Taken together, the research suggests that bilingual exposure at home and/or at school may facilitate children's language and reading skills in all of their languages, especially if children continue to develop language and/or reading skills in each of their languages.

Educational policy

Based on the bilingual and multilingual language and literacy research, education policy has increasingly tried to address the linguistic context to improve learning outcomes by including mother tongues in the classroom, often through bilingual education programs. Bilingual education programs vary by multiple structural characteristics: 1) the proportion of instruction in each language at any given time, for example 50:50 versus 90:10 mother tongue: official language instruction; 2) the order in which languages are introduced, for example, sequential programs that introduce the target language (often an official language) gradually versus simultaneous programs where there is an equal amount of instruction in each language at any given time; 3) the duration of instruction in each language, where programs may be early-exit (i.e., transition to the target language in grades 1-3) or late-exit (i.e., transition to the target language in grades 4-6) (citation needed). Programs may also be multilingual and incorporate three languages of instruction, such as in Hong Kong (Wang & Kirkpatrick, 2015). These structural characteristics may differ depending on the needs and goals of the community.

Research has found that bilingualism and bilingual education programs are associated with positive language and literacy outcomes, and less grade repetition, regardless of language immersion style (Hamidou et al., 2003; Lolo Monney, 2012; Bühmann & Trudell, 2007; Piper et al., 2016; Slavin et al., 2011). However, the reality is more complex. Learning outcomes associated with bilingual education programs appear to be dependent on how well and how consistently these programs are implemented. In contexts where some languages are primarily spoken languages and are rarely used in written form (if an orthography has been developed at all), there may be few print resources available to be used in classrooms (Ball et al., 2022; 2024; Sanogo, 2007; World Bank, 2021). Teacher training often only occurs in an official or majority language, leaving teachers feeling ill-equipped to teach in both languages of instruction (Akyeampong et al., 2013; Ball et al., 2022; 2024; Cleghorn et al., 1989; Metila et al., 2016; Wang & Kirkpatrick, 2015). These resource factors constrain teachers' ability to consistently provide high-quality bilingual instruction. Bilingual programs that ensure there are adequate resources and teacher training in all languages also demonstrate positive learning outcomes (August & Shanahan, 2006; Benson, 2020; Bühmann & Trudell, 2007; Cheung & Slavin, 2005; Chiatoh, 2014; Gfeller & Robinson, 1998; Muskin 1997; 1999).

School context and instructional practices

In terms of language-in-education policies, community and school-level factors matter for how well programs are implemented and whether they result in positive learning outcomes. Linguistic diversity, socioeconomic status, and school quality vary at the community and school levels. Whether or not the community supports the use of mother tongues in education also varies; studies have shown that communities may feel hesitant towards including languages that are not the official language or a majority language in the classroom. They may not be familiar with the benefits for learning and literacy of allowing children to use a language they already speak. They may also be concerned that it will hinder children's ability to become proficient in the official language, often the language needed for secondary school and future employment opportunities (Ball et al., 2022; 2024; Bühmann & Trudell, 2007; Cleghorn et al., 2989; David-Erb, 2021; Hovens, 2002; Ilboudo, 2010). Programs or policies that include community engagement elements are associated with better learning outcomes; educating the community about the value of learning in the mother tongue, providing literacy programs for parents, or legitimizing mother tongue instruction by formally assessing children in those languages are ways to promote community buy-in (Benson, 2020; Bühmann & Trudell, 2007; Hanemann, 2018).

Insights for improving literacy curricula, instruction, assessment and teacher education

[To be completed after the consultation workshop with contributions from participants.]

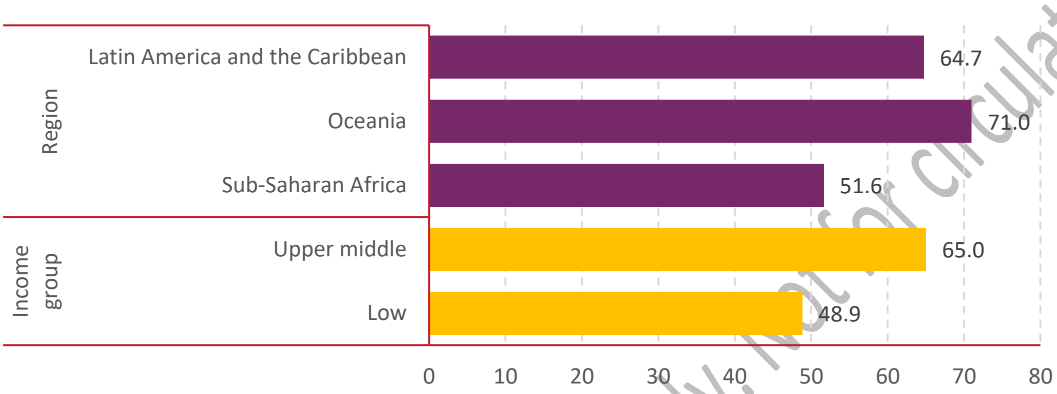
The science of mathematics learning

What is the challenge for policymakers?

[Under development]

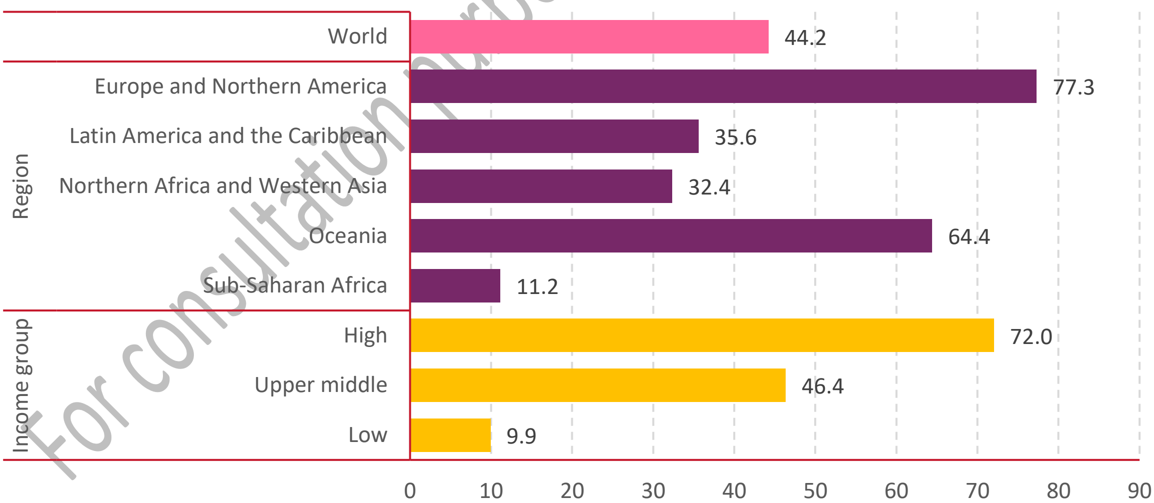
Mathematics skills are core to many STEM (Science, Technology, Engineering and Mathematics) careers. Furthermore, the current employment revolution has seen an increase in the use of data across careers, thus data science and quantitative literacy are increasing in importance (Royal Society, 2023). Understanding the science of learning for mathematics, particularly in the first ten years of life, is therefore crucial for society and the economy.

Figure 8. Proportion of students in Grade 2 or 3 achieving at least a minimum proficiency level in mathematics, both sexes (2019)



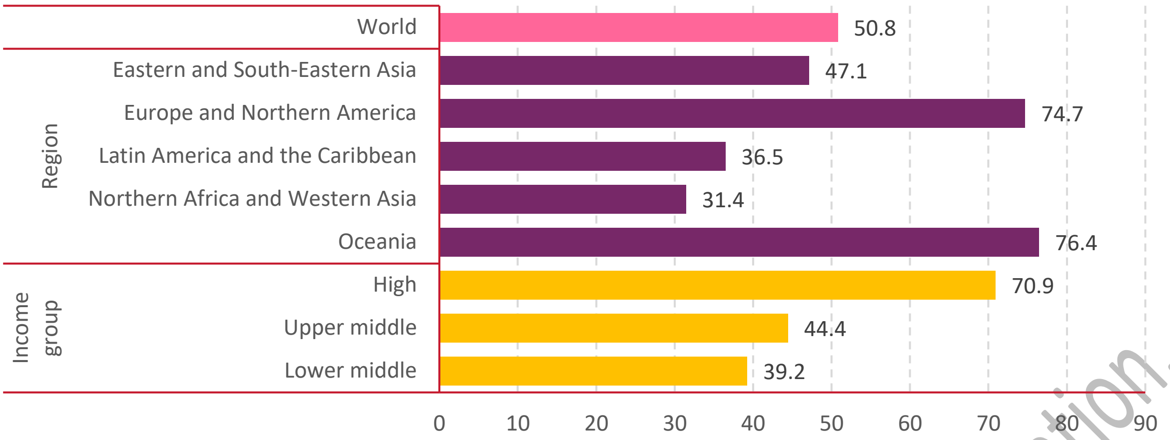
Note: It is not possible to report a global average due to poor coverage.
Data Source: UNESCO Institute of Statistics, SDG 4 Indicator Dashboard, data release March 2024. Available at http://sdg4-data.uis.unesco.org/

Figure 9. Proportion of students at the end of primary education achieving at least a minimum proficiency level in mathematics, both sexes (2019)



Data Source: UNESCO Institute of Statistics, SDG 4 Indicator Dashboard, data release March 2024. Available at http://sdg4-data.uis.unesco.org/

Figure 10. Proportion of students at the end of lower secondary education achieving at least a minimum proficiency level in mathematics, both sexes (2019)



Data Source: UNESCO Institute of Statistics, SDG 4 Indicator Dashboard, data release March 2024. Available at http://sdg4-data.uis.unesco.org/

Development of numerical cognition and mathematics abilities from early years to age 10

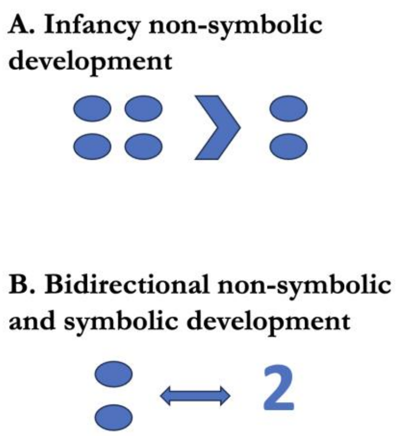
When considering the age at which mathematical concepts and skills are attained, it must be remembered that those abilities that depend partly or wholly on school instruction will be acquired at different ages in different educational systems. For example, the age of starting formal instruction ranges from 4 to 7 in different countries. It does not appear that, at least within the typical range in countries with universal education, the exact age of learning formal mathematical skills has a strong influence on the ultimate outcome. International comparisons, such as TIMSS (e.g. Mullis, Martin & Loveless, 2016) and PISA (e.g. OECD, 2023), show large differences between countries with regard to mathematics performance at the age of 14, but these do not seem to be influenced by age at starting school. However, while the age at which children acquire skills does not seem to influence long-term achievement in mathematics, mathematics knowledge is cumulative and basic skills need to be acquired before more complex skills can develop (Gilmore, 2023). Researchers have investigated differences in early mathematical knowledge between children who are similar in age but have differing years of education experience, depending on the school-entry (e.g. Rajagopol et al., 2022). Results showed that some skills, including counting objects and recognizing numerals, were stronger for children who had spent more time in school, whereas others, such as reciting the count sequence seemed more strongly influenced by age than education (Rajagopol et al., 2022). Importantly, children must be explicitly taught the meaning of number symbols (Merkley & Ansari, 2018), and early mathematics curricula should focus on foundational skills. For example, in South Africa, one study found that children were not starting Grade 1 with this foundational knowledge, and therefore the curriculum is mismatched with the learners' prior knowledge (Fritz at al., 2020). Such mismatched knowledge to curricula is likely to negatively skew children's mathematical progress.

An important concept in foundational mathematics is the concept of mastery. The findings of this research are reflected by the widely accepted instructional principles (National Council of Teachers of Mathematics [NCTM], 2014) suggesting that effective teaching develops students' understanding of concepts and connects this understanding to computational methods and strategies in their application to solve mathematical problems. Effective instruction instils both students' procedural fluency as flexibility to choose adequate computational strategies and methods and capacity to produce accurate answers efficiently, and procedural mastery, ability to instantly recall arithmetic procedures and to carry them out automatically. The combination of these two skills reduces cognitive load and frees up memory resources that can be used to monitor performance and to learn more complex procedures. For instance, in primary mathematics, gaining fluency and mastery of such aspects of number concept as cardinality and ordinal relationships between numbers, enables the student to proceed from concrete to abstract, reaching the ability to carry out mental computation. Such progression requires students' understanding of single-digit whole numbers, their magnitude, the relationships between them, and working with patterns. Developing automaticity of operations with single-digit numbers is critical, as these operations form the basis of all numerical procedures (e.g., Baroody & Purpura, 2017). Because students remember them better and use them more flexibly, students can think about other aspects of a problem and tackle new kinds of problems, which then leads to new understanding (Fuson, Kalchman, & Bransford, 2005; Codding, Mercer, Connell, Fiorello, & Kleinert, 2016).

From 0 to 2 years of age

Early spatial abilities are predictive of later mathematics competence (Gilligan, Flouri & Farran, 2017) and babies are developing spatial abilities from the earliest stages of mathematical development. Babies build spatial abilities through physical activity and rich embodied experiences. For example, when children learn to crawl, and then to walk, we see step-changes in spatial abilities (Clearfield, 2004). Similarly, toddlers' spatial exploration before they are two years old is associated with later spatial abilities and spatial language (Oudgenoeg et al., 2015), whilst parental spatial language at this age is associated with spatial ability and spatial language at age five (Pruden et al., 2011). Such abilities then allow them to build the cultural numeral systems and related operations. Reciprocal development begins once they begin to actually learn the symbolic system. For example, while an infant has the capacity to show that 4 dots are more than 2 dots, once they learn the "numeric language," this being the Arabic number system (1,2,3...), they become much better and faster at this (see Figure 11). This is because once the brain is able to provide a way of operationalizing a concept, it is able to reason through this concept. Consequently, the number system allows this innate spatial ability to improve over time – a development which would not start without learning the number system and its operating rules. A study conducted by Lyons and colleagues (2017) showed that learning the number system allows young children to further consolidate the early numerosity ability found at infancy. This shows the importance of learning the symbolic system early on.

Figure 11. Illustration of the bi-directional relationship between non-symbolic and symbolic systems.



Source: Authors.

Given the importance of spatial ability for mathematics, the spatial environment at home is an important contributing factor to consider. For example, opportunities for puzzle play, frequency of puzzle play between the ages of two and four years is associated with spatial ability at four years (Levine et al., 2012). These opportunities are often reduced in children from low-SES backgrounds and contribute to a spatial disadvantage gap (Levine et al., 2012). Such opportunities scaffold a child's ability to remember magnitude and order, numerical concepts we discuss in the next section.

From 3 to 4 years of age

Learning the cultural symbolic number system is as crucial for the numerate brain as learning the alphabet is for the literate brain. First, young children (as young as 2 years old) begin to learn the words for the symbols (e.g. 2 is vocalized as two). This may begin in the home or in schools, where numbers are mapped onto quantities in everyday activities. For example, if a child is playing outside with an adult, the adult may say "can you find two sticks" and increase numbers from there, showing the child what "two" is. They then learn to count and the basic order of numbers on a number line (thus rather than the meaning of order, just the sequence of the number line), where they slowly begin learning one-to-one correspondence (counting objects with corresponding number) and the number list. By 4 years old, young children begin to grow their understanding of number order (the sequence the number is in, and relative size compared to surrounding numbers). An important milestone in learning to use counting to represent quantity is learning the cardinality principle, which is the understanding that the last number word used when counting represents the total number of items in a set (Sarnecka, 2021). Once children reach some understanding of the cardinality principle, they can more accurately compare numbers (for example, saying that 8 is larger in quantity than 5; Clements and Sarma, 2021; Merkley and Ansari, 2016). Research shows that these milestones are reached earlier when tools and time are more frequently allocated to mathematics activities, pointing to the disparity between learning opportunities (e.g. Sarnecka et al., 2023; Silver & Libertus, 2022).

From 3 to 4 years, children are refining their spatial abilities. For example, making symmetrical patterns, comparing shapes, and responding to and using spatial language and gestures (Gifford et al., 2022; Farran et al., 2025). Children's spatial abilities can be trained at this age, leading to improved spatial abilities. Whilst spatial abilities are associated with mathematics performance at this age (Gilligan-Lee et al. 2023), transfer of spatial training to mathematics is not universal (e.g. Bower et al., 2020). Children in this pre-school age are also developing patterning abilities, which are associated with mathematics (Rittle-Johnson et al., 2019).

From 5 to 6 years of age

Children tend to start formal school at 5-6 years of age. They also show foundations of order (ordinality), where they begin to understand that 1, 2, 3 is a correct increasing order and that 2, 4, 6 is also a correct increasing order, although not in consecutive order (Hutchison et al., 2022Merkley and Ansari, 2016). This concept is quite difficult for young children, although they begin to fully understand it at around 6 years old. It's crucial that children develop this ability, as this is what allows one to represent and manipulate large or complex numbers later on, such that one might know that one million is greater than π and π is less than the $\sqrt{100}$ (square-root of 100). Simultaneously, children are able to conduct simple addition operations such as those they might visualize and predict on their fingers (e.g. 2 + 3 = 5). Teaching children arithmetic strategies with their fingers can increase early addition and subtraction learning (Frey et al., 2024). Spatial visualization is a key development at around 5 years, i.e., the ability to use a mental blackboard to manipulate objects. Spatial visualization is important for many aspects of mathematics, but particularly important for novel mathematical problem solving (Mix, 2019). Children's spatial skills at 5 years are predictive of their mathematical competence at 7 years (Gilligan et al., 2017) and 8 years (Gunderson et al., 2012). Training spatial abilities is effective at this age, leading to gains in number comparison tasks (Hawes et al., 2017) and missing term arithmetic problems (Cheng and Mix, 2014).

At 6 years old, children also slowly begin to understand place value, as they begin to use double digits. For example, 24 consists of the decade value (2) and the unit value (4). From here, children slowly understand how larger numbers are operationalized and spoken (such as when saying twenty-four, rather than two and four, and later conducting carry operations (Thompson & Bramald, 2002)). At six years old they begin to understand that "24" might mean "20" and "4" rather than "2" and "4", and at seven years old they conceptualize place value and the meaning of tens and units (Thomson & Bramald, 2002). At this stage, children also consolidate addition and subtraction. Merkley and Ansari (2016) show the gradual conceptual understanding young children build between 2 and 6 years, with stages differing based on number use at home, in school and SES, as SES is largely related to how often the child is exposed to numbers. Sense of scale develops from a reliance on relative positions to an understanding of proportions and relative distances (Gilligan et al., 20198), skills that are important for representing number lines and for proportional reasoning.

From 7 to 10 years of age

During this stage, children are also developing their spatial understanding of symmetry, progressing from reflecting patterns over a horizontal line, to reflecting over a diagonal line (Bornstein & Stiles-Davis, 1984), skills important not just for geometry, but also for understanding of equivalence (Lowrie & Logan, 2023). Evidence for effective spatial training at this age is broad, with spatial training that uses concrete materials showing larger effects than paper based or digital training (Gilligan et al., 2023; Hawes et al., 2022).

Spatially, shape composition and decomposition now involve the ability to predict two-dimensional nets from three-dimensional objects and vice versa and predicting the shape of cross-sections of shapes (Lowrie & Logan, 2023), to visualise, predict and draw from different perspectives (e.g. an object from above) (Mulligan et al., 2020), and to use angle, perimeter and area in the context of shape properties (Mulligan et al., 2020).

Beyond the age of 7, children's mathematical learning becomes increasingly dependent on what is required of them by their culture. Studies of this tend to focus on school-based learning, though other cultural practices are also important: for example, child street vendors develop arithmetical strategies that may be quite different from those typically used in school (see studies in Brazil by Carraher, Carraher & Schliemann (1985) in Brazil and by Saxe (1985, 1990, 2012) in Papua New Guinea).

School mathematics curricula vary in significant ways in different countries and regions, but there are common features typical of curricula for the 7 to 11 age range: place value and arithmetical fluency with increasingly large numbers; handling fractions and decimals; usually measurement, early geometry and pre-algebra/early algebra. Despite the expectations implied by curricula, it must be remembered that individual differences in arithmetic are very large, and that they are extremely marked by the end of primary school. For example, typical British class of eleven-year-olds is likely to contain the equivalent of a seven-year range in arithmetical ability (Askew, Brown, Rhodes et al, 2002; Cockcroft, 1982). While earlier-developing abilities such as subitizing, small number comparison and the cardinal word principle are essentially universal in non-dyscalculic adults, the abilities that are taught and expected to develop in 7-to 11-year-olds are more variable, even in adults. For example, many adults experience difficulty with fractions and decimals (Grossmann, 1983; Putt, 1995; Ryan & Williams, 2007; Siegler & Lortie-Forgues, 2015; Stacey, Helme, Steinle et al, 2001).

While people sometimes refer to arithmetic as though it were a single entity, there are several aspects of arithmetical performance, and arithmetical performance cannot be reduced to any one of these. These include memory for arithmetical facts; arithmetical procedural knowledge; arithmetical estimation; word problem solving hand derived fact strategy use (using known arithmetical facts, combined with knowledge of and reasoning about arithmetical properties such as commutativity and associativity, to work out unknown arithmetical facts). There are considerable individual differences in all these abilities, and dissociations and discrepancies can be found between the different abilities: for example, Dowker (1998, 2009, 2019) found that exact calculation, derived fact strategy use and estimation can all dissociate in primary school children. There are correlations between these components, and it is likely that each contributes to the development of the others, but there is no evidence as yet for any 'magic bullet' or specific component that. If taught, will reliably lead to good overall performance. Gilmore (2023, p. 1965) reviews recent evidence and concludes that 'individual differences in mathematical achievement arise out of a complex interaction of multiple cognitive and non-cognitive skills influenced by learning experiences. Consequently, pedagogy should not focus on some components … at the cost of others.'

As well as numerical abilities, domain-general cognitive abilities such as verbal abilities (Guez et al. 2023; Jordan et al., 2010), spatial abilities (Guez et al., 2023; Gilligan et al., 2019; McDougal et al., 2023), attention (Lefevre et al., 2013), working memory (Cragg et al., 2017; Simmons et al., 2012; Zhang et al., 2023), and inhibition of inappropriate or irrelevant responses (Clayton & Gilmore, 2015; Gilmore et al., 2013) all play an important role in the development of arithmetic. Attitudes and emotions, such as mathematics anxiety, are also related to mathematical performance, with most studies suggesting a bidirectional relationship between anxiety and performance (Cipora et al., 2022; Dowker et al., 2016). Thus, avoiding or ameliorating mathematics anxiety is likely to lead to better mathematical performance, and preventing or ameliorating mathematical difficulties is likely to lead to reductions in mathematics anxiety.

Although much of the existing research regarding this age group involves the development of numeracy, there are other important aspects of mathematics such as geometry, measurement and early algebra. Much more research is needed on the factors associated with performance in these areas.

Factors which facilitate or impede mathematical development and achievement

Spatial reasoning

Spatial abilities include the ability to understand the properties of objects such as their size and shape and their relationships to one another, as well as the ability to mentally visualise and manipulate objects in the mind's eye. Extensive literature has documented the robust finding that spatial abilities are positively associated with STEM subjects (Wai et al, 2009), whilst a meta-analysis of the spatial-mathematics relationship demonstrated a strong and consistent relationship between spatial ability and mathematics regardless of gender or age (Atit et al., 2022).

The association between spatial ability and mathematics has been attributed to four main reasons. First, there is evidence of shared neural activation for spatial and mathematical abilities (Hawes et al., 2019). Second, visualisation, the use of a mental blackboard, is a key skill to support mathematical problem solving, particularly of novel problems (Hawes et al., 2023; Mix, 2019). Third, numbers are typically represented spatially to convey mathematical meaning, such as the use of number lines, graphs and sketches (Mix, 2019). Finally, and perhaps most intuitive, mathematics is inherently spatial with subdomains such as geometry and measurement using mathematical concepts in space.

Crucially, spatial abilities can be trained, and spatial training transfers to improvement in STEM skills (meta-analyses: Uttal et al., 2013; Yang et al., 2020). Furthermore, Hawes et al.'s (2022) meta-analysis of transfer effects of spatial training to mathematics demonstrated consistent positive effects of spatial training. The effect size for mathematics improvement in children of the age range reviewed here were equivalent to 6 months of progress in mathematics. Furthermore, spatial training in the form of a 'spatialised curriculum' (e.g., replacing geometry curricula with spatial training on mental rotation, spatial visualisation, spatial orientation) demonstrate that pedagogical approaches to spatial training which involve professional development for practitioners are more effective for mathematics improvement than training isolated spatial abilities (Lowrie et al., 2017; Lowrie & Logan, 2023).

Use of support tools

There is general agreement that the use of manipulatives can support the mathematics understanding of pupils of all ages (Education Endowment Foundation, 2017). Manipulatives are any physical objects which are used with the intent of aiding mathematics learning, including mathematically structured ones such as Cuisenaire rods and Dienes blocks. Understanding can be defined in terms of mentally linking representations in different modes, including kinaesthetically, visually, verbally and emotionally, and of different levels of abstraction. Being multimodal, manipulatives therefore help build stronger memory networks. They can show transformations, operations and actions, including reversibility, unlike static images (Griffiths et al. 2017). However, there are caveats: teachers and pupils need to be clear about the links between the manipulatives and the ideas they represent, and to develop related images and symbols. For instance, children should be taught to visualise manipulatives and represent the mathematical relationships involved graphically, verbally and symbolically, so that they do not become reliant on them. The concreteness fading technique can help children learn the meaning of abstract symbols (Fyfe et al., 2015). This approach involves using manipulatives (i.e., physical objects) to demonstrate concrete representations of numerical quantity and relations, and gradually moving to visual representations, then ultimately replacing them with symbols. For example, the addition problem two plus three could first be modelled by using physical blocks, then represented with a picture of two and three squares, and ultimately represented as the abstract 2 + 3 = 5. This approach helps children develop procedural skills (i.e., knowing how) and conceptual understanding (i.e., knowing why) of arithmetic over the first few years of school. A recent study found that teachers, researchers, and parents tend to favour manipulatives with concrete features as students may find them more engaging (Foulkes et al., 2023), whilst spatial training studies that use concrete manipulatives were maximally effective for mathematics improvement relative to digital or paper-based spatial training (Hawes et al., 2022; Gilligan-Lee et al., 2023).

Mathematics anxiety

Mathematics anxiety (MA) is the strong negative emotions when taking part in mathematics related activities, such as doing homework, paying a bill or being asked about basic mental math computations (Hembre, 1990; Cipora et al., 2019; 2022). It poses a serious issue, and the latest research shows bidirectional effects between anxiety, on one side, and lack of proficiency with main procedures, namely arithmetic operations, on the other side, although this has been attributed to the most basic of numerical recognition tasks (Pizzie and Kraemer, 2017). Maths anxiety is distinct from general anxiety (Malanchini et al., 2017). Indeed, MA is separable from generalized anxiety, test anxiety and other math related disorders such as dyscalculia. MA results in compromised executive, for example lowered working memory, and can be exacerbated by poor executive, for example inhibitory control. This is because the anxiety component results in a rumination process (continued focused thoughts on fear and internal auditory rehearsal of fear, such as fear of failure or fear or reprimanding of the failure or difficulty) lack of ability to take in, processing and remember information, and the inability to inhibit rumination all result in obstruction of the procedural process of mathematics. MA is speculated to be caused by many factors, most of which may be due to social demands and limited educator training (Dowker et al., 2016). For example, studies found that educators who experience MA experience it on two different factors, first a personal one, such as paying a bill, and another as an educator where they don't feel they obtained enough training in mathematics specifically and so are anxious about teaching the math (Maloney et al., 2015; Scaeffer et al., 2020). It's shown that MA is often transmitted from educators, parents or peers where math is considered to be too difficult a subject.

In almost all countries studied so far, there is a negative relationship between mathematics anxiety and mathematical performance (Dulaney, Herts, Borgonovi, & Beilock, 2017; Lau, Hawes, Tremblay & Ansarim 2022). However, there is not the same consistent relationship between a country's overall mathematics achievement level, and the average level of mathematics anxiety among students in that country (Dulaney et al., 2017; Lee, 2009). Students in high achieving East Asian countries such as Japan and Korea tend to express high levels of mathematics anxiety, while those in high achieving European countries such as the Netherlands tend to express low levels of mathematics anxiety

There can be two essentially opposite errors in interpreting mathematics anxiety. One is to assume that mathematics anxiety is usually a symptom of mathematical learning difficulties. In fact, though mathematics anxiety is statistically negatively associated with mathematical attainment, high mathematics anxiety cannot be equated with dyscalculia, and it is quite possible to have either of these without the other (Devine, Hill, Carey & Szűcs, 2018). The other error is to assume that mathematics anxiety is almost universal, and that, unless one is unusually mathematically gifted, mathematics is intrinsically frightening. In fact, only a minority of people, if rather too large a minority, seem to suffer from disabling levels of mathematics anxiety.

Although mathematics anxiety is an important problem, it is not the only important aspect of attitudes and emotions toward mathematics. Self-rating in mathematics is usually found to be correlated with mathematical performance (Pinxten, Marsh, DeFraine, Van den Noortgate, & Van Damme, 2014). This may be because confidence improves performance, or because experience of success or failure affects self-rating, or most likely both. Some studies suggest that especially in primary school children, self-rating correlates more strongly with mathematical performance than anxiety does (Dowker, Bennett & Smith, 2012; Krinzinger, Kaufmann & Willmes, 2009; Wood, Pinheiro-Chagas, Júlio-Costa et al., 2012). At all ages, self-rating seems to mediate the relationship between anxiety and performance (Pinxten et al., 2014; Van der Beek, Van der Ven, Kroesbergen, & Leseman, 2017). A closely related construct is self-efficacy, which involves individuals' assessment not just of their current performance, but of their ability to learn new material and solve new problems. This has also been found to predict mathematics achievement (Özcan. & Eren Gümü, 2019; Pajares & Miller, 1994.

In contrast, positive attitudes to mathematics are related to mathematics attainment and do not just involve a lack of mathematics anxiety or other negative attitudes. Some individuals strongly enjoy mathematics. Van der Beek et al. (2017) found a positive correlation between mathematics achievement and mathematics enjoyment. Pinxten et al. (2014) found that mathematics enjoyment was a positive predictor of later mathematics achievement.

Insights for improving mathematics curricula, instruction, assessment and teacher education

[To be completed after the consultation workshop with contributions from participants.]

The science of social-emotional learning

What are the challenges for policy-makers?

Social-emotional learning (SEL) is a term that encompasses a large dynamic list of what is commonly referred to as non-cognitive and humancentric skills, attributes and competencies which are necessary for living successfully in the present and planning for future eras (Bryan, 2022). SEL is commonly considered a process by which individuals develop awareness and skills to manage emotions, set goals, establish relationships and make relationship decisions that support success in school and life more generally. Social-emotional competencies include self-awareness, self-management, social awareness, relationship skills and responsible decision-making. Fundamental elements of intercultural competencies, such as being able to clearly communicate with others from a different culture as children often have to do in school settings. Skills that link well with SEL are listening, respect, curiosity, openness, self- and other-awareness, perspective taking, reflection, empathy, compassion, relationship building and communication (Deardorf, 2020).

The importance of implementing social-emotional learning in a systemic manner in educational programs cannot be overstated yet policy makers experience challenges in doing this. Some reasons for the challenges are that assessing and implementing SEL at a system level is complex and multifaceted, often involving a need to convince multiple stakeholders (parents, teachers, administrators, among others) of its necessity in school curriculum support. Education policies are often not designed to include the explicit teaching and assessment of SEL in academic subjects despite growing research that shows the importance of effective SEL programs for the education system. Additionally, SEL programs and practices often vary across cultures (Gedikoglu, 2021), making an objective performance-based assessment challenging to design. Use of technology to simulate environments for SEL learning is often required but it brings in the problem of inconsistent access to devices across <<<geographical regions and the needed time investment, to use technological devices, on the part of educators. For teachers to effectively support their learners to develop SEL skills, they need to access professional development programs that make them improve their SEL skills and make them ready to teach children related skills (Feinstein, 2015). Additionally, SEL promotes collaborative learning, yet most education systems encourage competition despite research findings that has shown that collaborative learning coupled with greater emphasis on supporting learner voice and agency builds peaceful and sustainable communities (UNESCO MGIEP).

Assessing and implementing social-emotional learning programs in a systematic and structured manner is crucial for providing policymakers and practitioners with evidence about SEL benefits and to inform decision-making processes and strategic actions using an evidence-based approach. With reliable data on students' social and emotional skills, practitioners and policymakers can identify areas needing improvement and make informed adjustments to their respective field of action. This approach offers insights into the effectiveness of current educational strategies and interventions, allowing both policymakers and practitioners to determine whether their initiatives are achieving the desired outcomes (Abrahams et al, 2019). Ultimately, an evidence-based approach ensures that resources are allocated efficiently and that the strategies employed are grounded in empirical data, enhancing the overall educational experience for students.

SEL frameworks with real-world contexts

A review of the literature on SEL reveals that international experiences predominantly focus on skills such as emotional regulation, autonomy, collaboration, complex problem-solving and innovation (Osher et al, 2016; John & De Fruyt, 2015; Primi et al, 2021, Gotlieb et al, 2022; add refs from other chapters). Prominent frameworks, such as the Collaborative for Academic, Social, and Emotional Learning (CASEL; Osher et al, 2016), the Five Major Factors (John & De Fruyt,2015) and the UNESCO framework (Chatterjee Singh and Duraiappah, 2020), are widely recognized for organizing SEL into broader domains and delineating specific abilities within these areas.

CASEL has an important historical role in the SEL literature because it is a practice-oriented framework. It was organized considering efforts from educators, practitioners and researchers in the human development, educational and social psychology fields (Osher et al, 2016). In this framework, the domains are conceptualized as skills about to recognize and understand one's own emotions (self-awareness), to control impulses and maintaining perseverance in the face of challenges (self-management), to collaborate and develop relationships (relationship skills), to demonstrate empathy towards others (social awareness) and to reflect on ethical issues and make responsible choices (responsible decision making).

Similarly, in the last decade, OECD also started collaborative research on socioemotional skills in various cities of the world (De Fruyt et al., 2015; John & De Fruyt, 2015; Kankaraš & Suárez Álvarez, 2019). John and De Fruyt (2015) reviewed the literature and concluded that there was an emerging consensus that the multiplicity of socioemotional skills could be conceptually grouped into five major skill categories about how to interact with others (engagement with others), how to demonstrate empathy and build strong bonds with others (collaboration), how to plan and to persist to achieve one's own goals (task performance), how to regulate one's own emotions (emotion regulation), and how to exercise a creative and curious mindset (openness).

In line with global education goals, the UNESCO framework for SEL is based on the holistic development of learners, preparing them to contribute to sustainable, peaceful, and inclusive societies (Chatterjee Singh and Duraiappah, 2020; Gotlieb et al., 2022). This model is aligned with the United Nations' Sustainable Development Goals (SDGs), emphasizing the development of social, emotional, cognitive, and cultural competencies necessary for addressing global challenges. SEL in this framework is seen as a tool for fostering empathy, resilience, and ethical responsibility, encouraging learners to engage in meaningful social participation and respect for diversity, contributing to a more equitable world.

In all frameworks, the skills represent essential competencies to be cultivated throughout childhood and adolescence, particularly within educational settings. Such organization supports SEL development considering that broader domains may present more general concepts that might not be as tangible for practitioners, while specific skills within domains can help to operationalize more specific behaviours that need to be developed in interventions.

Development of social-emotional skills

Children are naturally born with the capacity to develop the core competencies of SEL, such as self-awareness, self-management, social awareness, relationship skills and responsible decision-making. Children's development is marked by both the changing importance of developmental tasks for their age range and related SEL expectations and abilities (Collaborative for Academic, Social and Emotional Learning, 2015). Successful achievement of developmental tasks predicts success in later higher order tasks and failure in these developmental tasks, likewise, predicts difficulty in achieving later age range tasks.

Infants and toddlers (0-2 years)

Infants typically show a strong inclination towards other people and find social interaction highly rewarding (Thiele et al.). They also have basic self-regulation abilities that largely involve self-soothing behaviours such as thumb sucking. At this age SEL development begins through caregiver child bonding. This bonding allows the caregiver to respond to the child's needs in a timely manner that enable the child to develop basic trust and confidence. Trust and confidence are essential for healthy attachments at this age and later on in life (Duschinsky, 2018). At this age babies learn to communicate through emotions, likely a precursor to mastering emotional regulation and impulse control skills (Malik & Marwaha, 2024).

Pre-primary school children (2-5 years)

This age is marked by a rapid development in children's language skills (NIDCD), and the emergence of crucial cognitive skills like Theory of Mind (ToM – the ability to understand others' perspectives) and executive functions (Best & Miller; Brüne & Brüne-Cohrs). Consequently, children become better able to interact with peers while managing their own emotional arousal, start to show prosocial behaviours like helping others (Song et al.), and being to follow social rules like collaboration and turn-taking (Kachel et al.). However, these skills are still immature and highly malleable at this stage, and children often rely on adults/older children to help them navigate the social world and manage their own emotional states (Lincoln et al.). At this age, it is crucial for adults to model good self-regulation strategies and support children to develop more autonomy in regulating their own emotions and behaviour (Lincoln et al.).

Early primary school aged children (6-10 years)

Social understanding continues to mature at this stage and children undergo the emergence of recursive ToM and the ability to interpret others' mental states to explain their behaviour (Im-Bolter et al.). Children also start to become more proactive and autonomous in their own self-regulation (de Veld et al.). As such, these children are at a point where they can form dyadic friendships and stable peer relationships, control their own impulses, express appropriate emotions for various situations, and exhibit flexibility in solving relatively complex social difficulties (Denham et al, 2009; Nagaoka, 2015).

As other capacities and natural potentials, SEL develops optimally through the relationships children have with others. Warm and respectful relationships promote continued growth and possible maturity of SEL competencies in children. Specific activities that promote SEL in home and school settings include play that help children understand different emotions and teaching that uses evidence-based strategies to teach, model and reinforce positive behaviour such as empathy, respect for diversity and other detailed in the Global citizenship Socio-emotional domain of learning (UNESCO, 2015).

The contribution of social-emotional skills to educational outcomes

The aforementioned key components that comprise social-emotional skills each have a unique and important role in supporting children's learning and their performance in the classroom. When children enter formal education, they are required, likely for the first time in their lives, to adapt to a highly structured environment that places demand on their attention in addition to their ability to cooperate and follow instructions (Lenes et al.). Thus, to fully benefit from school learning opportunities, children are required to draw on their ability to exercise self-control, self-regulate their attention and emotions, and integrate into the classroom's social environment. A child's ability to regulate their attention and behaviour is instrumental for them to be able to attend to important information, stay on task, filter out distractions, and remember the information that has been shared (Savina). Consequently, self-regulation has important cascading impacts on educational outcomes. For example, a recent meta-analysis (Robson et al.) reported that greater self-regulation at pre-primary age is associated with classroom engagement and social competency during the early primary school years, while self-regulation during primary school is associated with higher literacy and maths performance in early adolescence. Importantly, self-regulation has also been found to serve as a protective factor for academic achievement for children from marginalised or low-income backgrounds (Li-Grining et al.). As self-regulation is highly interlinked with emotional regulation, being more adept at managing one's emotional reactions and their manifestation is also related to reduced behavioural problems and good relationships with peers and teachers (Montroy et al.).

Social skills also play an important role in supporting children's academic outcomes. Children that are more socially adept, even as early as the pre-primary school years, tend to show better adjustment at school, and fewer difficulties related to emotional wellbeing (Frogner et al.). The ability to cooperate and communicate effectively helps children listen, follow instructions and take turns in the classroom (Pelco and Reed-Victor). In turn, these skills help them focus on and absorb academic content. More optimal peer and teacher relationships also support children's general psychological wellbeing. There is evidence that children who are well integrated in the school's social sphere, and have support from peers and teachers, experience higher levels of motivation, and confidence, allowing them to exhibit their optimal performance (Wentzel).

While the vast proportion of research examining the associations between SEL and academic outcomes is derived from the Global North, namely North America and Western Europe, emerging evidence from broader geographical contexts suggests that these links are relevant for educational systems worldwide. For example, Li et al. (2018) review two decades' worth of research which highlights the importance of self-regulation on Chinese children's academic performance, particularly in maths and the sciences. Similarly, in South America, Brazil and Chile have been identified as two countries that have made the greatest commitment to including SEL into their educational curricula, and reports suggest that SEL interventions implemented into school settings show promise in improving social-emotional competencies of students and their academic outcomes (Fernández-Martín et al.). Research in Tanzania and South Africa also suggests that parents and teachers place emphasis on SEL related constructs, such as children's emotional wellbeing and prosociality, as it can have a positive effect on desired school outcomes (Jukes et al., 2021). Importantly, it has been found that SEL curricula may be a particularly powerful tool for supporting children in areas exposed to crisis, conflict, or structural violence (Newaz). Landmark work by Aber et al (Aber, Tubbs Dolan, et al.; Aber, Torrente, et al.) in the Democratic Republic of Congo, Lebanon and Nigeria provide further evidence of this. In such settings, the ability to hone skills related to resilience and self-awareness can help young people and communities overcome adversity (Newaz).

For SEL to truly have benefits in typical and extreme settings (Aber, Tubbs Dolan, et al.) and around the world more generally (Newaz), much greater commitment is needed from policy makers to implement support mechanisms to develop this ability in children. There is much work to be done in creating culturally appropriate SEL frameworks, identifying appropriate measures, and supporting research-practice partnerships (Aber, Tubbs Dolan, et al.).

Support for leaners with special needs and difficulties

Individual differences in skills related to SEL are commonly observed among children of all ages. A number of factors, including mental health and environmental adversity (e.g., low socioeconomic status, adversity in the home/family) can have a negative impact on the development of executive functions, behavioural regulation, and emotional wellbeing (Finch and Obradovic; Porche et al.). Mental health difficulties are becoming increasingly prevalent among children, especially in the aftermath of the Covid-19 pandemic (Benton et al.; Hossain et al.). Issues such as depression, anxiety, sleep difficulties, and even suicidal behaviours are increasing in children as young as primary school age (Hossain et al.). Mental health difficulties, in turn, result in poorer school attendance and engagement, more disruptive behaviour, and poorer academic outcomes (Lawrence et al.; Porche et al.). SEL programs have demonstrated benefits for children's mental wellbeing and a reduction in externalising problems (Cook, Frye, et al.), as well as promise in benefitting students from a range of backgrounds to increase equity among diverse student groups (Lee et al.).

It is also crucial to support teachers in identifying and supporting students who might struggle with SEL. Student-teacher relationships are often bidirectional (Sameroff and Mackenzie; Zhang and Sun). Students who exhibit prosocial behaviours (such as helping others or sharing) and heightened engagement are likely to elicit positive responses from their teachers, thereby further promoting their positive social behaviours. On the other hand, children who struggle to regulate their behaviour, have poorer social skills, or cause disruption may prompt negative or harsh reactions from teachers, thus causing student-teacher conflict, and enhancing their difficulties adjusting (Skalická et al.). Increased conflict with a teacher reduces a child's interest in the academic material, as well as their motivation and confidence to learn, thus having negative consequences on their academic performance. This presents an important challenge for teachers, as they are expected to foster positive relationships with students that enhance their feeling of trust and belonging, while also grappling with a classroom of children with vastly diverse social, behavioural, and emotional skills and needs. This challenge is even greater for teachers in low-income and low-resource contexts that typically face working in larger classrooms but have reduced resources available to support student emotional and behavioural needs, and for managing their own stress levels.

Another issue of vital importance is for educators to be able to identify and adequately support students, such as those who are neurodiverse or have specific learning disabilities, who may need additional SEL support or for whom standard SEL curricula are insufficient without additional tailored support plans. Neurodiversity is a framework that is used to conceptualise the wide range of human neural and cognitive functioning profiles (Botha et al.). The neurodiversity framework has become crucial for encapsulating conditions such as autism spectrum disorder (ASD), attention deficit hyperactivity disorder (ADHD), and specific learning disabilities. Due to increased recognition and a drive for equity, the number of neurodiverse students in mainstream classrooms has increased substantially in recent years. Consequently, educators are increasingly required to tailor their approaches to be mindful of the strengths and difficulties of neurodiverse students. Relevant to SEL, ASD and ADHD both feature difficulties with executive functions, self-regulation, and attention (Karalunas et al.). Furthermore, a core characteristic of ASD is difficulty with social interaction and understanding the intentions and emotions of others (Tager-Flusberg). Autistic children also have sensory sensitivities that can make the classroom environment overstimulating and overwhelming (Fernández-Andrés et al.). Finally, neurodiverse children often experience mental health difficulties, particularly anxiety and depression, which have a significant impact on their adjustment to school life (Mitchison and Njardvik; Kim et al.).

These difficulties can have negative consequences for neurodiverse students' school adjustment, academic performance, and general wellbeing. Both ADHD and traits of ASD are related to externalising behaviours, poorer peer and teacher relationships, more negative attitudes towards school, absenteeism, and increased risk of bullying (Montes and Halterman; Chiang and Gau; Marsh et al.; Berchiatti et al.). Similarly, individuals with learning disabilities are more likely to experience adverse life events and social disadvantage, are at heightened risk for bullying, and may have reduced coping skills, which all increase the likelihood of developing mental health difficulties (Chatzitheochari et al.; Emerson and Hatton).

Reports of the effectiveness of SEL for neurodiverse children are less clear. For example, many SEL programs fail to include neurodiverse children or to assess their effectiveness in subgroups of children who are neurodiverse or have learning disabilities (Daley and McCarthy). Moreover, teachers report feeling underequipped to support students with disabilities and believe that this role falls within the permit of their special education needs colleagues instead (Pavri). It has also been highlighted that many SEL interventions for neurodiverse children are overly focused on modifying observable behaviours but pay less attention to the underlying cognitive and emotional processes, thereby undermining their long-term effectiveness (Cook, Gresham, et al.; Wendt et al.; Daley and McCarthy). A further issue with many interventions is the sole focus of ameliorating deficits, without attempts to leverage the multitude of strengths that neurodiverse children possess (Cherewick and Matergia). Neurodiversity affirming approaches, which build on strengths of neurodiverse children can serve to increase confidence and reduce some of the biases these children face, thereby improving their wellbeing (Cherewick and Matergia).

Support for social-emotional development among neurodiverse children and those with specific learning disabilities

There is a pressing need to invest in the development of SEL programs that are inclusive of, or aimed at, neurodiverse children and those with specific learning disabilities. Firstly, teacher training and the provision of materials and resources is required to support teachers to build on their understanding of what neurodiversity is and the cognitive and emotional mechanisms that underlie the observable difficulties neurodiverse children manifest. Increasing teacher knowledge can increase their confidence in working with, and supporting, neurodiverse children and those with specific learning disabilities. Investment into research-practice partnerships is essential for the development of neurodiversity informed approaches to SEL. In particular, it is important for programs to be able to target the underlying cognitive and emotional mechanisms of such groups, and to tailor their approaches to the specific needs of neurodiverse children. The final, and most crucial, aspect is the adoption of neurodiversity affirming approaches, which focus on leveraging the strengths of neurodiverse children to build their socioemotional and self-regulatory capacities.

Insights for improving curricula, instruction, assessment and teacher education for social-emotional learning

[To be completed after the consultation workshop with contributions from participants.]

The science of learning with digital technologies

What are the challenges for policy-makers?

While digital technology has increased access to education for millions, it doesn't guarantee better learning outcomes. Simple, well-matched tools, like DVDs in rural Chinese schools, have boosted learning (Bianchi, Lu, & Song, 2022), whereas inappropriate technology use, such as smartphones, can hinder academic performance (Lin et al., 2021). Excessive use of digital technology has also been linked to lower outcomes in OECD countries (Gorjón & Osés, 2023). These mixed results underscore the urgent need for more scientific, contextually-diverse research to guide policymakers on effective, evidence-based integration of technology. The science of learning can significantly guide these efforts.

The science of learning offers policymakers evidence-based insights on how to optimize the role of technology in education. The science of learning can inform the design, implementation, use and assessment of efficacy of educational technology in various ways. It can also guide the development of frameworks for evaluating the learning benefits of technology, notably through efficacy and effectiveness research studies (see Kucirkova, Lindroos & Vackova, 2024). Establishing guiding principles and benchmarks to evaluate what works in education technology requires scientific consensus and the integration of diverse evaluation paradigms and approaches. This consolidation is ideally informed by evidence hierarchies, allowing policymakers to base their decisions on the strongest available research. Such benchmarks can then guide the selection of specific tools, facilitate their recommended use across school districts, and support their inclusion in teacher professional development. This approach ensures that evaluations are not only scientifically rigorous but also practical for implementation in real-world educational contexts, supporting educators with tools that are both effective and aligned with proven impact.

In addition to the key concepts already introduced at the beginning of the report, such as working memory and attention, next are some concepts that are helpful for understanding the potential role of digital technology in learning and education.

Key concepts with relevance to learning with digital technologies

Learner engagement and gamification. Gamification is a technique used by technology designers to increase users' engagement. Gamifications tends to be more effective when tailored to individual learners' needs, improving performance and motivation (Hassan et al., 2019).

Rewards. Educational technologies often use motivational rewards, such as points or progress indicators, to enhance engagement (Huynh et al., 2018; Aibar-Almazan et al., 2024). Neuroimaging studies have linked such "gamified" elements to increased striatum activity and learning (Howard-Jones et al., 2016). Educational technology can trigger the release of dopamine through novelty features (Schomaker & Meeter, 2015), providing choice (Murty, DuBrow, & Davachi, 2015), and enabling social interactions (Schilbach et al., 2010).

Multisensory and multimodal learning. Multisensory educational technology can help students connect different representations of concepts, enhancing understanding. For example, digital learning tools can help children map orthographic and phonemic codes and have shown effective multimodal learning (Ahmed et al., 2020).

Congruent learning and congruency effects. Educational technology can facilitate connecting new information with existing knowledge by prompting learners to reactivate relevant prior knowledge, and can aid children, who have less prior knowledge, to make these connections (Brod & Shing, 2022).

Consolidation of learning. Educational technologies can support the consolidation process by providing opportunities for practice. However, excessive technology use, such as playing video games before bed, can disrupt sleep and negatively impact learning and memory (Dworak et al., 2007; Bartel et al., 2016; Almuaigel et al., 2021).

Spacing effects, repetition and adaptive learning. Adaptive educational technology can enhance practice and retrieval processes by personalizing content and testing based on the learner's needs (Muralidharan, Singh, & Ganimian, 2019).

Mobile learning. Learning across multiple contexts, through social and content interactions, using personal electronic devices.

Artificial Intelligence. Artificial Intelligence (AI) aims to enable computers to perform tasks associated with human minds, learning, and problem solving (Baker et al., 2019). AI in education is a field that combines computer science, statistics, and education. AI has been used to assist teaching, learning, pedagogical innovations, educational data mining, and learning analytics (Chen et al., 2020).

Open Education Resources. Learning, teaching, and research materials in any format and medium that reside in the public domain or are under copyright that have been released under an open license that permit no-cost access, reuse, repurpose, adaptation, and redistribution by others.

Open Education Practices. Practices that support the (re)use and production of Open Educational Resources through institutional policies.

Augmented reality. The technology that overlays virtual objects in the real-world.

Game-based learning. Learning through games rather than learning to play (Wu et al., 2012).

Impacts of individual difference on the use of technologies in learning

Individual differences that arise during development can help explain why different broad categories of digital technology vary in educational effectiveness according to educational level. Often, technology is indiscriminately provided without accounting for individual differences in learning, leading to varied outcomes that only become evident after assessment. Understanding neurodiversity is crucial for creating more equitable, inclusive and effective learning environments. We recall the earlier section on individual differences and neurodiversity, recognizing that there is considerable variability both among children and within contexts and that each learner brings unique cognitive, emotional, and social attributes that interact dynamically with their environment, resulting in diverse learning pathways (Duraiappah, et al, 2021). While learning with technology holds much promise, how can we ensure that technology in education addresses these individual differences to improve learning for all?

Table 1 collects and summarizes evidence from meta-analysis studies published in the literature on how technology in education might impact learning achievement differently in various age groups and educational levels.

Table 1. Effect of technologies on learning achievement based on educational level

Technology	Early childhood education	Primary education	Lower secondary education	Upper secondary education	Higher education
Mobile learning (Tlili et al., 2024)	Large	Large	Large	Large	Large
Artificial Intelligence (Zheng et al., 2023)	Not applicable	Small	Large		Large
OER and OEP (Tlili et al., 2023)	Not applicable		Small	Large	Large
Augmented Reality (Garzón & Acevedo, 2019)	Not applicable	Small	Small	Small	Large
Game-based Learning (Karakoç et al., 2022)	Huge	Huge	Huge	Huge	Huge
Griffith, S. F., Hagan, M. B., Heymann, P., Heflin, B. H., & Bagner, D. M. (2020). Apps as learning tools: a systematic review. Paediatrics, 145(1).	Large	-	-	-	-

Source: Authors.

Early childhood and primary education

As shown in Table 1, mobile learning and game-based learning have considerable effects on learning outcomes in early childhood education (0-6) and primary education (7-12). This can be attributed to the significant benefits that children derive from interactive and visual technologies, which enhance foundational skills by providing immediate feedback and engaging learning experiences (Quilez-Robres et al., 2021). Other studies show that explanatory feedback and programmatic levelling are key design features within educational apps for improving children's mathematical learning gains with this form of digitally-mediated instruction (Outhwaite et al., 2023).

In these early stages, children thrive on developing foundational skills and knowledge through concrete, hands-on experiences. Mobile devices offer interactive and smart features that innovate various teaching methods, thereby enhancing engagement and foundational skills for better learning performance (Tlili et al., 2024). Besides, studies show that mobile learning significantly enhances student involvement by providing greater flexibility and interactivity, which fosters a more personalized learning experience (Usman & Kusuma, 2020). These tools incorporating visual, auditory, and tactile stimuli have been shown to significantly enhance engagement and comprehension in young children. Multimodal and multisensory learning can cater to their developmental need for sensory engagement, symbolic understanding, and hands-on interaction. Such stimuli are particularly effective for young children where sensory-rich experiences can foster cognitive development by allowing children to explore, manipulate, and interact with their learning environment in ways that are aligned with their developmental capacities (Beschorner & Hutchison, 2013).

However, other research has found that the age and the language skills of the child also need to be considered when deciding if digital technologies are suitable. For example, Herodotou (2018) reports that children aged under 4 did not benefit as well from educational apps, compared to children over 4 years. Children with stronger language skills were more likely to understand the app content and instructions, and progress further through the educational app, than children with weaker language skills. This is likely due to the limited range of language (e.g., vocabulary used to explain task instructions) included in many apps. If children are unable to comprehend the app instructions, they are unable to effectively engage with the technology (Outhwaite et al., 2020).

In addition, children's social-emotional skills significantly impact how children interact with technological tools and benefit from them educationally. Game-based learning and mobile learning tools and activities tend to be designed to be collaborative, helping to fulfil the social-emotional needs of K-12 students and enhancing learning outcomes (Sung et al., 2015). These social-emotional benefits further support academic achievement by creating a positive and inclusive learning environments. Successfully completing levels and achieving goals in educational games also boosts children's confidence and self-efficacy (Li et al., 2024). However, it should be noted that children with low self-regulation may struggle to benefit fully from these tools without appropriate guidance and support.

In early childhood and primary education, the development of specific abilities such as literacy, numeracy, and motor skills are of paramount importance. Additionally, the enhancement of general cognitive capabilities, including memory, attention, problem-solving, and critical thinking, is crucial. Multimodal technologies, such as learning apps and games that allow for children's own creation of content with the support of adults and that are designed with safe and secure data processing, can support early childhood development (Kucirkova, 2014). Technologies that offer interactive and adaptive learning experiences can provide personalized learning paths, allowing children to progress at their own pace and experience an optimal level of challenge (Granic et al., 2014). These tools often incorporate gamified elements, and offer a rapid schedule of rewards, making learning more engaging and effective. For instance, apps that teach phonics and basic arithmetic through interactive games can help children grasp foundational concepts more quickly and enjoyably (Outhwaite, 2023), encouraging unsupervised repeated practice that leads to consolidation of new knowledge (Butterworth and Laurillard, 2010). urthermore, educational games typically require children to remember sequences or solve puzzles, which can improve their working memory and attention span while promoting cognitive growth (Kynigos and Yiannoutsou., 2018). High-quality educational maths apps can support children's attentional skills in a low-resourced context (Pitchford et al., 2019) and can help support the efficiency of maths instruction, so that other areas of the curriculum are not displaced (Outhwaite et al., 2019).

Therefore, it is helpful to start game-based during the teaching process of the young and maintain it in students' subsequent educational experiences (Karakoç et al., 2022), especially since younger learners (primary school) tend to achieve higher learning outcomes compared to older learners (secondary school) (Arztmann et al., 2023).

Secondary education

As shown in Table 1, similar to early childhood and primary education, mobile learning and game-based learning have significant effects on students' learning achievements. In contrast, Open Educational Resources (OER), Open Educational Practices (OEP), and emerging technologies such as AI and Augmented Reality (AR) are implemented in secondary education. According to (Garzón & Acevedo, 2019), AR has a greater impact on more mature students of higher education compared to younger students of primary or secondary education who will generally possess less executive function, including less working memory capacity. Issues such as the complexity of using the systems and multitasking can affect young users of AR applications (Akçayir & Akçayir, 2017; Garzón et al., 2019; Radu, 2014). However, AI, in particular, has a substantial impact on the learning achievements of both lower and upper secondary students, the application of AI technologies in junior and senior high school worked the best (Zheng et al., 2023).

Secondary school students are at a critical stage of cognitive development, characterized by an increasing ability to engage in abstract thinking, problem-solving, and critical analysis. During this period, students develop essential cognitive skills such as logical reasoning, metacognition, and the capacity to understand complex concepts (Zhang et al., 2024). The effectiveness of AI-assisted learning is influenced by two things: the students' confidence in using ICT and the positive experience in using AI applications (Chou et al., 2022). AI-powered adaptive learning systems provide personalized learning experiences by continuously analyzing student performance and adjusting instructional content accordingly (Holmes et al., 2019). This personalization ensures that each student receives the optimal level of challenge, promoting the engagement and practice required to achieve deeper understanding and retention of material. Additionally, AI tools like intelligent tutoring systems and virtual labs facilitate the development of higher-order cognitive skills by offering interactive and immersive learning experiences that encourage critical thinking and problem-solving (Zawacki-Richter et al., 2019). Secondary school students have the essential cognitive abilities to work with AI, and the features of AI can effectively address their developmental needs and significantly enhance their learning achievements.

During secondary school, students develop a deeper understanding of their own emotions, strengths, weaknesses, and values. Additionally, students also learn to develop strong relationship skills to communicate clearly, listen actively, cooperate with others, and resolve conflicts constructively in secondary school. AI-powered interactive platforms encourage collaborative learning, where students work together to solve problems and complete tasks, thereby improving their social awareness and relationship skills (Islam et al., 2024). AI can create safe, supportive, and inclusive learning environments by detecting and addressing emotional distress and providing tailored interventions (Sethi et al., 2020). This support enables students to develop resilience, enhancing their ability to adapt to stress and recover from challenges, while also fostering emotional intelligence by improving their capacity to recognize, understand, and manage emotions, which are crucial for their overall academic and personal success (Masten, 2014).

Higher education

As suggested in Table 1, technologies have a more significant impact on the learning achievements of higher education students compared to younger students. This may be because university students possess more advanced prior knowledge, cognitive development, intelligence, and social-emotional skills, enabling them to effectively utilize technologies for learning.

Nonetheless, OER and OEP have a more significant impact on the learning achievements of higher education students compared to younger students. Higher education students are engaged in advanced cognitive processes, including critical thinking, analytical reasoning, and problem-solving. OER and OEP provide rich, diverse, and up-to-date materials that facilitate deep cognitive engagement. The accessibility of high-quality resources supports students in conducting in-depth research, synthesizing information from multiple sources, and developing nuanced understandings of complex topics (Wiley & Hilton, 2018). Moreover, the flexibility of OER allows students to revisit and review content as needed, enhancing their ability to retain and apply knowledge effectively.

Thus, as indicated earlier, educational technologies are often lauded for their potential to offer "expert" instruction that exposes students to effective student-centred teaching practices at relatively low cost and high fidelity, offering many advantages such as self-pacing, immediate feedback, and increased motivation (Bower & Vlachopoulos, 2018; Mayer, 2010). Yet, systematic evidence indicates that the impact of technology on learning outcomes varies substantially, with some interventions being better than others, suggesting that technology used for instruction can have a positive influence on learning when carefully designed and well-implemented, (e.g., Tamim et al., 2011). Namely, tools that move instruction to more student-centred, dynamic and interactive strategies that provide cognitive support appear to produce the largest effects (e.g., Schmid et al., 2014). Optimal scaffolding to learning feature the design of high-quality software that tests students on key ideas, automatically places them in appropriate difficulty levels as a function of their performance and achieves consistency in scaffolding supports within and across programs (Wood et al., 2017).

A well-designed computer technology may alleviate the challenges that teachers face as they try to implement instruction. However, technology is a tool to support instruction rather than as a substitute for it. Hence, in addition to the design itself, it is important to bear in mind that this supportive role cannot be limited to a supplementary function where technology is merely added-on, by and large, minimizing teachers' agency in the instructional process or otherwise limiting teacher motivation to implement new pedagogical strategies. Therefore, it is imperative that teachers are adequately prepared and supported to make effective use of technology as part of their everyday instructional practice. This preparation includes ensuring teachers' active involvement in planning what kinds of technology to employ for specific learning goals, and how and when to best use it for achieving optimal pedagogical outcomes (Schmid et al., 2014). The preparation also includes fostering deliberate actions to provide highly structured, scaffolded teaching coupled with timely relevant feedback to students. However, ensuring high-quality teaching in every classroom remains a significant challenge, particularly in contexts where resources are sparse and skilled teachers are rare. For instance, research on pedagogy, curriculum, teaching practices and teacher education in LMICs indicates that teachers often heavily rely on undifferentiated knowledge transmission methods such as basic recall, rote learning, memorization, repetition, and recitation (e.g., Bold et al., 2017). Consequently, TPD has emerged as a crucial strategy to bolster their competencies and performance in class, elevate instructional quality, and ultimately improve educational outcomes and overall education.

Ensuring the learning benefits of digital technologies hinges on rigorous quality assessment, which should be informed by current scientific insights, conducted independently, and framed within a comprehensive evaluative structure. This approach is exemplified by the 5Es framework, developed by a research consortium under the Eduevidence.org initiative, which proposes a multifaceted lens to evaluate educational technologies. The framework systematically interrogates critical dimensions of digital learning quality through five central questions: Does it work? (efficacy), assessing evidence of impact on learning outcomes; Could it work? (effectiveness), evaluating potential scalability and adaptability across various educational contexts; Who does it work for? (equity), ensuring inclusivity and accessibility for diverse learner groups; How does it work? (ethics), examining ethical considerations, including data security and learner well-being; and How long does it work for? (environment), addressing sustainability and long-term value. Together, these criteria enable a robust, scientifically grounded review that holistically assesses educational technology's role in promoting learning, equity, and ethical standards across diverse educational settings.

The social-emotional development of higher education students is characterized by increased self-awareness, self-regulation, and interpersonal skills. OER and OEP contribute to this development by promoting collaborative learning environments and community engagement. Through OEP, students engage in peer learning, co-creation of content, and open discussions, which foster social awareness, empathy, and communication skills (Hodgkinson-Williams & Arinto, 2017). The collaborative nature of these practices helps students build strong relationships and work effectively in teams, enhancing their social-emotional skills. In addition, the use of OER and participation in OEP require students to navigate, evaluate, and integrate digital resources effectively. Students in higher education possess the essential ability to critically assess the credibility and relevance of digital information, synthesize diverse sources, and apply this knowledge to their academic work.

Adaptive technologies and personalized learning

To address the diverse needs of students, it is crucial to analyse how students learn and interact with each other and their environment, enabling personalized learning that enhances outcomes. This approach is known as learning analytics.

Learning analytics

Learning analytics (LA) has become a transformative tool in education, enabling the measurement, analysis, and reporting of data about learners to improve both learning experiences and environments (Long et al., 2011). While the rise in educational data and quantitative metrics has often conflicted with traditional teaching approaches, learning analytics offers educators new insights into student performance and supports personalized learning pathways (Clow, 2013; Siemens & Long, 2011).

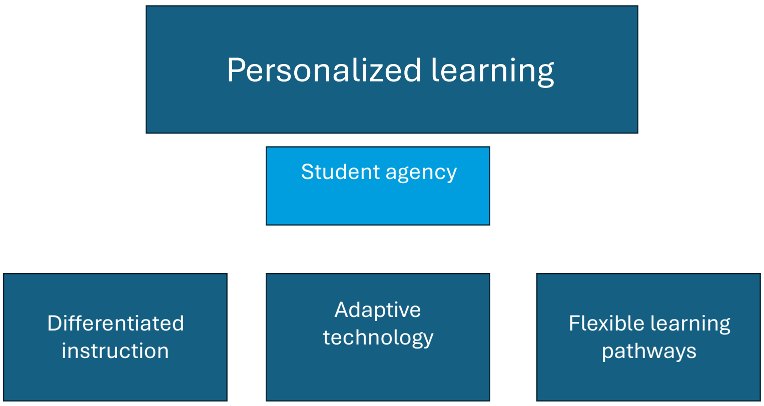
The process of learning analytics typically involves several stages. Initially, data is gathered from multiple sources, such as Learning Management Systems (LMS), student information systems, social media, and other digital platforms used in education. This data can include student demographics, engagement metrics, assessment results, and interaction data, among others. The next step involves cleaning and processing the data to ensure its quality and relevance. Advanced analytical techniques, such as predictive modelling, clustering, and network analysis, are then applied to identify patterns and relationships within the data. These insights can be used to predict student performance, identify at-risk students, and recommend interventions to improve learning outcomes (Gašević, Dawson, & Siemens, 2015).

A recent literature review (Zhang et al., 2023) shows that learning analytics in formative assessment improves digital education by providing timely, actionable feedback, generating student insights, creating learner profiles, enabling peer assessments, tracking progress, identifying learning strategies, and offering real-time corrections. However, implementing learning analytics faces challenges, including ethical concerns about privacy, data security, and potential biases (Pardo & Siemens, 2014). Issues around transparency, accountability, and student involvement impeder LA's successful integration into educational practices (Slade & Prinsloo, 2013).

Personalized learning

As educational systems globally move away from the outdated "one-size-fits-all" model, personalized learning (PL) is emerging as a solution to address diverse learner needs and backgrounds (Gunawardena et al., 2024). Personalized instruction, tailored to individual strengths and needs, can enhance learning outcomes for all students, including those with diverse needs and disabilities (Jones & Casey, 2015). However, personalized learning lacks a unified definition or implementation approach, ranging from teacher-led adaptations to student-centred learning environments (Zhang et al., 2020; Walkington & Bernacki, 2020). As Fitzgerald et al. (2018) highlight, rather than focusing on personalization per se, it is more effective to define what gets personalized (content), in which form, for which student, where and when. In terms of instruction, the hallmarks of effective personalized learning are adaptive instruction and learning, blended instruction, differentiation, and customized instruction (Shemshak and Spector, 2020). The key cognitive process that can support the benefits of personalized learning is to provide students with choices, thus increasing their agency in learning. An illustration of how these concepts relate to each other is in Figure 12.

Figure 12. Key components of personalized learning



Source. Authors.

Bulger (2016) differentiates between responsive and adaptive digital technology for personalized learning: responsive systems allow learners to customize their experience and choose their learning path, while adaptive systems adjust content based on learner behaviour and performance. To optimally design personalized educational technology with the science of learning in mind, Kucirkova, Gerard and Linn (2021) highlight three ongoing challenges in the design digitalized personalized learning: individualisation that is in tension with equity; group customisation that doesn't always benefit individuals and adaptation that may not be based on valid measurements. These issues are exacerbated by recent AI-driven personalized educational technologies. Large language models and AI now enable the full customization of content and learning experiences for individual learners and can function as interactive tutors.

Box. 1. Benefits and limitations of personalized learning.

Benefits of personalized learning	Limitations of personalized learning

• One-to-one learning with well-designed personalized digital technologies can enhance children's mathematics and literacy skills. • Personalized learning benefits struggling learners who require additional educational support • personalised learning opportunities (specifically explanatory feedback and programmatic levelling) were associated with enhanced learning outcomes with educational maths apps. This was based on a range of maths apps evaluated in various countries, including low- and middle-income countries, as well as the UK, the USA, and UAE (Outhwaite et al., 2023; Vanbecelaere et al., 2023). • High-quality educational apps can help prevent gender discrepancies in early maths development in low-income countries (Pitchford et al., 2019)	• The effect of PL on math and literacy was reported as small when compared to other methods (Major et al., 2021). • A medium positive effect on learning achievement but minimal impact from systems based on prompts, feedback, and diagnostics was noted by Tlili et al. (2024a).

Source: Authors.

Overall, advanced methods are required for evaluating what works in what contexts, for which learners and which skills. Evaluation routines that follow science of learning principles are those that employ multiple methodologies tailored to specific questions in a given context (Kucirkova, Brod & Gaab, 2023). Improved experimental designs and analytical methods are necessary to understand the true effects of personalized learning and address the black box effect (Tlili et al., 2024a). Furthermore, ethical challenges need to be addressed, particularly regarding the agency of students and teachers with AI-driven personalized edtech. UNESCO has developed AI competency frameworks to help both students (Miao & Shiohira, 2024) and teachers (Miao & Cukurova, 2024) be prepared to work effectively with AI-based learning systems. Personalized technologies, with their attention to each individual, could be harnessed to foster AI competencies, but for that they need to be designed by learning scientists and not only by commercial developers.

Insights for improving learning with digital technologies

[To be completed after the consultation workshop with contributions from participants.]

Conclusion

[To be completed after the consultation workshop]

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Appendix A

How has the Science of Learning been approached in other UNESCO reports?

[Under development]

As part of writing this report, we conducted a literature search of previous reports published or sponsored by UNESCO, specifically targeting the Science of Learning.

Many UNESCO reports address topics related to the science of learning, even if they do not mention it directly. These reports focus on areas like educational neuroscience, cognitive science, behavioural science, instructional design, and assessment and measurement in foundational subjects such as literacy and mathematics. These fields are essential to fully understanding the role of science of learning in education, and they are cited and incorporated into the literature reviews across the different sections of this report.

To understand which UNESCO reports explicitly refer to the science of learning, we searched for the term "science of learning" both as an exact phrase and as a broader topic in the UNESCO document depository. We reviewed past reports that referenced science of learning principles and incorporated the science of learning concepts. Examining these reports revealed that the term "Science of Learning" has been under-utilized in UNESCO's prior work. Namely, following the search in the UNESCO document repository, only one report was found to explicitly reference the science of learning in its main text: *"Learning at the Bottom of the Pyramid: Science, Measurement, and Policy in Low-Income Countries"* published by the International Institute for Educational Planning (IIEP). Other relevant reports are summarized in Table 1 below, including a brief summary of each report, along with full and short references, detailing how the authors applied the science of learning within their work.

Table 1. Results of systematic search for the use of Science of Learning in UNESCO reports

Report's reference	Short Summary	Use of term 'science of learning'
UNESCO IIEP (2018). Learning at the bottom of the pyramid: science, measurement, and policy in low-income countries. Paris: UNESCO.	The report, edited by Daniel A. Wagner, Sharon Wolf and Robert F. Boruch focuses on the significant educational inequalities faced by marginalized communities in low- and middle-income countries. It argues that these populations are often overlooked in national and international educational initiatives aimed at improving learning outcomes. The report emphasizes the need for targeted policies that address the unique challenges these groups face, advocating for improved measurement techniques to better understand learning conditions. By shifting the focus to those at the "bottom of the pyramid," the report aims to highlight how equitable access to quality education can enhance overall learning across entire nations.	The authors of the chapters in this report are all recognized scholars in the field of the Science of Learning, and the report itself is firmly grounded in science of learning principles. It integrates insights from various disciplines along with research specifically aimed at addressing the question: "What works for whom, why, and in what contexts?" By focusing on these elements, the authors outline how policy-makers can strive to make significant and lasting improvements in child outcomes. Moreover, the report highlights the Science of Learning as a novel framework for understanding effective educational practices, particularly in low- and middle-income countries.
UNESCO. (2024). Why the world needs happy schools: Global report on happiness in and for learning. Paris: UNESCO.	The report advocates for a shift in educational priorities to focus on learner well-being, highlighting that happiness and emotional well-being are essential for effective learning. The report introduces the Happy Schools framework, which emphasizes creating school environments that are joyful, engaging, and supportive.	The report explains that the Happy Schools initiative is grounded in research from the science of learning, which emphasizes that optimal learning environments should be active, engaging, meaningful, socially interactive, iterative, and joyful. The framework highlights the role of both teacher and learner engagement in fostering motivation for deeper learning. By incorporating joy and engagement into pedagogy, the initiative aims to enhance

		educational experiences, making them not only more effective but also more enjoyable for both students and teachers.
UNESCO-UNICEF. (2024). Global report on Early Childhood Care and Education. The Right to a Strong Foundation. Paris: UNESCO.	This first global report on Early Childhood Care and Education, jointly published by UNESCO and UNICEF, highlights the critical role of early childhood care and education in promoting school readiness and lifelong well-being. The report synthesizes global trends and scientific evidence on early childhood learning and development, emphasizing the need for equitable and quality access.	Chapter 3 reviews evidence underlying cognitive and social-emotional development and makes the case that this knowledge base should inform the design of curricula, pedagogy and assessment practices. Appendix 7 describes the science behind early childhood adversity for building lifelong resilience by drawing on brain and neuroscience research. Several papers of prominent science of learning researchers are cited in the report to highlight the role of science of learning in early childhood development.

Appendix B: Case studies illustrating how the science of learning can inform the development of digital technology

The following case studies provide some concrete examples for how the Science of Learning can be used to guide the design, implementation and evaluation of digital technologies. They were selected based on UNESCO's criteria for their relevance for the Science of Learning principles and empirical studies showing their impact on learners.

China

Education in rural areas often faces challenges such as limited resources, undertrained teachers, and a lack of modern teaching methodologies. In regions predominantly inhabited by ethnic minorities, cultural and emotional factors should be considered as well. This is especially true in Qinghai Province, a remote region in China where educational infrastructure is less developed compared to urban areas. In the digital age, the adoption of digital teaching tools has become a key strategy for enhancing both teaching and learning. The digital transformation of education has emerged as a crucial pathway for improving the quality of education in ethnic regions (Hu, 2024). However, as the 2023 Global Education Monitoring (GEM) report has revealed, while technology offers the opportunity to increase access, it can also exclude many on the wrong side of the digital divide (UNESCO, 2023).

In line with Hattie's Visible Learning Framework, the integration of digital tools in education must align with the key elements that drive effective instruction to optimize and enhance teaching quality (Hu, 2024). Drawing on practical teaching experiences, particularly in rural and ethnic areas, five critical factors have been identified for the successful implementation of technology-enhanced teaching and learning, including a student-centered teaching philosophy, diverse instructional methods supported by technology, flexible and active learning strategies, a conducive digital learning environment, and a strong focus on multifaceted evaluation and effective feedback (Hu, 2024). Based on these insights, four tailored digital education models have been adopted to address the unique needs and conditions of ethnic regions.

Dual-teacher classrooms empowered by the National Smart Education Platform

To promote the digital transformation of education, the Chinese government has established the "Smart of China" National Smart Education Platform. As one of the first pilot provinces for this platform, Qinghai Province has prioritized the innovative application of the smart education platform as a key element in its educational digital transformation. The province requires all schools to regularly integrate "dual-teacher" classrooms into their teaching practices. In order to effectively utilize the national smart education platform, Qinghai Province has engaged over 1,500 primary and secondary schools, more than 57,000 teachers, and over 880,000 students in deepening the application of the platform.

By utilizing the expert resources available on the national platform and through the guidance of these master teachers, local educators can follow and learn from these examples, creating a dual-teacher classroom experience. In these classrooms, segments of lessons taught by experts, such as key concepts, difficult points, and exemplary teaching practices, are played to enhance students' understanding of the material. This approach effectively addresses the imbalance in the distribution of high-quality educational resources in rural areas. The combination of online expert teachers and local educators in these dual-teacher classrooms not only allows students to benefit from top-tier educational resources but also ensures that teaching is tailored to students' needs, thereby making the learning experience more accessible and effective. Additionally, the provincial master teacher studios offer a professional development platform for teachers through a mix of online and offline open classes and demonstration lessons, providing opportunities for exchange and learning.

Satellite classrooms with remote synchronous interactions

To address the shortage of teachers and weak teaching capacity in rural and pastoral areas, Qinghai Province has implemented region-specific models of satellite classrooms, considering the unique characteristics of agricultural and pastoral regions. The goal is to deliver the most suitable high-quality resources to the schools and regions that need them most. In implementing satellite classrooms, two key factors must be considered: the gradient in teaching quality and the similarity in students' learning conditions. First, there needs to be a clear distinction in teaching quality between the front-end (leading) schools and the remote schools, with the former having a higher level of teaching quality and teacher capability. Second, the teaching conditions and student abilities in both the front-end and remote schools need to be sufficiently similar; if the gap is too large, the resources from the leading schools may not be well-received in the remote areas. Therefore, the implementation of satellite classrooms in Qinghai has been carefully coordinated based on regional and hierarchical considerations.

For example, the satellite classroom between Xining and Haidong. A total of 91 teaching studios and 176 listening rooms have been established in Xining and Haidong, where leading schools in Xining support weaker rural schools and teaching sites in Haidong. Both Xining and Haidong are located in Qinghai's agricultural region, characterized by a transitional zone from the Loess Plateau to the Qinghai-Tibet Plateau, with balanced economic, cultural, demographic, and ethnic distribution. Xining, as the province's educational and cultural center, has a higher overall teaching level compared to Haidong. Given the similarities in educational traditions, cultural environments, and student backgrounds between the two cities, the synergy created through the satellite classrooms is expected to result in mutual improvement.

This model plays a crucial role in addressing educational inequality by leveraging technology to provide more equitable access to quality education, particularly in ethnic and remote regions where educational infrastructure is less developed.

Famous school classrooms with high-quality educational resource sharing

To improve the quality of education in ethnic minority regions, Qinghai Province has implemented the "Famous School Classroom" model in 29 schools across 11 autonomous ethnic minority counties. Through this model, prestigious schools provide renowned online courses via a digital platform. These courses adhere to the "Four Simultaneous" approach, ensuring that students in rural and ethnic areas receive lessons at the same time as students in famous schools. Additionally, teachers in rural areas plan lessons simultaneously with their counterparts from these prestigious schools, and assignments and exams are administered concurrently across all participating schools. This strategy leverages high-quality resources to enhance the educational experience in ethnic minority regions, addressing disparities in access to quality education. For example, resources from Beijing No. 4 High School's online school are accessible to 133 middle schools in Xining, the capital of Qinghai Province, benefiting 130,000 teachers and students at no cost. This model ensures that students in rural and underserved areas receive the same high-quality education as their urban peers.

Additionally, Qinghai Province has developed partnerships with schools in more developed eastern provinces, importing high-quality curriculum resources to six Tibetan autonomous prefectures (Hainan, Haibei, Haixi, Huangnan, Guoluo, and Yushu). Through these partnerships, the eastern schools provide support via remote teaching and the "Smart Aid to Education" project. This includes collaborative online teaching, lesson planning, teacher training, and online classrooms, effectively delivering advanced educational resources to ethnic regions. This model enables a single school to share its resources with multiple rural schools, reducing the educational disparities between counties, as well as between urban and rural areas. By ensuring that children in rural and pastoral areas have access to high-quality education, this initiative helps gradually bridge the educational divide across Qinghai.

Flexible and interactive cloud classrooms

Cloud Classroom leverages advanced technologies such as cloud computing, the Internet of Things (IoT), and artificial intelligence (AI) to connect teachers, students, and educational content through a digital network, enabling teaching activities to take place in the cloud. With the support of cloud-based classrooms, both teachers and students have access to personalized, secure, scalable, and environmentally friendly next-generation digital learning spaces. This model allows students and teachers to access lessons, materials, and educational resources from anywhere with an internet connection, making it particularly effective in remote and under-resourced regions.

By utilizing cloud-based classrooms, schools can significantly reduce their investments in hardware and software, thus lowering educational costs. The technology allows teachers and students to connect through the network, facilitating both real-time and non-real-time interactive teaching. For ethnic regions, cloud classrooms offer unique potential and advantages. Qinghai Province, for example, has established cloud classrooms in 10 schools, specifically designed to support teachers in ethnic areas and schools with limited educational resources. These cloud classrooms integrate teaching management platforms, storage spaces, and digital IT educational resources, providing schools with new platforms for expanding information technology education, subject-specific learning, and independent inquiry-based learning across various teaching scenarios.

The four typical digital classroom models in Qinghai Province highlight the characteristics and practical experiences of digital classrooms in rural and ethnic areas. From these insights, it becomes clear that when adopting digital tools in such regions, the focus should be on student-centered development. Teachers need a clear understanding of their teaching processes and outcomes, using evidence-based, data-driven decision-making to help students establish connections between different areas of knowledge. By guiding students through learning pathways that progress from surface learning to deep learning and finally to transfer learning, teachers can help students develop a structured, interconnected, and expanded knowledge base that promotes deeper learning. Students, in turn, need to clearly understand their learning goals, learning paths, and desired outcomes. Transitioning from passive to active learning, they should be able to use self-regulation strategies such as self-planning, self-monitoring, and self-evaluation to continuously adjust and improve their learning processes.

To improve education in rural and ethnic areas, policies should focus on enhancing teacher training in digital tools, expanding digital infrastructure, and promoting student-centered learning. Partnerships between developed and rural schools should be strengthened to facilitate resource sharing, while comprehensive monitoring systems are needed to assess the impact of digital initiatives. By investing in teacher development, ensuring reliable digital access, and fostering flexible learning environments, rural students can benefit from high-quality education. Continuous evaluation and data-driven approaches will ensure that digital education initiatives remain effective and scalable, ultimately reducing educational disparities.

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Serbia

As technology advances rapidly, AI has transformed the traditional teacher-student relationship into a teacher-AI-student dynamic (UNESCO, 2024a). There is an increasing need to modernize education and enhance student engagement, particularly in developing skills essential for the future. Traditional pedagogical approaches often struggle to sustain student interest in the classroom. Studies have shown that robots can promote active engagement, problem-solving, and collaboration among students as active learning tools (Iliescu, 2023). The integration of robots into the educational environment offers an opportunity for children to develop critical thinking and creativity (Afari, 2017). Additionally, robots can serve as an effective scaffold for social skills development, particularly for students who are shy or have special needs (Rohlfing et al., 2022). The predictable and less intimidating nature of robot interactions can foster greater confidence in social situations. Furthermore, robots can act as co-learners or tutors, prompting children to explain concepts or teach the robot, thereby reinforcing their own comprehension and deepening their understanding of the subject matter (Mupaikwa, 2024)).

The European Union's (EU) renewed policy initiative, the Digital Education Action Plan (2021-2027), places a strong emphasis on technological literacy, problem-solving, and collaboration. In Serbia, a semi-humanoid robot equipped with advanced AI technology, known as Pepper, was used in the STEM class. Pepper is capable of interacting naturally with students, offering real-time emotional and performance feedback to enhance their learning experience. Additionally, Pepper engages in eye contact and physical movements with students, providing personalized interactions that adapt to individual learning needs and paces, which increases student engagement and improves overall learning outcomes. Furthermore, the integration of a ChatGPT add-on enriches these interactions, making them more dynamic and responsive to the context of the lessons. By incorporating Pepper, the school sought to create a more engaging and interactive environment for students aged 7 to 11.

To ensure the successful implementation of Pepper in the classroom, the project was piloted in three primary schools, accompanied by teacher training on integrating Pepper into their lessons, as well as the provision of ongoing technical support. Initial resistance from some educators, who were concerned about the complexity of the technology, was mitigated through professional development and continuous support. The outcomes were highly positive, with students displaying increased engagement, improved material retention, and greater motivation. Notably, students who had previously been disengaged exhibited significant behavioral improvements when interacting with Pepper.

However, several challenges have arisen with the implementation of Pepper in the classroom. On one hand, technical issues with Pepper's software occasionally disrupt classroom activities. On the other hand, concerns persist about teachers' attitudes toward using robots in STEM education and whether these robots can genuinely improve teaching outcomes. Moving forward, successfully integrating robots and AI into educational environments will require careful attention to optimizing the design of robots and addressing ethical considerations to ensure their safe, responsible, and effective use. This also involves fostering a collaborative relationship between human teachers and robot tutors (Tlili et al., 2023). Additionally, the adoption of AI demands a re-evaluation of teachers' roles and the skills they need in the AI-driven age, as well as preparing students to be responsible users and co-creators of AI technologies (UNESCO, 2024b).

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Kenya

What is the reading challenge in the country?

Literacy is a foundational skill closely tied to a nation's societal and economic growth. Global illiteracy is estimated to cost over a trillion US dollars in annual earning potential, with real losses in opportunity and human costs remaining immeasurable (Cree et al., 2022). Even though Kenya's adult literacy rate reached an all-time high of 83% (World Bank, 2022), UNESCO estimates that after six years of primary school only 25.5% of Kenyan students met the minimum reading proficiency level (UIS, 2024). Challenges such as large class sizes, limited resources, and inadequate infrastructure contribute to the poor quality of literacy instruction, with teachers often relying on rote learning and repetition (Bold et al., 2017). Despite mandated teacher professional development (TPD) in Kenya, the cascade model used for national TPD, combined with insufficient support, diminishes its effectiveness (Bett, 2016).

To address these challenges, we developed a learning intervention that incorporates technology for teacher professional learning, alongside the introduction of early literacy software (ABRACADABRA, ABRA, and READS, https://literacy.concordia.ca/en/) as classroom instructional tools. These resources are designed to complement effective literacy teaching practices, shifting from knowledge transmission to student-centered, interactive instruction. Initially piloted with 12 primary teachers and their students (Abrami et al., 2016), the intervention has expanded to nearly 600 classrooms across five regions in Kenya (Abrami et al., 2023).

How does the digital technology leverage the science?

Research shows that effective learning environments are purposefully designed, grounded in theory, and supported by evidence from the Science of Learning and Science of Instruction. These designs aim to minimize barriers to learning for both students and teachers (Mayer, 2008). The design of this intervention follows the same principles.

The intervention's first element includes ABRA, an evidence-based, interactive early literacy software, and READS, a catalogue of multinational and multilingual digital stories that complement ABRA's content. Drawing on the science of reading and reading instruction (e.g., NRP report, 2000), ABRA addresses key literacy areas—Alphabetics, Fluency, Comprehension, and Writing—along with critical subskills such as blending, letter-sound correspondence, decoding, and vocabulary. Research underscores the importance of teaching these skills actively and systematically, progressing from basic to more advanced levels, with comprehension building from phonological processing to word identification and, ultimately, meaning-making (Shanahan, 2020). Initial instruction focuses on symbol-sound relationships, advancing from decoding one-syllable words to multi-syllabic words, while linking word-reading with spelling and meaning (Ehri, 2020). Achieving automaticity in word-level reading skills is crucial for sentence and text comprehension, the ultimate goal of reading (Kim et al., 2021).

While teaching alphabetic code being an essential part of reading instruction in ABRA, the software offers a balance between code-emphasis and a literature-rich context (Jager Adams, 1990), ensuring all instructional activities are tied to story texts and vice-versa. In the ABRA Student environment, 33 activities are dynamically linked to 17 stories of various genres. The ABRA Evidence Matrix (figure 1) illustrates the connection between stories and alphabetic activities, outlining activity scope and content at various levels. Evidence matrices are designed for all ABRA stories and for all text- and word-level activities. For instance, ABRA's Word Counting activity targets word-level sound discrimination, with two levels of difficulty based on the number of words students count in sentences. This activity is linked to multiple stories, providing students with contextualized learning experiences that foster skill transfer and prevent rote memorization.

Figure 1. Matrices for skills addressed in ABBA stories

Matrices for skills addressed in ABRA stories: Alphabetics

Skill Area	ALPHABETICS										
Skill	Word Counting	Syllable Counting	Same Word	Word Matching	Rhyme Matching	Word Families	Auditory Blending	Auditory Segmenting	Blend-ing Train	Basic Decoding	Word Changing
Story Titles											
Folk and Fairy Tales											
Little Red Hen	X	X	X	X	X	X	X	X	X	X	X
Dove and the Ant	X	X	X	X	X	X	X	X	X	X	X
Three Billy Goats Gruff	X	X	X	X	X	X	X	X	X	X	X
Henny Penny	X	X	X	X	X	X	X	X	X	X	X
Frogs and the Well	X	X	X	X	X	X	X	X	X	X	X
Poetry											
I Can Move Like A…		X	X	X	X	X	X	X	X	X	X
When I Open My Eyes		X	X	X	X	X	X	X	X	X	X
Darryl! Don't Dawdle	X	X	X	X	X	X	X	X	X	X	X
Feelings		X	X	X	X	X	X	X	X	X	X
Fiction											
Waterfall					X	X					
Non-Fiction											
How a Bean Sprouts	X	X	X	X	X	X	X	X	X	X	X
Independent Picture Books											
Fruit Family											
Where Am I?											
Canadian Wild Animals											
Four Seasons											
My Town											
Counting to Ten											

As readers advance, their reading comprehension becomes associated with the active use of meta-cognitive strategies that help regulate the process of knowledge and meaning construction. Cain et al. (2004) pointed out that it is the active use of higher-level strategies that predict reading comprehension beyond word recognition and language ability. These strategies include knowledge of text structure and its features, inference making as an ability to discover the causal structure of a narrative text, and comprehension monitoring as a skill to verify understanding and make repairs where meaning breaks (Pressley, 2002). The instruction on meta-cognitive skills including prediction, sequencing, summarizing and comprehension monitoring that improve reading comprehension are, therefore, integrated in ABRA stories. The huge body of evidence on the effects of reciprocal teaching techniques on reading comprehension (e.g., Ehri et al., 2001; Pressley, 2002) is reflected in ABRA capacity to support student peer reading whereby students can work in pairs or triads – this feature is especially important in the contexts where classes are large and access to devices is limited.

Research suggests that strong reading instruction also develops a set of sustainable drivers, which an independent reader typically possesses, such as motivation (for instance, Guthrie et al., 2007) and reading enjoyment (for instance, Clark & De Zoysa, 2011). At the core of ABRA activities is game playing that engages young students in reading and writing and increases their motivation. When students complete an activity, they are rewarded with a mini game. Game-like feeling is enhanced with ABRA characters who are linked to a literacy skill and offer personal stories the child can read or listen to. Additionally, boys and girls can identify themselves with cartoon characters who guide them through each activity. Designed to dispel gender stereotypes, the main ABRA character, Julie acts as a positive role model for young girls, showcasing her adventurous spirit, whether parachuting, diving, or steering a boat.

When students learn to read, it becomes increasingly important that just-in-time, scaffolded support and guidance for their learning is available to them (e.g., Van der Kleij et al., 2015). ABRA provides students with instantaneous error detection and scaffolded feedback. The embedded support tailors the degree of scaffolding provided, as students interact with the tool. If students answer incorrectly, they are provided with visual and/or auditory guidance or can seek help.

The cognitive effects of computer-driven differentiated instruction (e.g., Deunk et al., 2018) are accounted by ABRA design in several ways. First, a teacher can monitor each student's progress through the ABRA-generated assessment report and address the difficulties they are having. Second, most activities have several difficulty levels allowing students to learn at the appropriate level. ABRA also allows students to progress at their own pace, and the dynamic activity-story linkage allows for an abundance of practice.

ABRA design is based on the solid principles of instructional design for multimedia learning that work to encourage learners to engage in appropriate cognitive processing during learning while not overloading the processing capacity (e.g., Mayer, 2008). For example, ABRA relies on auditory and visual channels of processing, components of a well-designed multimedia that successfully captivate young students' attention and maintain their focus on the active construction of meaning as the student manipulates images to learn, for instance. At the same time, instructions are provided orally with a possibility of replaying them; each story embeds oral prompts based on segmenting and blending. The characters' input is also auditory and all demos are accompanied by audio explanations.

Finally, technology is effective when woven into a comprehensive literacy pedagogy model (e.g., Cheung & Slavin, 2012) that combines instruction with support to teacher professional learning. Prioritizing teacher agency, the Teacher environment in ABRA generates an assessment report that tracks class or individual student activity within the software and allows teachers to inform their instruction and. Teacher resources give access to dozens of unscripted print-based and multimedia support materials also adapted to Kenyan contexts. The ABRA Parent environment offers multimedia materials geared to aid parents support their child's literacy development in the home.

The intervention's second element is the literacy teacher professional development. This evolved into a blended TPD program that combines learning online and in-person with synchronous and asynchronous learning. The design draws from the important body of evidence on effective TPD models (e.g., Darling-Hammond et al., 2017; Mishra & Kohler, 2006; Sims & Fletcher-Wood, 2021), systematic reviews of technology-driven TPD interventions in the Global North (e.g., Schmid et al., 2023; EEF, 2020) and those in the Global South (Hennessy et al., 2022) as well as our own selective narrative review of empirical studies of in-service learning of primary and secondary-school teachers in the Global South with a special focus on the design of technology-based TPD strategies (Head et al., 2023). Cost-expectancy-value model (Wozney et al., 2006) served to ensure the design accounts for teacher motivation to use technology. Collaborative work with literacy subject-matter experts and contribution from Kenyan educators also informed the design.

For instance, according to the narrative review by Head et al. (2023), effective forms of technology-driven TPD are subject-specific (e.g., Hassler et al., 2020); integrate face-to-face components in technology-based interventions and blend asynchronous and synchronous instruction (e.g., Schmid et al., 2023); rely on teacher familiarity with the tools where each is used for a distinctive educational purpose (e.g., Anwar, 2017); provide a platform for peer dialogue (e.g., Bett & Makewa, 2020) and professional interaction (e.g., Motteram & Dawson, 2019), incorporate mechanisms for monitoring teacher learning progress (e.g., Wolfenden et al., 2017) and for providing formal feedback (e.g., Wambugu et al., 2018); and, prioritize cost-effectiveness (e.g., Lim & Liang, 2020). To increase the adoption of new pedagogical approaches, the TPD strategies should be culturally relevant (e.g., Kennedy & Laurillard, 2019); foster teacher ownership over learning (e.g., Simoncini et al., 2021); focus on student learning and practical pedagogies (e.g., Anwar, 2017); demonstrate and model effective practices and stimulate reflection (Kennedy & Laurillard, 2019); cultivate collaborative environment for teacher learning (e.g., Saenz Rodrigez et al., 2017); and motivate teachers to advance their professional learning and instructional practice (Truong & Murrey, 2019).

Hence, the literacy TPD program was designed to develop teachers' understanding of the core literacy skills such as Alphabetics, encompassing Pre-alphabetics, Phonemic and Phonological Awareness and Phonics, and Fluency, Comprehension, and Writing (NRP report, 2000). Teachers were then guided on how to teach these effectively and provided with strategies on how to implement the student software to this end. Blended delivery offered three in-person sessions interspersed among nine units of each online module. Each module was designed with built-in opportunities for interaction with instructors, peers, and the content itself, features integral to the success of remote education (Bernard et al., 2009). The content was presented in both print and multimedia mediums, and each screen had an audio button as an optional aid for users that are visually impaired. Web conferencing software was used to conduct sessions online, with WhatsApp being used as a forum for peer interaction between sessions. Teachers completed units and associated readings to acquire knowledge about early literacy concepts and to integrate implementation skills into their teaching. Quizzes, assignments, and WhatsApp posts exposed the change in teachers' knowledge across the TPD modules. In addition to literacy knowledge, teachers' perceptions of early literacy instruction were surveyed over time. They also completed and reflected on lessons that they implemented which integrated ABRA activities. To reinforce professional learning, the model paired teachers with trained peer mentors who provided ongoing support to teachers within their schools. These and other features also ensured that teachers develop positive expectations of success, enhanced value of technology integration, with minimal personal investment – motivation components driving teacher agency including autonomy, progress and attainment.

How does the technology align with the national curriculum, pedagogies, and teacher training?

Together with Aga Khan Schools and World Vision, the team worked with the national and local governmental agencies. For instance, in 2020 following Kenya Institute for Curriculum Development approval of ABRA, the software was made accessible on the Kenya Education Cloud (https://lms.kec.ac.ke/course/index.php?categoryid=315). However, Kenyan stakeholder agencies are many, with each performing a unique or overlapping functions in the national education system. As a result, we formed a Literacy Working Group of stakeholder agency representatives. The intent with this group was to collectively set objectives, develop strategies towards scaling the literacy project, and determine the necessary elements for expansion of the program throughout the country.

Lastly, to increase contextual relevance, we mapped the national English Language curriculum with the TPD and learning tools and designed supplemental teaching materials (e.g., Teacher Guide, classroom resources), and added locally relevant stories to READS.

How was it implemented and tested?

The implementation and testing unfolded as a series of studies starting with the 2012 pilot study structured as a cluster-randomized trial (Abrami et al., 2016) and followed by the quasi-experimental studies (two non-equivalent group pre-post-test design) completed in 2015-2016, 2018-2019 and 2022. While all studies feature the use of a standardized measure of reading achievement and the length of the intervention implementation, the 2022 study focused on the impact of blended literacy TPD on teacher practices and student learning (Lysenko et al., manuscript in preparation). All quasi-experiments included a considerable qualitative research component – for instance, a study exploring facilitators and barriers to the uptake of learning technology by Kenyan educators (Lysenko et al., 2022).

What were the results?

ABRA and READS have been deployed in classrooms around the world. Implementing countries include Canada, England, Australia, Hong Kong, China, Kenya, Rwanda and Bangladesh. We synthesized evidence from Kenyan research conducted through 2019. As presented in table 1, the overall average effect size (statistically adjusted for school effects) based on the 18 comparisons and 2,626 primary students from grades 1-3 is +0.43 whereas the highest effect is +0.53 in reading comprehension. The obtained effect sizes suggest that after having been taught with ABRA, an average student scored at the 50th percentile would increase her percentile scores to 67 in overall reading and 70 in reading comprehension.

Table 1
Overall Weighted Average Effect Size (Random Effects Model): Adjusted and Unadjusted Data ***by Outcome Type*** *and Heterogeneity Statistics for Overall Reading Effect Size (Fixed Effect Model, Unadjusted Effects Only)*

Population Estimates	*k*	g+ (p value)	*SE*	Lower 95th	Upper 95th
Listening Comprehension					
Unadjusted Effects	6	0.469 (0.01)	0.18	0.11	0.83
Adjusted Effects	6	0.417(0.000)	0.12	0.17	0.66
Reading Comprehension					
Unadjusted Effects	6	0.639 (0.000)	0.18	0.28	1.00
Adjusted Effects	6	0.527(0.000)	0.13	0.26	0.79
Vocabulary Knowledge					
Unadjusted Effects	6	0.397 (0.04)	0.19	0.02	0.78
Adjusted Effects	6	0.365 (0.01)	0.14	0.10	0.63
Overall READING					
Unadjusted Effects	18	0.491 (0.000)	0.10	0.30	0.69
Adjusted Effects	18	0.427 (0.000)	0.07	0.29	0.56
Heterogeneity Analysis $Q_T = 288.07$ ($df = 17$), $p = 0.000$, $I^2 = 94.10$					

*A d-type (Cohen's d) standardized mean difference effect size (Cohen, 1988) was used as the common metric. To correct for small sample size bias, d was then converted to the unbiased estimate g (Hedges & Olkin, 1985)

The primary studies (e.g., Abrami et al., 2016; Lysenko et al., 2019) consistently show that ABRA-READS benefitted both boys and girls about equally. And while all students learned, low-performing students and struggling readers were often able to learn the most (Abrami et al., 2016; Lysenko et al., 2019). Indeed, the most recent results (Lysenko et al., in preparation) indicate elimination of the Matthew effect, i.e., the cumulative reading disadvantage suggesting that differences between high-ability and low-ability students tend to increase as they progress through school. Further, learning gains retained beyond the initial intervention period -- the 2015-2016 study suggests that those who used ABRA and READS for more than one year maintained an advantage in literacy development. The 2019 investigation of ABRA usage in a remote region, where national examination results are poor, demonstrated that with ABRA software learning gains were important (Abrami et al., 2020). Finally, the reading improvements transferred to other subject areas including Mathematics, Science and Social Studies (Abrami et al., 2016).

In sum, the impact of the ABRA-READS intervention on students is evident. Such outcomes are especially valuable since it was undertaken by regular teachers within their regular unscripted English lessons in their regular classrooms. Even though much of the current scientific evidence on effective instructional uses of computers suggests that the instruction is most successful when taught by researchers or trained professionals (e.g., Okkinga et al., 2018), this study was able to capture the impact of ABRA-READS software use in the real-world conditions of Kenyan primary schools where classes are large, there is a deficit of efficient technology infrastructure, and the ratio of students per computer is high. Yet, the teachers embraced pedagogical sophistication of the learning technology for the benefit of their students. We associate such growth of teacher professional autonomy in the context where innovation is traditionally heavily scripted (e.g., TUSOME in Piper et al., 2018) with the targeted intervention including technology-driven literacy TPD and the system of follow-up support. This intervention is powerful as its design is rooted in the research-proven principles of instructional design and solid evidence on technology-based professional learning of teachers while being founded in the science of reading, i.e., evidence on literacy skills and subskills for emerging readers and how to teach them effectively along with the integration of technology for learning into classroom instruction.

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