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Developments in educational neuroscience: implications for the *art* and *science* of learning

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ABSTRACT

Learning is a complex phenomenon where a learner constitutes a system operating at neural, physiological, cognitive and social levels, with interactions between and across processes and levels, effecting neural to cognitive to social levels and vice versa. In tracing historical paradigms, theories of learning have been traditionally fragmented in nature, typically focusing on sub-process or sub–levels of the system. For example, theories of cognitivism focuses on internal processes and connections that take place during learning, negating observed behaviours or outward behaviours of learning, while theories of social constructivism place strong emphasis on human development and knowledge construction that is socially situated, with less attention paid to individual differences and variations. In recognizing inherently complex interrelated learning systems, a more integrated and comprehensive understanding of learning is necessary. Such an understanding entails research endeavours that can harness multiple, complex parameters of the learner system through mapping and understanding interactions between and across learning processes and levels. Such endeavours entail the use of multiple sources of scientific evidence, across multi-modal data capture modes and multi-levels of analyses, informed by multi-disciplinary theoretical framings. In this paper, we argue that an overarching scientific ethos towards learning optimizations need artful implementations of pedagogies and interventions that close the circle—from scientific findings translated into practical applications in education and back to addressing problems in education as impetus for evidence-informed theorizations of learning.

KEYWORDS:

Science of learning, research practice translations, teacher education, classroom practice

View correction statement:

Correction

An important issue in educational neuroscience is to close the circle from neuroscience to education and back to neuroscience again. Not only can findings from neuroscience research inform educational practices, problematisations derived from educational contexts should inform trajectories of neuroscientific investigations. Critically, the iterative processes between neuroscience, behavioural research and pedagogic design represent a core interdisciplinary strategy in advancing *Science of Learning* frontiers (Butterworth & Laurillard, 2017). As a progressively advancing field, the Science of Learning (SoL) is defined as an approach that *recognises the value and importance of cross-fertilisation across traditional fields of study, drawing on many different methods and techniques to understand how learning occurs – with the ultimate goal of optimising learning for all* (JHSLI, 2019). Recent advancements in Artificial Intelligence and data science can also aid in advancing SoL with systemic views of data and models in tandem with the micro-levels of analysis in learning and cognition. An SoL approach aims to gain deeper insight into the study of learning through interdisciplinary fields and seeks to transform educational practices (Meltzoff, Kuhl, Movellan, & Sejnowski, 2009). Human learning and the constant interaction with varying stimuli bring about learning in everyday life (Meltzoff et al., 2009) and emphasise the importance of context. In recognising learning as a human instinct where changes in social norms, human relations, means of communication, pace of knowledge obsolescence and technologies create new demands on the nature of learning in current twenty-first-century contexts (HKU, 2019), how people learn matters more than ever before. Fundamentally, learning is complex and it involves the interplay of cognitive, social, developmental and environmental systems (Master, Meltzoff, & Lent, 2016). Such a complexity necessitates a comprehension of the underlying principles of learning in a multifaceted approach, that attend to connections between biological, psychological and behavioural processes, contexts of learning and educational outcomes, to provide a strong resource base for teaching and learning. Recent studies were able to demonstrate that strong relationships between neuroscience, psychology, learning sciences and education have helped learners to develop the skills needed to thrive in today's classroom settings (Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013; Roediger & Pyc, 2012; Weinstein, Madan, & Sumeracki, 2018). Data for SoL studies, however, do not solely stem from neural sources, rather sources of data range from individual neurons, to neural networks and from isolated cognition or behaviours to integrated cognition or behaviours at the individual, group or systems level (Horvath, Lodge, & Hattie, 2017). Palpably, the array of studies depict SoL as a rapidly advancing field that synthesises a huge body of expertise and knowledge of human learning with the use of scientific findings from various disciplines to better develop evidence-informed strategies that can improve teaching and learning outcomes.

Developments in the *Science of Learning*

Tracing the development of learning paradigms, early learning theories were most commonly understood through the behaviourist perspective where it lies largely on the foundation of stimulus-response (Thorndike, 1898). As the computational information-processing era developed, a shift in emphasis took place in education when cognitivist approaches to learning became influential (Mayer, 1992). Progressively through evidence-informed research, constructivist approaches of learning developed to provide important insights and new perspectives into how learning occurs. Stemming from the works of Piaget (1952), the learning focus was on an individual's active role in integrating new information with existing knowledge that was posited to lead to meaningful learning (Jones & Brader-Araje, 2002). Vygotsky (1978) extended constructivist learning, illuminated by his research, which emphasised social interaction as the central tenet of learning. He maintained that the understanding of learning cannot occur in the absence of a social context. For example, newborns as young as 42-min old could demonstrate successful imitations of human actions such as tongue protrusion and mouth opening (Meltzoff & Moore, 1983). Additionally, infants by 6 months of age are found to initiate more looks at caregivers when presented with unanticipated than anticipated situations (Walden, Kim, McCoy, & Karrass, 2007). Further studies also reported how children used themselves as a model to make sense of the behaviours and experiences of others which results in their own learning (Meltzoff, 2007). Social interactions are posited to mediate one's *zone of proximal development (ZPD)*, defined as the area between an individual's capability to perform alone and the possibility to achieve only with the guidance of a more knowledgeable other, commonly an adult or a more advanced peer (Vygotsky, 1978). Building on the ZPD model, Wood and colleagues (Wood, Bruner, & Ross, 1976) used the concept of scaffolding to provide a better understanding of the social interaction between the individual and the expert. Through techniques of "scaffolding" during which an expert presents relevant instructions to facilitate an individual's mastery process when the task is over and above one's ability (Wood et al., 1976), it is argued that an individual's potential of knowledge construction increases exponentially as a result of scaffolding. Arising from research studies on scaffolding, critical features were identified for effective teacher-student guidance (Puntambekar & Hubscher, 2005), which include, a shared understanding towards common goals between expert (teacher) and individual (student), consistent evaluation of individual's development and tailoring of support to meet learning needs, and phasing out of scaffolding supports when the individual becomes competent.

Educational neuroscience perspectives

Viewed from a neuroscientific lens, an example of the applicability of Vygotsky's theories on the zone of proximal development, and the dynamic organisation of psychological functions are its centrality to understanding fundamental child development and paediatric neuropsychological evaluations (Weiler, Willis, & Kennedy, 2019). Ioannides (2017) further connected socio-constructivist theories of ZPD with understandings from trajectories of neural network properties wherein he defined the ZPD as activities that are outside one's normal physiological range of brain activity (n-PRoBA). n-PRoBA activities can possibly occur within existing neural systems under guidance by teachers or advanced peers, especially during play. Specifically, the ZPD refers to what existing neural networks can do but have not done so yet, and as such they are not likely to require any reorganisation of basic neural networks or changes in regions of the brain, particularly that of the midline self-representation (MSRC), which comprises two areas of the brain, the first area MSRC1 being on the dorsal medial prefrontal cortex (dMPFC) and the second area, MSRC2, in the precuneus in the midline posterior parietal cortex. Interestingly, lending a neuroscientific lens to constructs such as the ZPD affords a quantification of the n-PRoBA in terms of activity and configuration of brain networks during operations that the learner is doing routinely, e.g., at rest (i.e., activity of the Default Mode Network while resting), or in a set of simple and complex tasks. A neuroscientific lens on a learning construct such as the ZPD may present different scales of measurements of learning while at the same time providing some norming of basic developmental trajectories of the brain across life. This is to say that while learning can be manifested at different levels, be it neurally, physiologically, behaviourally or socially- the advancement of different modalities of data capture can now afford significant insights into traditional “black boxes”. As elucidated, a rather fluid potentiation “zone” such as the ZPD can now be quantifiably explained in terms of neural change as “implicit indicators” of learning, potentially augmenting the ZPD literature base which predominantly analyses learning and development arising from scaffolding processes through observed behaviours (Berk & Winsler, 1995; Silvetti, Seurinck, & Verguts, 2011). Notwithstanding, there remains a need to cohere the multiple levels of analysis that can be scaffolds for learning from across the neural to social dimensions.

Similar strands of research on learning have also taken an augmented neuroscientific view to add “black box insights” into ongoing discussions from both learners’ and teachers’ perspectives. These include examples such as studies about self-regulatory abilities (Khalil, Minces, McLoughlin, & Chiba, 2013) and inhibitory distractions (Tierney, Krizman, Skoe, Johnston, & Kraus, 2013) based on identified brain regions (Figure 1) and epidemiology of neuromyths (Howard-Jones, 2014) prevalent amongst teachers in relation to incorrect assertions about how the brain is involved in learning (Dekker, Lee, Howard-Jones, & Jolles, 2012). To this end, prior theoretical models of human learning that tethered almost exclusively to behavioural data (Howard-Jones et al., 2016) are now afforded construct validity to provide additional “measures” of learning, in terms of neural and biologically grounded insights.

Figure 1. Brain regions that are commonly activated for studies of self, theory of mind, threat detection, and self-regulation (Heatherton, 2011).

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Pervasive neuromyths surrounding neuroscience and education premised on the belief that learners perform better when taught in their preferred learning styles (Howard-Jones, 2014) is a classic, well-known example. Another common myth highly regarded by educators is the use of hemispheric dominance of the left and right brain to explain for individuals' differences (Howard-Jones, 2014). Given the complexity of learning processes, it is not surprising that a single-minded focus on proposing monolithic learning styles lacks practical application to how humans learn. Yet even with such logical postulations, many learning styles and singular learning strategy "myths" continue to perpetuate in classrooms. While it is necessary for future examinations to take a step further into investigating interactions between combined strategies that learners might utilise interchangeably during learning processes, the prevalence of non-optimal classroom practices such as perpetuating brain-based misinformation about learning point to a more critical need for immediate efforts to resolve misunderstandings and increase collaborations between researchers and educators.

Taken together, the array of scientific research that *draws* on different methods, techniques, and data collection modalities to understand how learning occurs are catalysing deeper integrated perspectives for the understanding of learning, cutting across not just quantitative or qualitative paradigms, but so too, levels of analyses and its subsequent findings. What is clear, the study of learning has made enormous epistemological shifts primarily informed by evidence generated from scientific research – from learning as response acquisition to learning as knowledge acquisition, and towards learning as knowledge (social) co-construction and as a physio-biologically grounded phenomenon. Yet, to what extent have the array of scientific research findings, such as that of socio-constructivist orientations, permeated into teaching and learning? Are classroom activities designed to leverage n-PRoBA potentiation and MSRC reconfigurations? Or do we still observe classrooms of monolithic instruction with teachers dominating the instructional space upfront? Even if neuroscientific evidence is negated, how frequent can we find classroom spaces that manifest shared goals between teachers, as the recognisable expert, and individual learners? Or that which reflects a consistent evaluation of individual's development and tailoring of support to meet learning needs while gradually fading off as the individual becomes competent? As variations occur across education systems and cultural contexts, the importance of integrating scientific evidence into actual teaching and learning applications represents how classrooms eventually *become*. We argue that such a *becoming* process entails an important "*art*" that needs to accompany the *"science"*.

The importance of the "art" accompanying *science of learning*

Too often, research findings are not translated into authentic learning contexts (Roediger, 2013) in optimal evidence-informed ways. Despite researchers and educators having the same goal to improve learning outcomes, their endeavours may not align (Master et al., 2016). While much of the extant literature in SoL research revealed favourable findings, their applications in classrooms may be still considered premature (Daniel, 2012; Howard-Jones, 2014; Roediger & Pyc, 2012; Thomas, Ansari, & Knowland, 2019). Roediger and Pyc (2012) cautioned that recommending strategies which are still under development could fail due to the lack of practicality and clear instructions. Master et al. (2016) highlighted how research findings typically remain inaccessible to others apart from researchers themselves. Inherently, this may be due to the "double" complexity involved in i) interpreting "complex" research papers and scientific findings and ii) designing for the findings to be applicable and implementable in authentic classroom contexts which are inherently *complexified* by diverse variations in terms of learner profiles, classroom contexts, and education policies.

Notwithstanding, a number of *SoL* research studies have explored the evaluation of "translatable" strategies to improve teaching and learning outcomes. Weinstein and colleagues (Weinstein et al., 2018) provided in-depth analyses on six evidence-based learning strategies applied in classrooms which have received strong support. These six strategies comprise spaced practice, interleaving, retrieval practice, elaboration, concrete examples, and dual coding identified through SoL research. Similarly, Dunlosky et al. (2013) evaluated 10 learning strategies, of which 5 were concluded to be effective for learning, while the other 5 were deemed less useful. The two most frequently used techniques, highlighting or underlining and rereading, were concluded to be ineffective. Other ineffective strategies include summarisation, keyword mnemonic, and imagery for text. In a parallel paper, Roediger (2013) did a summary on the "brain-based" strategies in lieu of the findings reported by Dunlosky et al. (2013), purporting that strategies arising from SoL domains to optimise learning outcomes need not be expensive. As Dunlosky et al. (2013) reported, findings translated into practice testing, distributed practice, elaborative interrogation, self-explanation, and interleaved practice are effective and affordable, making them practical for adoption in everyday formal and informal learning practices. The accessibility and efficacy of these strategies can be critical motivators for educators to incorporate them into their teaching practices as it is recognised that *non-radical* redesigns face less implementation barriers in augmenting their current pedagogical repertoires.

Recognisably, while dissemination of information to educators and provision of applicable methods for evidence-informed teaching practices is crucial for change in education to take place, it represents an impetus that still lacks an appropriate follow-through to see impactful change from SoL research to education and back. For instance, despite scientific evidence denying the effectiveness of certain pedagogical techniques, several of these remain widely adopted in classrooms (Dunlosky et al., 2013). As an example, rereading is reported as one of the most commonly utilised techniques (Carrier, 2003) in classrooms yet scientific investigations have demonstrated a lack of effectiveness in rereading (Callender & McDaniel, 2009; Dunlosky et al., 2013). Limitations in judgment that rereading allows learners to better comprehend materials might be attributed to familiarity, which might not necessarily lead to learning (Karpicke, Butler, & Roediger, 2009). As another example, retrieval of information from memory done through self-testing processes is reported to positively influence learning and is associated with long-term retention (Roediger & Karpicke, 2006a). These results were also extended to real-world environments where self-testing led to deeper learning and more enduring retention (McDaniel, Roediger, & McDermott, 2007). While self-testing is traditionally used as an assessment tool, recent findings have emphasised it as a means of learning (Roediger & Karpicke, 2006b). Within this vein, we are at a juncture to realise the strong interrelations between not just teaching and learning, but assessment too. If we think of teaching and learning visually as a triangle, made up of curriculum, pedagogy and assessment, it may appear “lop-sided” (Goh, 2013), given the lesser attention accorded to scientific basis of assessments than teaching and learning components. While conventional assessment has been seen as a tool used by the teacher to measure learners’ performance in learning, a broader view elucidates assessment in the form of self-feedback, teacher feedback or peer feedback that can be used as a powerful tool for learning (Tan, 2012). This brought forth the notion that translation to the real world is not “simple” as a singular theory itself cannot directly drive the application (Thomas, Ansari, & Knowland, 2019).

Aside from close tripartite relations between the science of teaching, learning and assessments (Figure 2), crux for change to occur is the role of educators as crucial agents to mediate these aspects in terms of translational work. The latter represents an *art* necessitating not just information pertaining to research findings of optimal scientific-informed techniques and strategies for teaching and learning, but so too an understanding of the theoretical mechanisms and epistemological underpinnings of ways to effectively design and implement them in authentic learning settings (Daniel, 2012). Figure 2 visualises the tripartite relationship with the multiple levels of learning and learners – from neural and bio-physio to social-cultural – and its outcomes which necessitates relevant form of assessment, and curriculum.

Figure 2. Interrelations between the science of curriculum, assessment, teaching and learning.

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Although research findings within the SoL sphere have been promising in recent years, it is not without limitations. Variations in the degree of fidelity between scientific findings to authentic classroom applications remain a longstanding problem (Daniel, 2012) in the field's impact on education. While an interdisciplinary *science of learning* base can mitigate gaps between research and practice, what remains critical is a consonant need to develop teachers' *art* of designing, to pull together findings from scientific research, integrating them into skilful conceptions of actual implementable schemes of work and lesson designs, with clear objectives of maximising optimal student outcomes through clear curriculum planning and assessments. In pursuit of a successful convergence, while researchers ought to design experiments targeted at resolving authentic classroom issues, educators should also be armed with a basic understanding of proposed interventions (Ansari & Coch, 2006). The communication loop between researchers and educators has to be skilfully maintained for effective changes to take place in classrooms – the facilitation of which we argue requires an *art* that i) coalesce state-of-the-art research across multiple domains, ii) develop judicious interrelation of insights associated with diverse theoretical perspectives from neuroscience, pedagogy and classroom praxis, iii) disrupt deeply rooted disciplinary cultures (e.g., of neuroscience, and of education) and its field-specific methods and language, and iv) catalyse shared discourse and resonant language terms so that experts from one field can use and extend the knowledge from another, and vice-versa.

SoL for teacher education: integrating the *art* and *science* of learning

The cognisance that SoL research does not seek to "air drop" neuroscience findings into educational settings and hope for miracles remains critical. Recognising that the domain of SoL is a painstaking endeavour of building *corridors of explanation* from neuroscience findings to psychological constructs to classroom instruction and back (Varma, McCandliss, & Schwartz, 2008), emphasises the importance of establishing *researcher–practitioner partnership models* for the advancement of SoL in education. The model entails a mutual collaborative endeavour towards understanding learning at respective nuanced levels, which include neural, psychological, and behavioural mechanisms underlying learning, experimentation and implementation in the classrooms, and assessing the efficacy of methods and interventions for broader education system implications. Framed by an overarching evidence-informed ethos that draws on multi-level and multi-dimensional approaches in the science of learning and development, the principles of teaching learning and assessments, and the research methods that facilitate strong connections between biological processes, contexts of learning, educational outcomes and systemic impact (Jamaludin & Hung, 2019), interdisciplinary threads about learning should be drawn from diverse fields such as cognitive science, neuroscience, anthropology, computer science and progressive technologies (e.g. Artifical Intelligence), network science and analytical statistics. With this encompassing resources base, teachers and instructional/learning designers become key stakeholders for the utility of SoL knowledge to be effectively translated into impactful pedagogical applications (Lovat & Smith, 2003), albeit with the cognisance that intervention science is currently still at its "infancy".

We posit that the role of teachers functioning as "brokering" optimal translations of basic SoL research into effective learning interventions is critical for remediation and personalising trajectories of learning as SoL extends deeper insights into correlations of prevailing classroom practices with learning principles identified. Fundamentally, this will have implications on teacher education. If teachers are to be designers of effective learning environments, SoL perspectives can provide the multi-level dimension of sources of data for more predictive designs for learning. For example, without partnering teachers in the design and implementation of an intervention strategy, for say, low progress maths learning in early primary learners, the value of the SoL-informed interventions in remedying, for example, distal causes of too little experience of numbers in maths learning, may not be maximised. This can happen if teachers do not use the designed intervention and its accompanying pedagogy for supporting independent learning through the provision of intensive practice, alongside the classroom syllabus. Additionally, without establishing a developmental partnership with teachers, underlying reasons and individual differences in learning may not be nuanced, as learning problems (such as cognitive difficulties specific to numbers or limitations in spatial perception and visual representation in Maths learning) remain *opaque* to teachers. As such, there is a strong value proposition in partnering teachers in an SoL research agenda, in terms of both maximising intervention strategies of remediating learning difficulties and developing teachers' pedagogical repertoire that commensurate with rapid developments in the neuroscience literature.

A model of teacher education informed by SoL may include creating a dialogical space for expanding teachers' design repertoires where teachers will have access to i) video case studies of learners working on designed tasks; ii) analyses of the nature of learners' difficulties; iii) screencasts of brain images, talking through what the images mean in terms of how the brain is developing differently for different learners; iv) links to remediation strategies or platforms, with video explanations of the brain science and pedagogical science that underpins it; v) lesson plans for how the designed interventions might be introduced into a class with different underlying reasons for learning differences, with the teacher having access to the data collected; and vi) activities in which teachers can report back on their SoL "tinkering" and "experimentations", and compare their experiences and activities with other teachers. Teachers may also have the opportunities to reflect on their own learning design, interpreting data from students' outcomes from the interventions, and learning collaboratively from the results, with support from SoL researchers. In a study by Howard-Jones, Winfield, and Crimmins (2008), teachers were found to have developed better pedagogical concepts in terms of progression from simplistic cause-and-effect thinking to one where neuroscience was used an as additional data source to deepen concepts. In another study by Clement and Lovat (2012), participant teachers were presented with neural processes of creativity. As they dialogued and reflected about the information presented, the data were also used to augment teachers' awareness of the metacognitive processes involved in creative thinking (Clement & Lovat, 2012) in terms of developing teachers' awareness of the different mental states present within a creativity classroom and how interventions could be implemented appropriately. Such knowledge that is further generated through teachers' engagement with neuroscientific data is both "scientifically valid and educationally relevant" (Howard-Jones, 2014). What is critical to note is that findings from SoL research, such as neural processes of creativity shared with teachers, are not meant *by and itself* to improve classroom practices. Rather, the evidence is meant to *exploit* neural findings, for example, as one data source, interfacing to deepen teachers' understanding of how learning occurs. While taking into account understandings from other sources such as cognitive psychology to seed practical insights, teachers can begin to think about and "*artfully*" design for utility in their classroom. More importantly, the dialogical and reflective space that accompanies the introduction of SoL understandings to teachers is of *primary* importance that facilitates teachers' deepening of an *integrated perspective of learning*. As knowledge of learning and underlying theories supporting pedagogical practices develop and deepen, such a process can positively affect the dispositions of teachers by improving their sense of efficacy, moving them from passive stances to having more agency in designing for their learners as empowered educators. In our preliminary runs of SoL workshop for educators at the National Institute of Education, Singapore (Figure 3), teacher participants shared their post-workshop reflective thoughts:

Table

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Figure 3. An educator experiencing a “hands-on” live session of neural imaging at an SoL workshop in NIE.

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It is interesting to note that teachers’ encouraged perspectives post-workshop resonated with the view on how teachers’ *reflection on the processes that comprise cognition could lead to altered perceptions* (Clement & Lovat, 2012). Similar efficacies in deeper understanding about scientific underpinnings of learning as acknowledged by teachers have also been reported in other studies (e.g., Dubinsky (2010), Dommett, Devonshire, Plateau, Westwell, & Greenfield, 2011). Concurrently, educators at the SoL workshops brought up pragmatic concerns such as “*how to actually use the data for students’ learning experience*” and “*how research could be scaled up to full classrooms in real lessons, to study the efficacy of various pedagogies or interventions*”. To this end, the cognisance that findings from “neat” laboratory settings into “complex” classrooms is never a straightforward pursuit (Horvath et al., 2017) needs to be continually foregrounded. For example, the work on translating knowledge arising from SoL research into downstream gains need to take into account contextual factors of classrooms such as class size, teacher workload and even school culture with regards to its stance on an evidence-informed pedagogical ethos.

Towards an advancement of education

Proposed translational efforts such as that in the form of pipeline organisation of educational neuroscience dissemination (e.g., Gabrieli, 2016) will not achieve the degree of "depth" of optimising learners' potential. Instead, the process of applying findings from "laboratories to learning" includes iterative steps of i) identifying foundational learning principles, ii) correlating prevailing classroom practices with learning principles identified with a view to probing and deepening explanatory foundations for successful learning strategies, iii) developing *original, effective and specific* teaching and learning strategies, and iv) grappling with inherently contextual, dynamic, and multiple classroom variables. The journey is undeniably rife with procedural and philosophical gaps, yet we need to persist with *researcher–practitioner partnership models* as educational needs progress along with time in this ever-changing world. Teaching and learning strategies that seemed to work previously may not suffice in the face of current expectations that demand shifts from broad-based education to more personalised and targeted trajectories of learning for maximal outcomes. Moving along macro to micro continuum of learning (Jamaludin & Hung, 2019), SoL is an inherently complex field with its multiple modes of data sources, dimensions of analyses, and levels of interpretation. Yet, as Kalbfleisch (2015) articulated, in an age where complexity defines our living and being, SoL affords an explanatory power that, while complex, can eventually simplify our understanding of learning processes to the best set of optimal principles that address questions and problems of human learning. In emphasising optimal understanding of learning with up-to-date empirical evidence, SoL is aimed to seed not only novel ways of thinking about education but so too open up insights into different yet complementary disciplines to create an advancement in education today. The hope must be that the *science* of learning is *artfully* implemented to impact education, thereby propelling our system to greater heights.

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Disclosure statement

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