What are the Implications of Psychology and Neuroscience Research for STEM Teaching and Learning?

Vision and Commentary for the Royal Society Vision Committee

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EXECUTIVE SUMMARY:

OBSERVATIONS

1. The Mapping Study showcases a substantial body of literature that could inform teaching practices, and lists 14 specific practices that could be used by teachers in a wide range of contexts to support learning. This suggests that evidence-informed teaching practice has the potential to improve education outcomes.
2. There is an appetite for reimagining STEM education using insights from psychology and neuroscience. Teachers are generally less cautious than academics about the feasibility of implementing new practices, in particular those that involve parents in the process.
3. The commentary suggests a future in which teachers, educationists, psychologists and neuroscientists collaborate to investigate and inform teaching practice in order to develop a world-class STEM education. This requires a comprehensive dialogue between researchers and teachers. Other stakeholders will also need to be involved (including parents, the media, local authorities, central government).
4. Concerns focused on the low quality of existing educational software and its peripheral use within classrooms, while simultaneously acknowledging that technology could revolutionise education, and should be embraced. The success of educational software rests on its development by collaborative teams of students, teachers, researchers and technologists.

SUGGESTIONS FOR SPECIFIC ACTIONS

5. A maths equivalent of 'Reading Recovery' would ensure that children recording the lowest achievements in numeracy after their first year of school are able to catch up with their peers, and go on to succeed. The central importance of mathematic ability in STEM subjects underlies this suggestion.
6. Practical maths and science lessons that integrate core knowledge are desirable, as these classes would be engaging and motivating, and would develop skills that are valuable in employment and within society. This approach is supported by psychological research that shows that integrating concrete examples with abstract representations help some students apply existing knowledge to a novel domain; a skill essential in STEM subjects.
7. Teaching students strategies that maximise their learning is highly desirable and feasible, particularly as it supports life-long learning. However, it requires space in the curriculum to ensure the topic is given the gravitas it deserves.
8. Creating resources that allow parents to demonstrate STEM skills in everyday life is highly desirable, as it will improve attitudes and increase both participation and achievement. Feasibility will depend on the level of support provided to parents via resources and schools.
9. More opportunities are needed to foster the creation of links between theorists and practitioners in order to create the multi-disciplinary teams needed to bring about this positive future in STEM teaching practice.
10. We must identify and overcome hurdles to conducting research on teaching methods in schools. Hurdles include ethical consent, resourcing and recompensing teachers, use of high quality educational software that can be experimentally manipulated, remote data-collection for research purposes, research frameworks that abide by the principle of 'do no harm', and the adoption of randomised controlled trials in an educational context.

APPROACH AND METHODS[1]

We approached teachers and researchers, educationists or technologists (henceforth non-teachers) and presented them with a series of 'big ideas' that could shape the future of education if influenced by psychological research[2]. We chose these 'big ideas' in order to elicit reactions to a range of potential shifts in educational practice arising from the Mapping Study and the wider public debate on the future of education. While some of the ideas are already championed and implemented in some schools, they are not widely practiced.

We asked respondents to rate the desirability and feasibility of the 'big ideas' and comment on their ratings. We received 40 completed responses[3]. Participants were free to not give ratings and to explain their reasons in their comments. We were not expecting revolutionary insights, but rather common ground informed by many voices with first-hand experience of psychological research and / or teaching practice. Their answers showcase an exciting vision for the future of brain science[4] research in education.

[1] Appendix 1 provides a more detailed description of the methods used.
[2] Appendix 1 describes the provenance of the 'big ideas'.
[3] Appendix 4 provides names and affiliations of those respondents that wished to be acknowledged for their contribution to the report.
[4] We use the term 'brain scientist' throughout to indicate researchers of a psychological or neuroscientific field of study. We have used this term in order to embrace the full range of research areas from behavioural to biological outcomes measures.

Findings

The participants' ratings[5] of feasibility and desirability of each 'big idea' have been used to classify each one of them into four categories:

- worth actively pursuing (highly feasible and desirable)
- easy to implement (higher feasibility, lower desirability)
- worthwhile (higher desirability, lower feasibility)
- difficult and needing more research before being worthwhile (lower desirability, lower feasibility)

For each 'big idea' given below, we have summarised the concept, and followed this with a faithful synthesis of the views expressed by the respondents; illustrative quotes from respondents' comments are footnoted.

Outcomes to actively pursue:

An evidence–informed education system:

According to the Mapping Study, we can be optimistic about the increasing quantity and quality of psychological and neuroscience research that can inform education. However, improving the accessibility of research and emphasis during teacher training is a key challenge.

Respondents' Commentary:

The greatest area of concern was the maturity and reliability of research[6]. Some commented on the poor dialogue between teachers and brain scientists[7], as well as the paramount importance of interpersonal insights that are only available to teachers[8].

Many also commented on the value of psychological insights to learning[9], and suggested teachers would welcome the input, as it would improve their teaching craft[10]. Others expressed concern that psychology is likely to offer far more than neuroscience[11] and that care should be taken to avoid propagating popular neuro-myths.

[5] Appendix 2 provides an analysis of the ratings data.
[6] "Most teachers will see it as desirable but the problem of media "bad science" and contradictory scientific exercise makes it difficult to reach a consensus of opinion." Teacher
[7] "Issue of feasibility relates to a poor track record of educational psychology and cognitive psychology engaging in a meaningful dialogue." Academic
[8] "Teachers bring significant humanistic insights and acumen to their day-to-day interactions with children." Academic
[9] "Anything that has been proven to have a positive effect on learning should be pursued to help our students." Teacher
[10] "Teachers have long needed these insights - effective teachers have acquired them and have recognised their value, but a deliberate, conscious teaching of these issues to trainee teachers has now become a requirement." Other
[11] "Psychology and education science have much more to offer than neuroscience which may confuse rather than help (q.v. neuromyths)." Academic

What are the Implications of Psychology and Neuroscience Research for STEM Teaching and Learning?

Teaching students strategies to maximise their learning:

Modern psychology and neuroscience have highlighted many factors that affect academic achievement, some of which have been presented in the Mapping Study.

Respondents' Commentary:

The most frequent positive comment suggested that educating students about the factors that impact learning and cognition could be a way of promoting lifelong learning[12]. Many respondents also mentioned the importance of giving this space[13] and gravitas[14] within the curriculum and timetable[15]. Greater understanding of, and buy-in to, teaching practice by students was identified as a consequent benefit[16], as was improving revision strategies[17]. Enjoyable learning through repetition that facilitates the mastery of foundation knowledge should not be disparaged, but rather seen as essential for the subsequent acquisition of higher understanding[18]. The conflict between the crucial role of sleep in supporting cognitive function[19] and school start time and parental schedules was raised, as was the need for parental support in ensuring students get enough sleep[20]. Concern was raised that regardless of knowing these techniques, students might not use them[21].

[12] "Learning how to learn is the key to life-long learning." Academic
[13] "Feasible as many schools have time currently unused that this could fill, it would not be a strain on the timetable." Teacher
[14] "This already happens but inefficiently and with insufficient gravitas given to it." Teacher
[15] "Truly innovative, progressive schedules, programs and systems that would allow children to follow through on what they know are best practices for their lives and learning are starting to be considered and used in small private schools or by homeschoolers. [We should] educate school policy makers and administrators in the above areas so that they can start to implement meaningful schedule and educational design." Other
[16] "Many, many students do not understand how they learn. This can lead to resentment for example when asked to complete questions on a subject recently discussed, an important part of securing knowledge. This would allow them to buy-in more to the strategies used by teachers." Teacher
[17] "This lack of understanding is also found when students come to revise, many spending a lot of time on inefficient revision techniques. Breaking this cycle from the beginning will only produce happier pupils with greater understanding." Teacher
[18] "There has been a tendency to emphasise understanding and disparage rote learning that depends on repetition. But that fails to take into account the complex ways in which knowledge and competences of many kind need to be layered, with lower level layers mastered so that details are immediately accessible when needed by higher levels. Great teachers are able to develop games and class activities that have the repetition built in, laying a deep foundation for further development." Academic
[19] "Although we know that it is best for kids to get their sleep, parents are compelled to wake them up and send them to school so they can go to work." Academic
[20] "This would be easy to get teachers to promote but you would need to get parental support." Teacher
[21] "Would students apply this knowledge? That would probably be much more difficult." Academic

Feasible and less desirable outcomes:

Dual conceptual and practical science and maths lessons:

The ideal is to develop a scientific (and mathematical) enquiry curriculum that develops three characteristics in students: curiosity to frame novel questions; scepticism to investigate the answer using careful experimental design and rigorous data analysis; and an appreciation for deep explanatory theories about the natural world. This outcome requires students to apply conceptual knowledge (e.g. experimental design, statistical tests) to a novel real-world problem and to use the data generated to create for themselves an abstract understanding of the problem space.

In other words, scientific and mathematical enquiry requires transitioning between concrete and abstract knowledge, and reasoning at the appropriate level for the outcome desired. Consequently, practical (and concrete) experience of scientific discovery, and using mathematics to solve novel problems may have great educational value as they provide opportunities for students to transition knowledge between concrete and abstract domains.

Respondents' Commentary:

Respondents commented overwhelmingly on the value of developing applied, productive and creative skills in maths and science alongside traditional theoretical and conceptual understanding[22]. The main reasons for support were student engagement and motivation[23], and developing the most essential skills[24] for long-term participation in STEM subjects[25] [26] that are valuable in employment[27] and in society[28].

Many commented that students had greater capacity to learn through self-discovery than is currently reflected in teaching practice[29]. Confident[30] and well-resourced[31] teachers were considered critical to successful, widespread implementation of practical learning opportunities, as was the necessity of integrating theoretical and enquiry-based learning[32]. Conceptual and practical classes in science and maths should be complementary[33].

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22 "It would be brilliant if everyone could apply the knowledge they learn it a practical way." Teacher
23 "This is most desirable because pupils will most certainly learn better if they are engaged and curious about a subject area." Teacher
24 "This would make STEM subjects much richer fields of learning. Context is a most useful aid to learning and memory. " Academic
25 "Dual factual and practical science and math programs would be an optimal solution to many issues in teaching these subjects. The truly meaningful aspects of learning math and sciences could be reinvigorated. " Other
26 "Lots of the key skills to becoming a scientist revolve around experiments- planning, implementing and analysing. Separating the teaching of these skills from the teaching of pure fact would allow more focus on these key and often overlooked skills. However the teaching of scientific history can also act as a perfect partner to these practical lessons. By using examples of history and how scientists actually used the practical skills that are about to be taught, teachers can paint a fuller picture and engage students on an emotional level as well as the logical one." Teacher
27 "This would prepare students for their working life which is likely to necessitate this type of skills." Academic
28 "Pupils need to understand the maths behind scientific theories and claims if they are to be informed citizens." Teacher
29 "Groups of children, with Internet access, can learn anything by themselves." Other
30 "This requires teachers who are confident in their subject knowledge. They will need examples and general help." Academic
31 "It may be difficult to implement research projects in schools, considering the limitations of the teaching staff and schools in terms of equipment and time." Academic
32 "Ideally the two approaches should be balanced. Knowledge of key concepts underpins the application of that knowledge to create new solutions and thinking." Other
33 "The three types of classes (science history, practical science, and practical maths) could complement one another. Students could study the history of a scientist and a particular technique they used, then go on to design and implement their own experiment using this technique, then analyse their data results in the maths class. This way the functional and theoretical aspects would remain separate and distinct whilst still providing an overarching narrative to engage the students." Teacher

Desirable and less feasible outcomes:

Encouraging parents to demonstrate STEM skills in everyday life:

Numerous initiatives (e.g. BookStart) have promoted an understanding among parents of the importance of reading with their children. This act demonstrates the cultural value and purpose of reading and writing, fosters positive attitudes amongst children, and ultimately improves children's reading performance (Senechal & LeFevre 2002). Resources that correspondingly engage parents and children with STEM subjects may similarly improve attitudes to those subjects.

Respondents' Commentary:

Creating resources that allow parents to demonstrate STEM skills in everyday life is highly desirable, particularly among teachers where this rated as the most attractive 'big idea'. The main concerns raised were whether parents had the necessary skills and knowledge[34] and whether they would see the value of it[35]. Care should be taken to avoid increasing inequality between socio-economic groups by making demands of parents that only some can achieve[36]. Concern was also raised about removing focus from reading as it is a core skill for accessing all subjects including STEM subjects[37].

The most common positive comment judged that encouraging parents to demonstrate STEM skills in everyday life would improve attitudes[38] and increase participation and achievement[39]. Many respondents also mentioned that resources would be easy to create[40] and be popular with children[41]. A greater understanding of STEM subjects by parents was seen as an ensuing benefit that may help change the wider culture[42].

[34] "Not all parentally transmitted teaching is always positive or even correct, let alone inspiring. Parents themselves frequently under educated and are thus less confident in passing on their knowledge." Other
[35] "This will be difficult to achieve as it will involve changing the culture of society and there are inevitably parents that will not engage or see value in it" Teacher
[36] "This must not become yet another means by which those parents with the knowledge, skills and awareness further enhance their children's chances at the expense of those parents who are less able to provide this level of support and engagement." Other
[37] "Be wary of diluting the emphasis on the need for parental involvement in reading - reading is the way in to many STEM activities." Academic
[38] "This must be done. Pupils surely get most of their thoughts and feelings about school from their parents. If the parents are encouraging and nurturing in the same way as the school, the development of the child can only improve." Teacher
[39] "A brilliant idea that could make science and other areas second nature to students." Teacher
[40] "Science is actually extremely popular with people of all ages. Educational videos would be a very easy way to engage parents, likewise suggestions of simple and safe experiments." Academic
[41] "Many parents would welcome books and other tools to do this. Children would love it. Possibly even more than story books." Academic
[42] "Parents will improve their own understanding of STEM subject areas, improving their ability and producing more STEM-positive mind-sets." Teacher

Fostering closer relationships between teachers and researchers:

Research institutions and health practitioners frequently collaborate in multi-centre randomised controlled trials (RCTs) to evaluate behavioural interventions informed by psychological science to support primary care. Examples include advice on quitting smoking and weight-loss guidance. Education may similarly be transformed by fostering a closer relationship between research institutions and schools, with RCTs of classroom interventions accelerating adoption of new practices informed by the brain sciences.

Respondents' Commentary:

Academic respondents raised concerns about the transferability of research to the classroom given the wide range of physical, social and teaching environments[43]. Both non-teachers and teachers raised the issue of the cost[44] of compensating teachers[45] for involvement, with teachers additionally indicating that they have little time[46]. A lack of shared culture and even distrust between researchers, schools, teachers, students and parents were judged to reduce the feasibility[47].

Nevertheless, the idea was generally seen as highly desirable[48], particularly if reciprocal[49] and based on developing deep predictive models of learning. The use of RCTs was raised conditionally under the principle of 'do no harm'[50]. Ethical approval was seen as a stumbling block that will need to be overcome by engaging school authorities[51]. One teacher was very positive about the benefits of collaborating directly with researchers, rather than via other mediating bodies[52].

[43] "What works in one setting does not necessarily work in others - due to the wide range of variables present - physical environment, social environment, quality of teaching etc." Other
[44] "Teachers and school are up for it and enjoy engaging with educational research but the cost of releasing teachers from classroom duties to allow time for this is prohibitive to schools." Teacher
[45] "The difficulty here comes from the likely perception of both practitioners and researchers of having to bear an added burden. Usually this can only be negotiated by increases in salary." Academic
[46] "The difficulty will be to fund teachers to increase their non-teaching time to enable them to engage with research." Teacher
[47] "I can imagine teachers, parents and schools reacting negatively to such repartnerings. Part of what may foster a more positive, open attitude among teachers, schools and parents might have to do with focusing, above all, on the needs of the students." Other
[48] "This should be done, and the only real place to test and validate education hypothesis is in real classrooms." Other
[49] "I like the fact that this includes research being informed by practice and learning from practice." Academic
[50] "There are strong ethical considerations around experimenting with children's education. This may be mitigated by modelling on medical trials and offering the experimental method of education on top of what is currently already done, to ensure nothing is lost." Other
[51] "The timeframe of 2033 is a good one to support this point. It gives enough time for researchers to get more involved and thorough educational trials to be held in order to help improve education practice for the better. It also gives time for this whole procedure to be set up and approved by government/school authorities." Other
[52] "Having worked closely with [researcher name provided], the benefits of working with professionals outside of schools are immense. I would love for us to work more closely with research institutions to develop cutting edge curricula and schemes of work for students and to cut the politics out altogether. Surely all this needs is teachers to be given a little more time and space to have discussions with researchers and dialogue to be initiated." Teacher

Outcomes that are difficult and need careful design to be worthwhile:

Aligning education with childhood development:

The Mapping Study described the on-going research into those precursive abilities (i.e. executive function) that relate to early success in school. This research area may result in (1) tools for assessing precursive skills and (2) targeted catch-up programmes for disadvantaged learners. These tools might be useful from reception until the end of compulsory schooling, but may be of particular value at transition points, such as the start of primary and secondary school. Data about typical and individual difference in cognitive and emotional development may also inform curriculum aims and design.

Respondents' Commentary:

The most frequent positive comment referred to motivational[53] and engagement benefits of providing an environment in which learners succeed[54]. The most common negative comment referenced the need to recognise individual variation[55] and the need for appropriate challenge[56]. Others commented that age (the existing metric) is a poor determinant of ability[57] and that managing heterogeneity in the classroom is a challenge for teachers, which is not always successfully addressed[58]. A neuroscientist commented that current research would support this endeavour[59], but two teachers expressed concern that psychological evidence can be overstated[60] and inappropriately communicated[61]. The use of games[62] and individually adaptive teaching software[63] may increase feasibility, as would a more flexible starting age of school[64]. Resistance from teachers due to lack of resources[65] or conservative mind-sets[66] may decrease feasibility.

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[53] "A curriculum tailored to the stage of development would be more motivational to young people and provide appropriate stretch and challenge." Teacher

[54] "Children who consistently fail very quickly become disillusioned unmotivated and disruptive. Any challenges to feasibility would be balanced by motivated learners." Other

[55] "Individuals are going to be different, and therefore it would difficult to accurately design a system to fit around something so variable as brain development." Other

[56] "There is an issue of offering young people what is believed to be the correct level of education based on their perceived abilities, rather than their actual or potential abilities - and stretching and challenging young people, beyond their perceived ability remains an important." Other

[57] "It is desirable, because children differ widely in the pace of development and chronological age is a poor indicator." Academic

[58] "Good / effective teachers would probably argue that they already do, albeit frequently at the sub conscious, instinctive level. Elevating this to a more conscious, planned level is, intellectually clearly the correct thing to do." Other

[59] "More knowledge is being collected about cognitive development, and the enthusiasm for educational neuroscience suggests that experimental studies investigating changes in education to match cognitive development will be run in the coming decades." Academic

[60] "Our knowledge of the brain and how it develops is improving, but it is still no-where near the level where we could, or should, confidently use it to make decisions for us." Other

[61] "For this to happen a system needs to be place where the results of new neuroscience and psychology studies should be readily available to teachers in a digestible format." Other

[62] "Games tend naturally to adapt to the developmental stage of the child/adolescent, but only if they are facilitated correctly. So much waste in that, when it could relatively easily be improved manyfold." Academic

[63] "With new technologies we can change assessment to track growth." Academic

[64] "It might be desirable to include options for repeating a year or postponing school entry when the child is clearly not at the right developmental stage to benefit from formal teaching." Academic

[65] "The issue is with the right will on the part, and training, of teachers and schools, and with the right resources." Academic

[66] "Research is easy compared to conservative mindsets - on the part of teachers." Academic

Mastering key facts and skills using online teaching platforms:

Online teaching platforms (e.g. The Khan Academy) that are enhanced to leverage the same engagement and motivational characteristics of computer games could benefit students and teachers[67]. Additionally, such platforms offer instantly accessible information on all students' progress, thereby facilitating rapid intervention – programmatic and teacher led – for struggling individuals.

Respondents' Commentary:

Teachers and non-teachers had similar desirability and feasibility ratings for this idea. Overall there were serious concerns that must be addressed in order to make it worthwhile. Existing learning games[68] and teaching platforms[69] are not good enough to be of widespread use in classrooms and should be improved by having a closer relationship to pedagogy[70], be of higher quality[71], as well as tested[72], peer-reviewed and certified by teachers[73]. Adaptive online learning is a good target but should complement rather than replace traditional methods[74] that benefit from social and collaborative elements[75].

Individual adaptivity that personalises education is the main gain[76]. Some existing resources (BBC Bitesize, Mathletics, Khan Academy) are effective and easy to use[77]. Interactive problem-based platforms might also offer excellent and social learning experience[78] (e.g. brilliant.org). Nevertheless, effective use often requires adult supervision[79] [80] and care should be taken to avoid increasing inequality of education[81]. Online delivery systems enable economies of scale that support the inclusion of minority interests[82], multiple approaches to teaching the same topic, collaboration with experts[83], rapid updating of curricula[84], and the sharing of outstanding teachers across the world[85].

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[67] Some core characteristics of computer games are that they provide individually adaptive environments that evoke deliberate practice to achieve mastery and that success has some element of chance.
[68] "Sometimes it works (mathletics), some examples are really patronising and time wasting." Teacher
[69] "Khan Academy is poor quality compared to what could be done online, with intelligent systems." Academic
[70] "Good idea but needs to be supported by specific pedagogical skills to make best use of it." Other
[71] "The utilisation of technology to enhance learning has surely got to be one of the key focusses of the next period of time. However, we must insist on the very highest quality rather than the latest good idea." Teacher
[72] "I am all in favour of new technologies being used well but a lot of piloting and development work will be needed." Academic
[73] "By 2033 … schools should be capable of quickly testing, validating, then adopting new technology." Teacher
[74] "programmed instruction has long been a goal, to complement traditional instruction" Academic
[75] "It is important not to neglect the social aspects of learning." Academic
[76] "Any initiative acknowledging individual differences and engaging learners accordingly is desirable." Academic
[77] "Pupils already use BBC Bitesize to revise which they find easy to access and user friendly!" Teacher
[78] "An interactive problem-based collaboration focused platform would be great." Academic
[79] "No technology can make up for having a teaching professional present as nothing is more engaging than an actual human being." Other
[80] "This can be very effective (my wife uses it a lot in her home tutoring), but it does require supervision." Academic
[81] "The access [to technology] that children have in school and at home must be the same for all." Teacher
[82] "Most games encourage additional exploration (eg: through hidden power ups / game items and/or by offering achievements). These can be used to tempt students to explore some subjects in further detail than what is already covered in class." Other
[83] "Games or digital technologies could offer the ability to easily collaborate with classmates or even STEM professionals." Other
[84] "Digital software is easier and cheaper to update, meaning students could always be taught the latest theories in any STEM area." Other
[85] "We need MANY, and probably constantly changing/evolving teaching platforms, selected by groups of teachers according to their needs, talents and interests, and the requirements of their pupils, selected from all over the world, and shared with outstanding teachers in other countries." Academic

DATA-DRIVEN IMPROVEMENT OF ONLINE CURRICULUM AND CONTENT

Digital technology can unobtrusively capture a range of objective and subjective performance metrics. Its use could broaden the range of information used by teachers and other bodies to inform teaching and curricula development. By combining the analysis with demographic and self-reported interest data, new domains of the curriculum could be developed to better engage specific groups of students whose needs and interests are not currently met.

Respondents' Commentary:

Teachers and non-teachers had significantly different opinions about data-driven improvement. Non-teachers rate desirability higher than feasibility and the reverse pattern is seen for teachers. Both groups are concerned with the choice of performance metrics[86] and that data could instead be used to judge teachers[87]. It is also essential that data collection and subsequent use is not onerous to teachers[88] or students[89], and is not used to label students who may develop in different ways[90]. Valuable data would balance short- and long-term performance metrics[91] with the aim of informing how to best develop knowledge and skills that can be applied flexibly and creatively to new challenges throughout life[92].

Nevertheless, academics saw huge potential in tracking real-time indices of student learning[93] that illuminate the different trajectories towards mastery[94]. Systems and the data collected should be designed and controlled by educators and students[95]. Some outstanding schools have achieved this, but it requires huge levels of trust between staff[96].

[86] "The difficulty for education in using data is that the overall goal of education is hard to define." Other
[87] "Not always trustworthy as data can become the way staff are judged and lead to teaching to the test and manipulation of certain data." Teacher
[88] "Automatic monitoring and data collection should relieve teachers of a lot of admin. There are pitfalls in making this too centralised." Academic
[89] "Everything that distracts the teacher from immediate interaction with his/her students is a bad idea." Academic
[90] "The data used at the moment is often poor e.g. KS2 results. Pupils become labelled very early on in their lives. This is not always desirable; pupils develop in different ways." Teacher
[91] "Data driven improvement is always a sound strategy - the key question for education is what exactly are the measures we are trying to improve. Schools often use exam results, but does this hold any relevance once the students enter the real world?" Other
[92] "How can we get kids to develop their information-processing architectures so that they can deal flexibly with new challenges and opportunities in later life and come up with novel creative solutions to hard problems?" Academic
[93] "There is no doubt that modern information systems, machine learning, and "big data" should be harnessed to provide real-time indices of student learning for teachers and administrators." Academic
[94] "Big Data and new technologies allow for the collection of copious data and good data mining so we can focus on growth, development, and different trajectories towards mastery. The task is easy in the sense that we know enough now to start. It is hard in the sense that there is much to learn and some harm we can do if we are not careful." Academic
[95] "The system must be designed by educators and learners, not computer techies. It should be un-intrusive, flexible (teachers and learners choose what data is collected for what purpose), powerful (collect qualitative data) and provide instant feedback." Academic
[96] "Outstanding schools are already doing to this to a large extent. It involves a huge amount of trust in the systems and in the reasons for doing it, but is a hugely powerful tool." Teacher

Functional specialism within the teaching profession

Unlike in other sectors (e.g. medicine or business) teachers are expected to fulfil a wide range of functions, including lesson designer, coach, counsellor, and disciplinarian. The teaching profession may benefit from developing individuals into functional specialists with particular expertise. This would be an efficient way to increase the skill sets available in schools to include novel proficiencies such as collaborating in academic research, curating online platforms, performing statistical analyses of performance data, or creating educational games.

Respondents' Commentary:

Functional specialism within the teaching profession scored relatively low on the feasibility scale. Teachers rated the desirability more highly than non-teachers, but it was nevertheless low priority. The main concerns raised were to avoid a 'production line' mentality[97], as teachers like the variety in their work[98] and the teacher-student relationship is of paramount importance[99]. Nevertheless, functional specialisation and collaborative teaching may help less able teachers[100], is attractive to some teachers[101], and may revitalise teacher training and careers[102].

To some extent, functional specialism already happens: outside school people specialise in developing new resources and practical activities, setting curriculum and national examinations[103]. Within school, teachers take on responsibility for broader school improvement[104]. However, closer relationships with businesses and universities may be useful to support these endeavours[105].

[97] "An intelligent workforce needs diversity in their daily tasks - production line mentality is ill-suited to education." Academic
[98] "Teachers are teachers because they relish taking on all of the roles mentioned above." Teacher
[99] "Classroom assistants can be of help, especially in lab sessions but nothing should stand in the way of the teacher engaging with his/her students." Academic
[100] "This is desirable for average or poor teachers but not for good / outstanding teachers." Teacher
[101] "This sounds like paradise! Teachers are expected to possess such a wide range of skills and so a shift to specialising in order to be more effective seems great. The teaching team should consist of different people with different skills. For example, I am effective in communicating with students, working with them in the classroom environment but would appreciate working alongside someone able to generate some creative ideas about teaching approaches that could then be developed and used." Teacher
[102] "This has the potential to revitalise teacher training and teaching careers." Academic
[103] "We already have such specialism - different people often specialise in developing new resources (e.g. textbook writers), developing new practical activities (e.g. those who work for SAPS, NCBE, ASAB), science technicians, those who set national examinations, etc." Academic
[104] "There is already the scope available for those with an interest in data analysis, pedagogy etc to take this further as a teacher and contribute ideas towards improving the running of the whole school. Having individual experts liaise with schools would be of benefit but forcing teachers into these pigeon holes whilst taking away their control of the entire teaching process would be very negative for teachers, students and learning." Teacher
[105] "A stronger link in schools to the professional STEM community could help bring some functional specialism into the classroom and inspire the children. There is definitely value in having teachers more involved in the vision of education, [...] where they can collaborate with business to help develop teaching equipment and platforms." Other

Future research

Respondents raised a balance of education science and psychological science questions[106]. These highlight the wide range of envisaged possible futures[107]. Some assume the continued existence of classrooms, teachers and direct-instruction[108], while others envisage a larger role for learning software[109] combined with greater opportunities for self-directed learning[110].

One respondent suggested a maths equivalent of 'Reading Recovery'[111] which might ensure that children who are the lowest achieving in numeracy after their first year of school also catch up with their peers and go on to succeed. This suggestion is supported by the central importance of mathematics ability in STEM subjects and the evidence discussed in the Mapping Study about precursors for achievement.

Another respondent asked whether children can learn to read by themselves. Evidence-informed games exist online that train elements of learning to read (i.e. GraphoGames); it may be possible for academics, teachers and game developers to collaborate to create and test adaptive learning games that teach children to read. This suggestion is supported by the central importance of reading ability in STEM subjects.

[106] Appendix 3 provides a selection of the topics raised.
[107] "The typical classroom dynamics of sitting students down in rows of desks, with one teacher lecturing the whole class for a good portion of the day, for nine months of the year, on the content that is supposedly essential for the students to learn that year, is clearly a relic of the past. Yet any innovations in the classroom are merely details or embellishments tacked on to what is never questioned to be the only option for a learning model." Other
[108] Learning in classrooms is a complex system in the technical sense and therefore not open to controlled studies. We need to know how classrooms operate as complex systems and what limits this puts on inferences we draw from controlled studies." Academic
[109] "The effectiveness of remote learning (Khan Academy) in comparison with teacher led, classroom-based learning." Teacher
[110] A study on how long it takes a group of children to 'know' something without being taught, but by using the Internet. Other
[111] 'Reading Recovery' helps children who are the lowest achieving in literacy after their first year of school to catch up with peer at the start of school, and provides a foundation for long term success. (http://readingrecovery.ioe.ac.uk/about.html)

Discussion

Some themes arose from the commentary across the overall questionnaire:

1. Respondents were generally positive[112] to both the desirability and feasibility of the ideas presented, and to the overall ambition of the Royal Society[113] to champion a world-class STEM education[114] and suggested partners with whom to collaborate[115].
2. Respondents demonstrated visionary thinking and envisaged a wide variety of possible futures, while remaining grounded in reality. They raised legitimate and thoughtful political, economic, social, technological, legal, ethical and demographic constraints.
3. Respondents identified the need for multi-disciplinary collaborative teams to advance educational research and technology; with a particular emphasis on the unique insights brought by teachers.
4. Numerous stakeholders outside the school environment (parents, the media, local authorities, central government) influence teaching practice. A constructive relationship with these groups and their support of the overall vision will be essential.
5. The positive benefit of cultivating motivated, engaged, happy and curious students that enjoy learning and the central importance of the teacher-student relationship was raised multiple times, as was the social experience of learning.
6. Respondents commented on the importance of equipping students with an explicit understanding of the transferability of their learning, skills and learning skills beyond the confines of the classroom in all domains of life. Some examples include, learning how to learn and applying abstract knowledge to novel concrete problems.
7. Facilitating appropriate challenges in heterogeneous classrooms is difficult. Games and intelligent learning systems were suggested as solutions; but, existing educational software and games were described as being of low quality, poorly linked to pedagogy and used ineffectively[116].
8. Any demands on teachers, researcher, parents or students beyond their existing responsibilities must be properly resourced and supported with time, money and training. New initiatives should be shown to add value compared to displaced initiatives.

[112] "I like all the proposed ideas." Academic

[113] "I am really encouraged the Royal Society is taking a lead on this." Academic

[114] "Just to say that I very much the approach you are taking in this project. Science and Maths education is in deep trouble and a fundamental re-think is absolutely essential." Academic

[115] Particular mention was made of the Wellcome Trust, the Nuffield Foundation, Mathematics Mastery and the Education Endowment Foundation.

[116] "Debriefing is the key to learning from games, and yet it is hardly ever done, and when done, is badly done!! Too much hype about games because kids like them, but little done to help games actually produce learning." Academic

SYNTHESIS

There is definite appetite for the 'big ideas' presented, with some schools already implementing the types of ideas suggested here. The heterogeneity in teaching practice points to a freedom to experiment where there is enthusiasm, appropriate resourcing and commitment from stakeholders. This in turn suggests that incorporating multidisciplinary collaborations between teachers, researchers and technologists will be possible where there is the will and stakeholder support.

The Mapping Study presents a substantial literature that could inform teaching practices. This suggests that an evidence-informed teaching practice has the potential to improve education outcomes. Current practice has often developed slowly via trial and modification: while it is therefore likely to be effective, it has not yet been subjected to the type of rigorous testing required of behavioural health initiatives[117]. The case could be made that it is unethical not to bring a disciplined scientific evaluation process to the development of a world-class education system.

The commentary suggests a future in which teachers, educationists, psychologists and neuroscientists collaborate to develop a world-class STEM education. As existing relationships are weak, the notion of an evidence-informed teaching practice is in its infancy; as such, development will be evolutionary, rather than revolutionary, and will take time to mature. Behavioural health research models may provide an example of a viable approach. New practices, initiatives or resources should be certified by a recognised institution to protect all stakeholders from low quality offerings.

Aside from digital technology's potential educational value[118], from a research perspective, widespread use of educational software would enable large-scale, yet unobtrusive, data-collection for research purposes. Furthermore, educational software developed by research teams could facilitate controlled experiments within their design. The success of research via educational software will rest on collaborative teams of teachers, researchers and technologists supported by appropriate governance and ethical frameworks.

CONCLUSION

Key observations and suggestions for specific actions are provided in the executive summary. Ultimately, the future of incorporating the principles derived from neuroscientific and psychological research into educational practices will arise from high quality multi-disciplinary collaborations. It is by harnessing and uniting the expertise of many separate fields that we will develop a world-class STEM education.

[117] Examples include advice on quitting smoking and weight-loss guidance.
[118] For instance: rich educational simulations and games, individually adaptive learning programs that provide appropriate challenge, automated assessment and instant feedback, teaching of minority interests across geographic areas where teachers are not available, broadcasting the very best lecturer to all students and low cost revision of existing materials and distribution of new materials.

APPENDICES

APPENDIX 1: METHODOLOGY

APPROACH:

The initial concept was to ask psychologists, neuroscientists, education scientists and teachers, about the impact and educational value of the psychologically informed teaching practices arising from the Mapping Study. However, the Mapping Study highlighted the gulf between psychological research and educational practice and revealed little common ground to explore.

Instead, we asked academics, teachers, educationists and technologists about the 'big ideas' that could shape education if influenced by psychological research. The 'big ideas' presented were extrapolated either from the Mapping Study or from the public debate on the future of education.

PARTICIPANTS

Responses where gained from: 15 academics (5 STEM, 5 Psychological Sciences, 5 Education Science), 15 teachers, 10 others (educationists, technologists, others). Many respondents also brought broader experience shown in the table below. All except three wished to be acknowledged as contributors to the report.

At least one year's experience in …	Count
Creating and curating online learning resources	9
Creating extra-curricular learning experiences	20
Designing and developing educational games	7
Developing educational technology	8
Researching a psychological, neuroscientific or educational science at postgraduate level	13
Researching another STEM subject at postgraduate level	12
Teaching in a primary school	4
Teaching in a secondary school	17

MATERIALS

Participants completed an online questionnaire by rating (Likert scale (1-7): 1 low, 7 high) the desirability and feasibility of 'big ideas' for education and provided comment on their ratings (or lack thereof).

All these were prefaced by a vignette which served to explain and expand upon each 'big idea' to ensure they were all comprehensible to a non-academic audience unfamiliar with the terminology used.

Questionnaire Questions

- Rate the desirability and feasibility of:
  1. systematically designing education to align with childhood development.
  2. encouraging parents to demonstrate STEM skills in everyday life.
  3. teaching students strategies to maximise their learning.
  4. dual factual and practical science lessons.
  5. dual factual and practical maths lessons?
  6. teaching key facts and skills using an online teaching platform bespoke to the UK curriculum.
  7. data-driven improvement of curriculum and content.
  8. functional specialism within the teaching profession.
  9. an education system informed by evidence from the psychological, neuroscientific and educational sciences.
  10. fostering closer relationships between teachers and researchers.
- Other Questions:
  11. What questions about teaching practice would you like to have researched?
  12. Do you have any other thoughts that you would like to share with us?

The provenance of the questionnaire questions

The 'big ideas' presented were extrapolated from the Mapping Study, workshops facilitate by the Royal Society Vision Committee team or from the public debate on the future of education.

The idea of 'systematically designing education to align with childhood development' (Question 1) stems from the research into precursive cognitive abilities, as discussed in the Mapping Study, and their impact on school outcomes. We have extended this idea beyond the precursive cognitive abilities at the start of school, to ask how an understanding of general and individual physical, emotional and cognitive development could shape teaching practice and curriculum design to the end of compulsory schooling.

The idea of 'encouraging parents to demonstrate STEM skills in everyday life' (Question 2) stems from the research into the impact of parental attitudes on students' attitudes and school outcomes, as discussed in the Mapping Study. Changing parental attitudes, or helping parents to demonstrate positive attitudes, may change student attitudes and impact school outcomes.

The idea of 'teaching students strategies to maximise their learning' (Question 3) is an example of the "application of psychology and neuroscience to teaching and learning" as requested by the Royal Society but not addressed in the Mapping Study. There is evidence that students perform better if they are made aware of better revision techniques and apply them (Koriat et al., 2004).

The idea of 'dual factual and practical maths and science lessons' (Questions 4 and 5) stem from research into the development of abstract knowledge, presented in the Mapping Study, and how to ensure this knowledge is activated in 'real world' circumstances (Goldstone & Son, 2005).

The idea of 'teaching key facts and skills using online teaching platforms' (Question 6) comes from the growing interest in online teaching platforms (e.g. Khan Academy, MOOCs)[119] and in particular adaptive learning platforms (e.g. Reading Eggs[120], GraphoGames).

[119] http://www.scientificamerican.com/article.cfm?id=big-data-make-big-inroads-into-schools
[120] http://www.economist.com/news/briefing/21580136-new-technology-poised-disrupt-americas-schools-and-then-worlds-catching-last

The idea of 'data-driven improvement of curriculum and content' (Question 7) is logically derived from the potential to increase the use of online teaching platforms as, if they prove successful, they will enable vast metric tracking that will facilitate continual improvement and may inform education research.

The idea of 'functional specialism within the teaching profession' (Question 8) arises from the broad observation that in order to pursue the other ideas suggested, teachers' roles are going to need to encompass far more skills than they currently do. One realistic solution to this is facilitate functional specialism within the teaching professions, whereby different individuals within a school or geographic area offer expertise in particular domains. For instance, creating content for online platforms or collaborating with researchers.

The idea of 'an education system informed by evidence from the psychological, neuroscientific and educational sciences' (Question 9) is the central question addressed by the Mapping Study.

The idea of 'fostering closer relationships between teachers and researchers' (Question 10) arises directly from the conclusion of the mapping study as a way of facilitating 'an education system informed by evidence from the psychological, neuroscientific and educational sciences' (Question 9).

The invitation to suggest 'questions about teaching practice that you would like to have researched' (Question 11) was included in order to evaluate whether there is common ground between teachers and researchers that would benefit from 'fostering closer relationships between teachers and researchers' (Question 10).

The invitation to express 'any other thoughts that you would like to share with us' (Question 12) allowed us to capture any other comments.

PROCEDURE

Participants known to the Royal Society were invited by email to participate in an online questionnaire that was expected to take around 30 minutes to complete. After completing the questionnaire, respondents nominated additional people to participate. We received 40 completed responses; three expressed concern and four expressed positive attitudes to the questions or approach taken by the questionnaire.

ANALYSIS OF RESPONDENT COMMENTS:

Respondents provided comments to the 'Big Ideas' in two free text boxes labelled 'this is not desirable or feasible because' and 'this is desirable and feasible because'. This allowed us to separate comments of concern from comments of support. The themes raised by the comments generally were listed and for each comment all the themes raised were marked. This allowed us to identify the most common themes raised.

CRITERIA FOR INCLUSION:

It is not possible to report all the data gathered; inclusion was guided by the topic's relationship the mapping study, the brain sciences and the Royal Society's Vision Committee Aims.

"We want inspirational education systems that will deliver both scientifically and technologically informed, engaged citizens and appropriate numbers of qualified people who wish to take up science and technology-based careers." Sir Martin Taylor

National numeracy and literacy statistics that show that[121]:

- ~80% of adults in the UK have maths skills below an equivalent to GCSE A*-C grade.
- ~50% of adults in the UK have literacy skills below an equivalent to GCSE A*-C grade.

Therefore, we have interpreted the aim to mean that we should transform education for all students so that levels of STEM literacy in the adult population are altogether higher and the numbers who wish and are suitably equipped to pursue STEM or STEM-related careers increase. To this end, we have prioritised discussion and commentary of 'big ideas' that will transform education for the central cohort of students, the 60% that surround the average performance, by prioritising ideas that benefit primary and the equivalent of pre-GCSE learning rather than learning at higher levels.

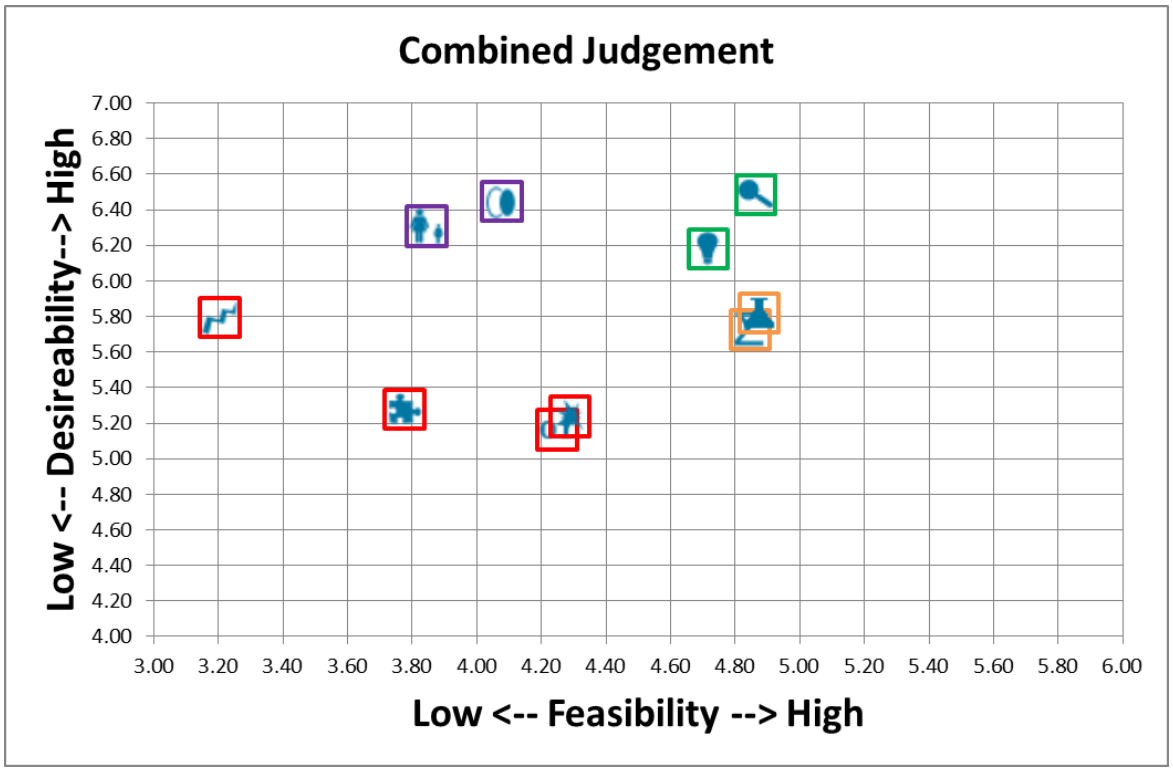
[121] http://www.nationalnumeracy.org.uk/news/16/index.html

Appendix 2: Results

Ratings of Desirability and Feasibility

The statements given for respondents to respond to were vignettes of a 'visionary' future, and as such were optimistic. It is not appropriate to infer desirability and feasibility from these ratings alone. Relative desirability and feasibility may provide some guidance as to which ideas should be most actively pursued. Generally, desirability scores were higher than feasibility scores.

Relative Ranking:

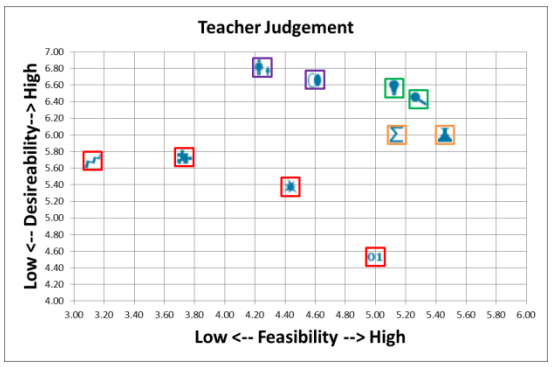


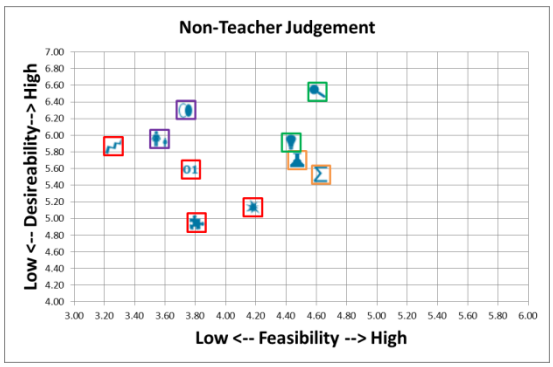
Creating an education system informed by evidence from the psychological sciences and teaching students strategies to maximise their learning were given the highest ratings for desirability and feasibility. This category of ideas should be actively pursued (green outline).

Dual factual and practical maths and science lessons were considered desirable and highly feasible suggesting that they could be introduced quickly (orange outline).

Fostering a closer relationship between teachers and researchers and encouraging parents to demonstrate STEM skills in everyday life were considered difficult but worthwhile (purple outline).

Aligning education with childhood development and functional specialism within the teaching profession received the lowest feasibility scores. Using adaptive online technology to teach facts and skills and data driven improvement received the lowest desirability scores. However, the scores were not low, indicating that these ideas need to be considered and designed carefully to address shortcomings and thereby maximise their potential (red outline).





Large differences in opinion between non-teachers and teachers are seen for encouraging parents to demonstrate STEM skills in everyday life, dual factual and practical science lessons and data driven improvement. High consistence in opinion was seen for aligning education with childhood development and using adaptive online technology to teach facts and skills.

RESPONSES

The table below provides the number of people that responded at a given rating level to the desirability and feasibility for each question. To illustrate, the mode response to the data driven improvement desirability question was a '7' (high) with 14 responses at this level. In contrast, the mode response to the corresponding feasibility question was '3' with 9 responses at this level.

Rating	1	2	3	4	5	6	7
desirability	10	11	10	30	55	69	184
dataDrivenImprovement	2	2	2	7	7	3	14
developmentTrajectories	1		1	4	7	11	15
evidencePsychology				1	4	8	24
fosteringRelationships				1	3	12	22
mathsDualComponent	1	2	2	1	6	3	18
parentRoles		1		2	5	6	25
scienceDualComponent		3		3	6	3	18
studentLearning			1	3	5	9	21
teachingRoles	4	2	2	1	6	5	16
technology	2	1	2	7	6	9	11
feasibility	19	36	75	75	71	46	45
dataDrivenImprovement	2	2	9	8	6	5	4
developmentTrajectories	5	9	10	7	6		2
evidencePsychology	1	3	3	6	11	6	7
fosteringRelationships	3	4	8	7	8	4	4
mathsDualComponent		2	5	7	9	2	8
parentRoles	3	6	9	9	4	4	4
scienceDualComponent		1	7	6	5	7	6
studentLearning	2	1	6	8	7	10	5
teachingRoles	3	5	6	9	10	2	1
technology		3	12	8	5	6	4

APPENDIX 3: FUTURE RESEARCH

WHAT QUESTIONS ABOUT TEACHING PRACTICE WOULD YOU LIKE TO HAVE RESEARCHED?

Respondents were also asked to suggest questions for further research. The following are a selection of specific topics raised.

- Psychological questions:
    - Sleep and school start times
    - Impact of diet, breakfast and snacking on learning and attainment
    - How to balance direct versus indirect learning
    - Effectiveness of self-directed learning
    - Impact of the timing of feedback
    - Developing relational versus instrumental learning in mathematics
    - Development and layering of abstract reasoning
    - Developing problem-solving and knowledge transfer
    - Impact of threat perception among learners
    - How to change the beliefs and attitudes of teachers
- Education Science questions:
    - Effectiveness of remote learning (i.e. Khan Academy)
    - Can software be developed to teach children how to read independently?
    - Can a 'maths' equivalent to 'reading recovery' could be developed?
    - Impact of setting in mathematics
    - Impact of class size
    - Impact of long summer holidays
    - Impact of charismatic teachers
    - How to foster curiosity, engagement and self-motivation
    - How content mastery impacts confidence
    - The value of the teacher-student relationship and how this changes in secondary school
    - Impact of access to technology (calculators, internet) during assessment
    - Reliability and quality of peer assessment
    - Stress and resilience screening for teachers
    - Dynamic and ecology of existing classrooms
    - Dynamic and ecology of self-directed, investigative and facilitated classrooms

Teachers were interested in a wider range of topics including the impact of sleep, diet, threat perception, setting and stress. Some topics have an established academic literature perhaps indicating that this knowledge has yet to be successfully communicated to teachers or that it is a growing and promising area for future research (abstract reasoning, knowledge transfer). Other topics have an established literature outside the context of education that might be inferred from (attitude change, charismatic leadership).

APPENDIX 4: ACKNOWLEDGEMENTS

The following respondents would like to be acknowledged for their contribution to the report.

Name	Affiliation
Barbara Thompson	Caterham School
Ian Crews	Bodmin College
Dan Kirby	The Cooper School
Lucy Hudson	South Hunsley School
Karen Dow	South Hunsley School
Mike Ollerton	Making Mathematic Accessible
Simon Clay	Mathematic in Education and Industry
Craig O'Hara	South Hunsley School
Kate Chaytor	Sacred Heart Language College
Dennis Archer	Bedales School
Ged Green	Bedford School
Dan Honnor	Bedford Modern School
Daulton Redmond	RSA Academy
Professor Anne Watson	Department of Education, Oxford University
Professor Michael Reiss	Institute of Education
Professor James Gee	Arizona State University
Dr Stephen Campbell	Simon Fraser University
Dr David Crookall	University of Nice
Professor Chris Jarrold	Bristol University
Professor David Green	UCL
Dr Iroise Dumontheil	Birkbeck
Dame Uta Frith, FRS	UCL
Dr Sashank Varma	University of Minnesota
Professor Steve Furber, FRS	University of Manchester
Professor Jung Achim	University of Birmingham
Professor Tony Gardner-Medwin	UCL
Professor Aaron Sloman	University of Birmingham
Professor Sugata Mitra	Newcastle University
Mark Wakefield	IBM UK Ltd
Sandra Wharton	Mathematics Adviser B and S Training Ltd
Catherine Oates	Galaxy Learn
Michael Clark	ARK
Jodie McDaniel	STEM Ambassador
Alex Frith	Usborne Children's Books
Dr Michael P Carter	Principal, Twin Learning LLC
Rich Chatwin	Science Gamed

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